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Muon Background in a 500 GeV TESLA Linear Collider

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Abstract

Muon background estimations for a 500 GeV c.m.s. energy TESLA linear collider are presented. Muons mainly from the Bethe-Heitler pair production mechanism are transported (by means of two independent programs) through the beam line until they either range out or reach the collider experiment hall. The amount of the muon flux is investigated as a function of the source position for different beam design variations. The effect of additional dedicated tools (toroids or magnetic cylinders) is also investigated.

1 Introduction

In e^+e^-linear colliders muons produced in electromagnetic beam-nucleon interactions in the collimation and final focus sections can produce an untolerable background in the experiment detector.

When electrons or positrons strike beam-halo collimators, muons are produced by a varity of mechanisms:

- Bethe-Heitler process with $\gamma Z \rightarrow \mu^+\mu^- Z$
- photopion production $\gamma Z \rightarrow \pi(\rightarrow \mu\nu)$ + anything
- direct e^+ annihilation, $e^+e^- \rightarrow \mu^+\mu^-$.

Out of these, the most important muon source is the Bethe-Heitler process which produces about one order of magnitude more muons than the others.

Historically, G. Feldman wrote the program MUCARLO when the MARK II detector at the Stanford Linear Collider (SLC) went into operation and saw a huge number of background muons coming from beam-halo collimators in the SLC final focus system. The program confirmed the origin of the muons, and it was possible to design special toroids which reduced the background considerably. The problem is expected to be worse in a 500 GeV linear collider for a number of reasons: the final focus bending angles are smaller, the muon momentum spectrum is much harder, the number of beam particles/pulse is (in general) designed to be larger, and the linac is close to the detector. L. Keller and S. Rokni adapted the program MUCARLO for the NLC linear collider design at SLAC [1] to estimate the expected muon background rate. This program has been installed at DESY-IfH Zeuthen by L. Keller and, with his help, the TESLA 500 GeV beam line parameters were implemented. In parallel, an independent program based on the CERN package GEANT has been written in Zeuthen so that more confidence on the reliability and an idea of the systematic errors would be obtained. Both programs rely on identical muon production procedures [1] and approximately identical beam line configurations; they differ in the muon tracking routines and in the treatment of the magnetic fields in the iron of the dipole and quadrupole magnets.

2 The beam line, the detector and the source

After the main linac the beam transport system up to the interaction point (IP) consists of the collimation section, the big bend and the final focus section, as sketched in Fig. 1.

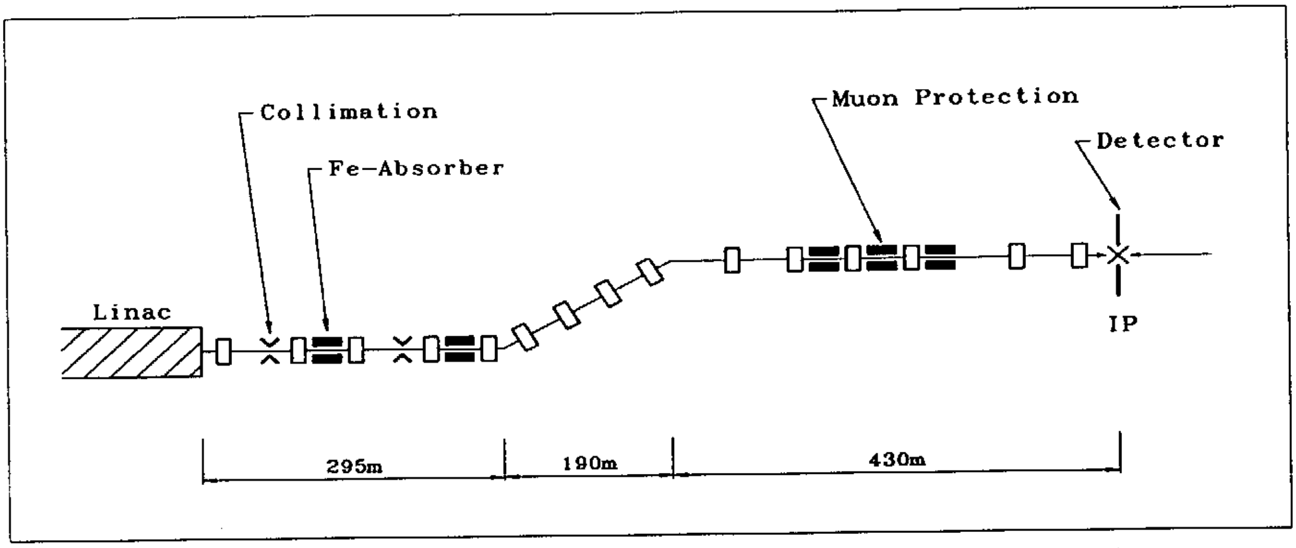

Figure 1: Sketch of the TESLA final focus beam line.

The TESLA beam lattice for 500 GeV c.m.s. energy has been designed by R. Brinkman [2] and has been adapted into our programs. The collimation section (with a length of ~295 m) involves a series of bending, quadrupole and sextupole magnets with a total bend of 7.69 mrad. It contains two dedicated titanium collimators to get rid of large beam tails. At some distance further downstream, iron absorbers (of size 1 m in beam direction and 1 m in diameter) are positioned. The big bend for muon background suppression follows. It involves 20 bending magnets with a total bend of 20.04 mrad and various quadrupole magnets. The last part of the beam line consists of the final focus section; it is ~ 430 m in length and produces a total reverse bend of 10.32 mrad. A variety of quadrupole and sextupole magnets will squeeze down the transverse bunch sizes. In our calculations we assumed that all the beam transport components are installed in a 3 m diameter concrete tunnel embedded in sandstone. Concrete support girders under the beam line elements are assumed, and dipoles and quadropoles include return flux in the iron and pole tips.

A cross section of the tunnel as assumed in the programs is schematically shown in Fig. 2a. This configuration will be denoted as the standard case in this paper and serves as reference for other somewhat modified beam transport and tunnel versions.

The detector is approximated to be a disc of 4.5 m radius, centered at the interaction point. All muons which hit the detector are counted, irrespective of their energy.

The source of the muons can be placed anywhere between the start of the

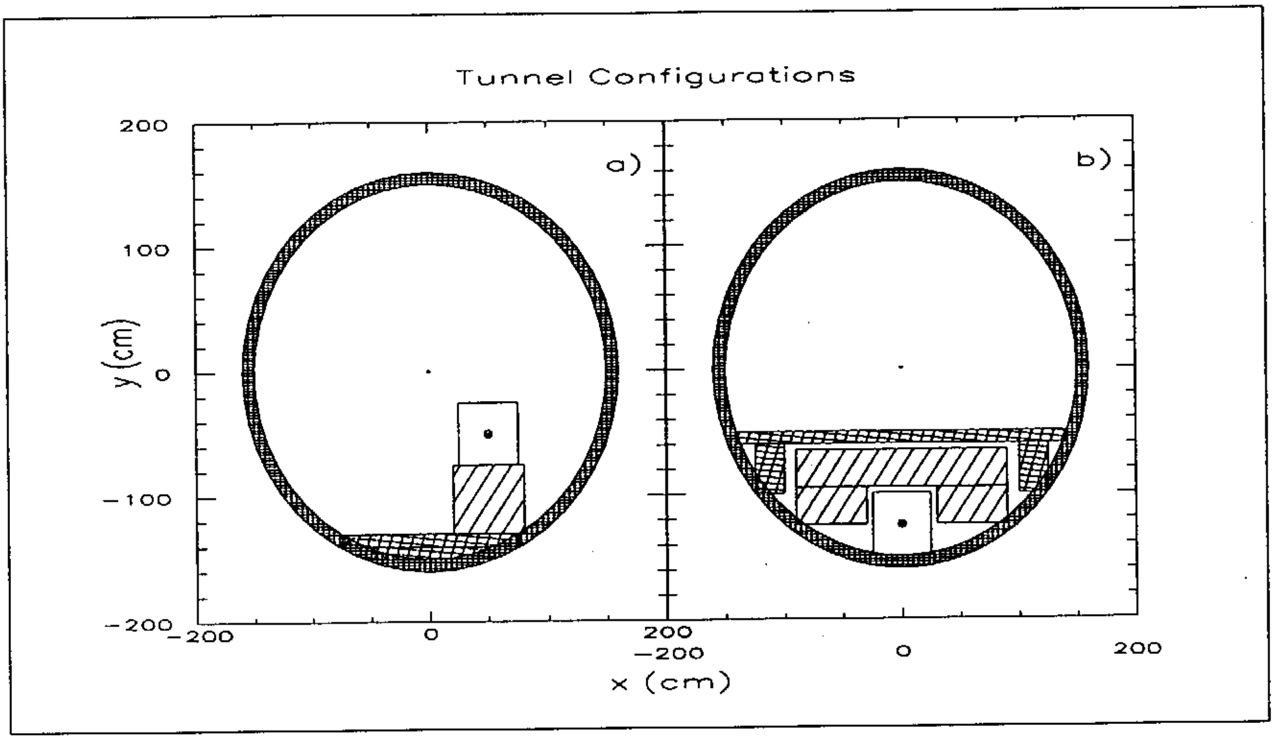

Figure 2: Tunnel configurations considered in this study.

collimation part and the IP. Its material and thickness are variable, and unless otherwise specified, the results presented in this study are for 20 rl of tungsten[1].

The assumed energy of the beam particles is 250 GeV. Muons are produced in the source randomly according to theoretical momentum and angular distributions. They undergo multiple coulomb scattering and energy loss and are bent in magnetic fields on their way to the detector. Fig. 3 shows an example of the momentum distribution of all muons as generated at a preselected point in the collimation section and, for those muons which reach the detector (typically one out of about 10^4), their original momenta at the source (hatched) as well as their momenta remaining after energy loss when they appear at the detector (cross-hatched).

Throughout this study the worst case is assumed, in the sense that the positron beam is always chosen so that direct annihilation production, $e^+e^- \rightarrow \mu^+\mu^-$, is included.

For completeness, some of the relevant design parameters of a 500 GeV TESLA linear collider are given: 5.15 10^{10} particles/bunch, 1 μsec bunch separation, 800 bunches/train and 10 bunch trains/sec [3]. Due to the relatively large bunch separation of 1 μsec we do not expect pile-up of muon signals produced from different bunches.

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[1] The use of other materials with different (and reasonable) radiation lengths does not alter the results significantly.

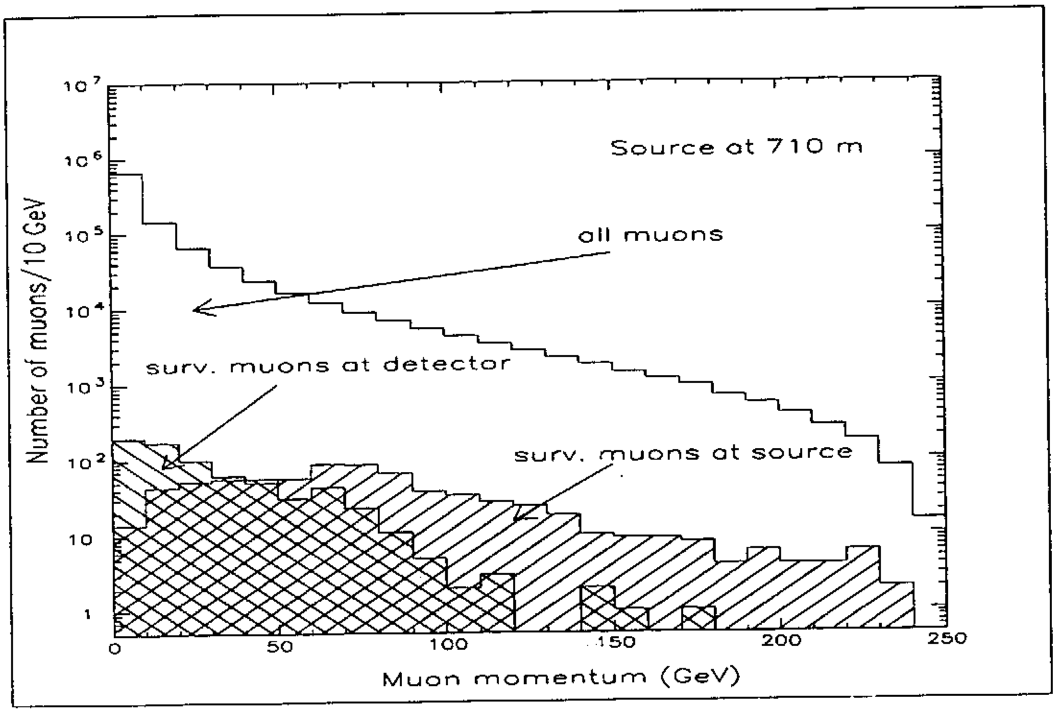

Figure 3: Muon momentum spectra for all muons as generated and for those which reach the detector. For the latter the hatched distribution corresponds to the original momenta while the cross-hatched includes energy loss.

3 Results

Fig. 4 shows, for our standard case, the number of beam particles which must hit the source in order to produce one muon in the detector, as a function of the location of the source. The full curve corresponds to the results obtained from the SLAC program while the dashed curve is obtained by means of the GEANT based program developed in Zeuthen. The results agree within a factor of 2 to 3. On average, the number of beam particles needed to produce one muon in the detector increases roughly exponentially with the distance to the IP. Interactions of beam particles are most probably expected, if at all, in the collimators which are located 710 m and 799 m upstram of the IP. The muon fluxes resulting from these positions are indicated by arrows in Fig. 4. As can be seen we expect about 140 respectively 20 muons in the detector if 1% of the particles of a TESLA bunch (beam-halo particles) hit one of the collimators. These numbers are probably unacceptable so that additional measures have to be taken in order to reduce the muon background.

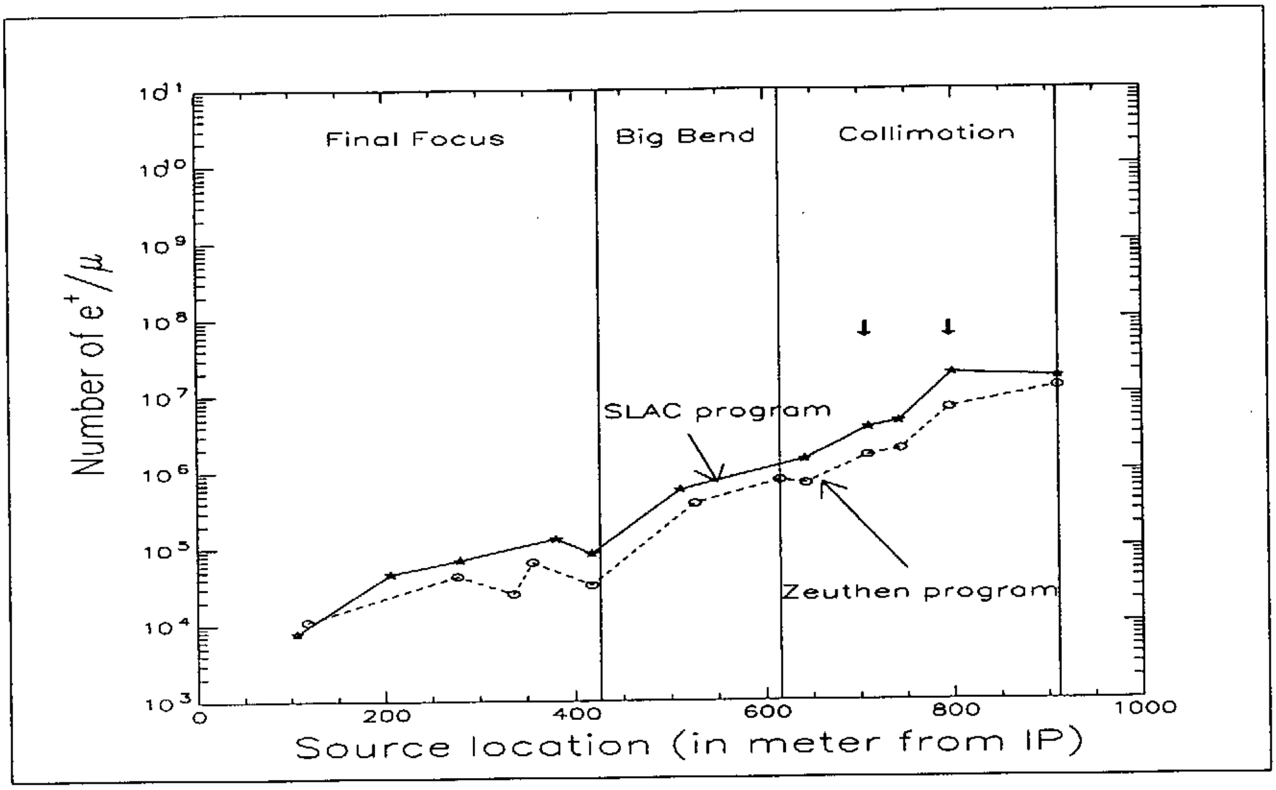

Figure 4: Number of positrons which hit the source in order to produce one muon in the detector as a function of the source location. The arrows indicate the location of the collimators.

3.1 Beam line position, tunnel size and material

Due to the predetermined bending direction of the beam line in the collimation and big bend sections, we expect the muon background rate to depend on the location of the beam line elements in the tunnel. It is found that positioning the beam line elements 0.5 m sideways from the tunnel center in the direction of the bend (as indicated in Fig. 2a), the muon rate at the detector is about four times less than in the case where the beam line is deplaced in the direction opposite to the bending[2]. However, the closer the muon source is to the IP, the weaker the dependence on the positioning in the tunnel.

Another suggestion is to place the beam line to the bottom of the tunnel and to cover it with e.g. 50 cm concrete on which further equipment may be installed. Filling large parts of the remaining open volume close to the beam line with moveable concrete blocks, as indicated in Fig. 2b, increases muon absorption further. Results for such a situation are presented in Fig. 5 as a function of the tunnel radius (dotted curve), and compared with the case of

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[2] In the SLAC program, such a sideway displacement into the bending direction is adapted from the beginning. The Zeuthen program, on the other hand, assumed the beam line elements to be in the center of the tunnel. About 50% of the differences between the results from the two programs in the collimation section in Fig. 4 can be ascribed to this.

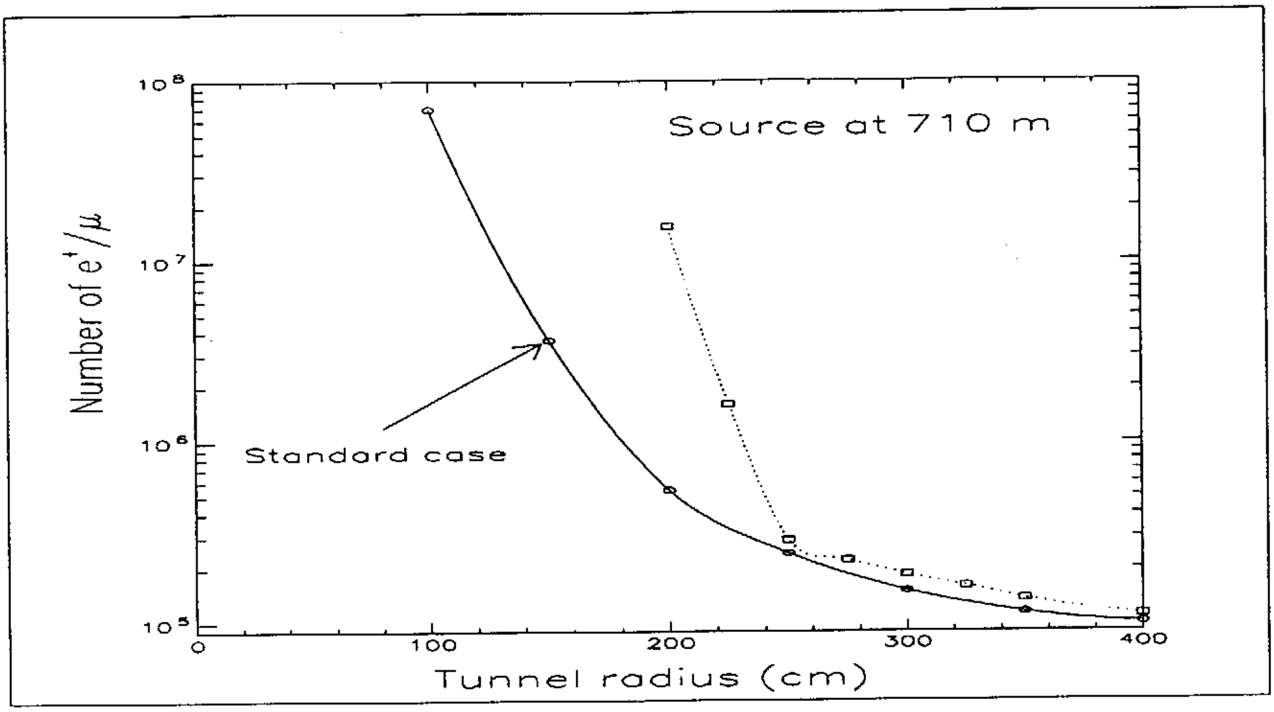

Figure 5: Number of positrons which hit the source in order to produce one muon in the detector as a function of the tunnel radius, for two locations of the beam line. The solid curve corresponds to the location as indicated in Fig. 1a while the dashed curve to that of Fig. 1b.

the beam line location as indicated in Fig. 2a. At radii $\lesssim$ 2 m the reduction of the muon rate by beam line repositioning and by surrounding it with concrete, is substantial. It can be seen that e.g. for a tunnel with 4 m diameter, the muon rate in the detector is reduced by at least one order of magnitude.

Fig. 5 illustrates another important issue, namely the dependence of the muon background rate on the tunnel diameter. Clearly, the smaller the tunnel cross section the larger the gain in the muon flux reduction. This gain decreases however with increasing radius and becomes negligible for large ($>$ 2.5 m radii) tunnel sizes, independent of the beam line locations considered.

As indicated in Fig. 2, no further material is assumed in the simulation programs to be in the tunnel. The impact of any material on the muon background rate has been simulated for an extreme (and unrealistic) case, namely flooding the tunnel with water. Fig. 6 compares the muon rates obtained under such conditions with our standard case. For sources located in the collimation section the number of beam particles needed to produce a muon in the detector is now increased by 2 to 3 orders of magnitude and, as expected, the effect gets smaller with decreasing distance to the IP.

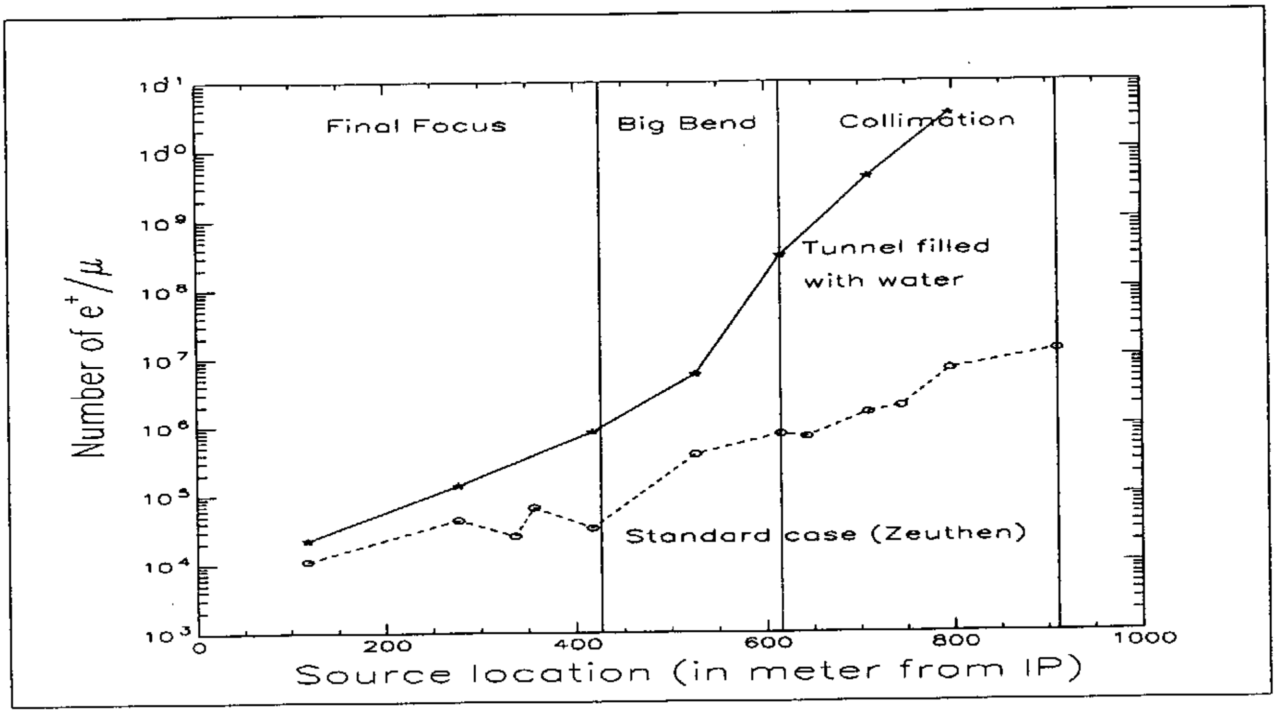

Figure 6: Number of positrons which hit the source in order to produce one muon in the detector as a function of the source location, for the standard case and the case of a tunnel filled with water.

3.2 The big bend section

It has been suggested that the addition of a big bend to a straight beam line should reduce the muon flux in the detector to a tolerable level. Muons produced upstream of the big bend (in the collimation section) propagate very close to the beam direction and, when they reach the big bend, continue more or less in their original direction, leaving the tunnel and, provided they have enough energy, bypassing the detector. The beam particles, on the other hand, are deflected by the big bend.

The impact of the big bend on the muon rate is demonstrated in Fig. 7, where the standard situation is compared with either the case with no big bend at all (corresponding to the point of the big bend length of zero) or the cases of extended big bend sections in steps of 100 m of air. The presence of the big bend as designed for the 500 GeV TESLA linear collider [2] reduces e.g. the muon flux by $5/36 = 0.14$ for a source positioned 710 m upstream of the IP. The reduction factor varies slightly with source position within the collimation section. We conclude that the big bend is important for muon background reduction; about one order of magnitude reduction can be obtained. A prolongation of the big bend (by a tunnel without equipment) further reduces the muon flux as seen in Fig. 7, and e.g. for a 500 m tunnel prolongation almost

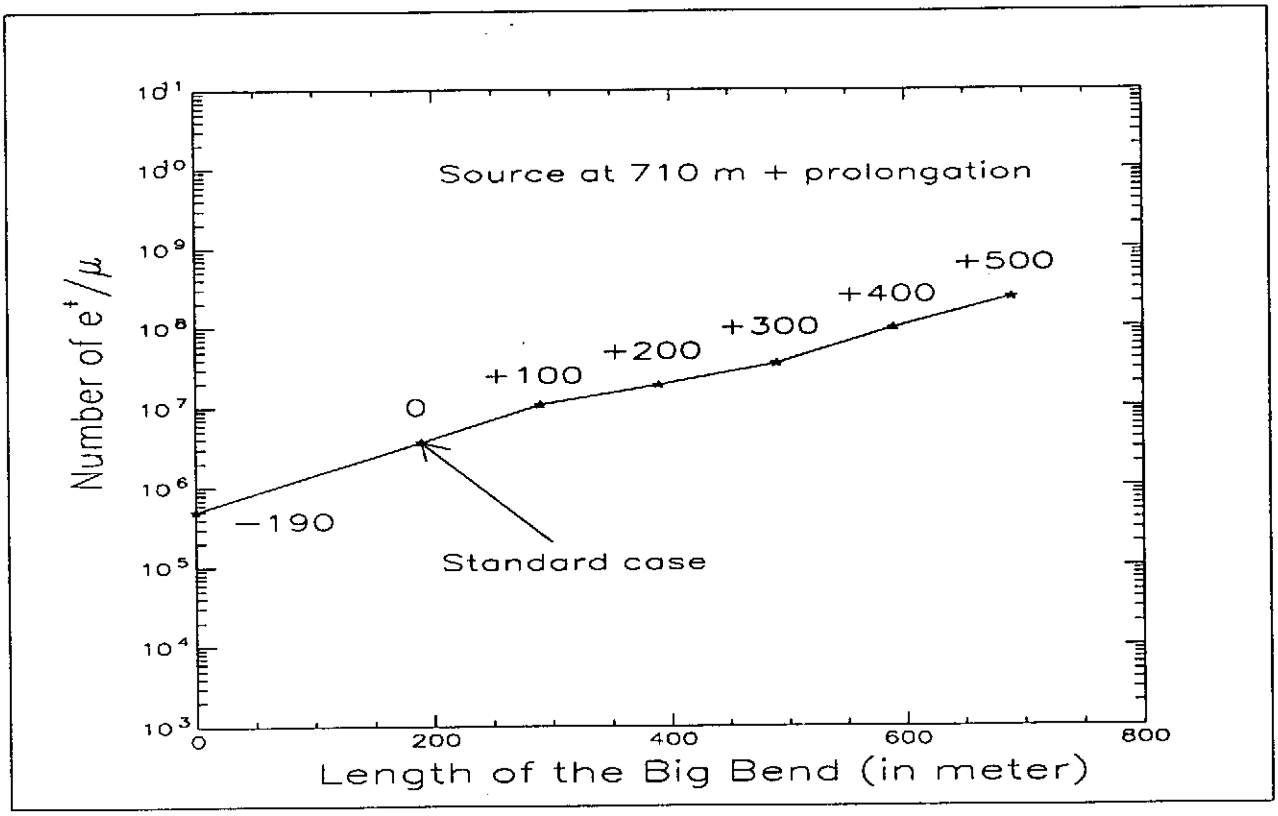

Figure 7: Number of positrons which hit the source in order to produce one muon in the detector as a function of the length of the big bend.

two orders of magnitude fewer muons reach the detector.

3.3 Magnetized toroids

An efficient method of muon background reduction suggested in ref.[1] consists in the installation of a series of magnetized iron toroids in the final focus section. In the simulation programs it is assumed that these toroids are 9 m long and completely cover the tunnel cross section except for a small vertical gap of the size of the beam line. They have a field of 16 kG of alternating polarity. In total seven toroids were assumed, one in the big bend and six (located in pairs) in the final focus section. The toroid in the big bend is somewhat extended into the sandstone so that better muon absorption is achieved. A nearly equidistant distribution of the final focus toroids with polarities as indicated in Fig. 8c gives the best solution. Fig. 8 provides a general impression of the behaviour of the surviving muons on their way to the detector and of the effect of the toroids on the muon flux. Fig. 8a shows muon tracks for the standard case of no toroids, Fig. 8b the standard case supplemented by toroids without magnetic fields while in Fig. 8c the toroids are magnetized. The number of muon tracks (normalized to e.g. an incidence of 2.5 10^9 particles 710 m upstream of the IP) which reach the detector are 715, 186 and 6 for the three cases (in Fig. 8a and b only a part of them is shown to avoid saturation in displaying muon tracks). The impact of the magnetized toroids on the muon behaviour and their number in the detector is clearly visible. The muon flux at the detector as expected for the three cases discussed, as a function of the source location is shown in Fig. 9. It can be seen that the toroids, if magnetized, improve the muon flux reduction by about two (or more) orders of magnitude; $\sim 10^9$ beam particles interacting in the collimation section are needed to deliver one muon into the detector. If we scale this number to the anticipated TESLA bunch intensity of $5\ 10^{10}$ particles/bunch, we expect only a handfull of muons in the detector even for a complete dump of the beam before the bending section.

3.4 Magnetized cylinders

An alternative tool to reduce the muon flux has been proposed in ref. [4]. The idea is to add large nested magnetized iron cylinders with azimuthal magnetic fields of opposite-polarity. These cylinders should be located downstream from, and close to, each muon source and should be long enough to either range out muons or to cause enough energy loss so that the muons are unlikely to reach the detector. We demonstrate in Fig. 10 their impact on the muon flux for a particular case: three cylinders of 9 m length and 1.5 m radius, with a current of 100 A in 48 windings, are located in the collimation respectively final focus section. While some improvement compared to the standard case is seen, the gain in background reduction is considerably less than with the magnetized iron toroids. However, there is room for further improvements by optimizing the number of cylinders, their fields, positions and sizes; this alternative to the system of toroids should therefore not be excluded in further studies.

3.5 Muon rate from secondary interactions

Under ideal conditions one expects that practically all beam particles travel through the beam line up to the detector hall. If beam particles interact at all, this will most probably occur in the collimator material where in most of the cases electromagnetic showers of electrons, positrons and photons are produced. These particles are supposed to be absorbed by iron absorbers further downstream of the beam line so generating with some probability additional muons which may eventually hit the detector. The rate of such muons has been estimated by simulating the interactions between the beam particles and the collimator material and tracking the produced secondaries (photons, e^+, e^-) to the absorber. Their average energy and impact point on the absorber are

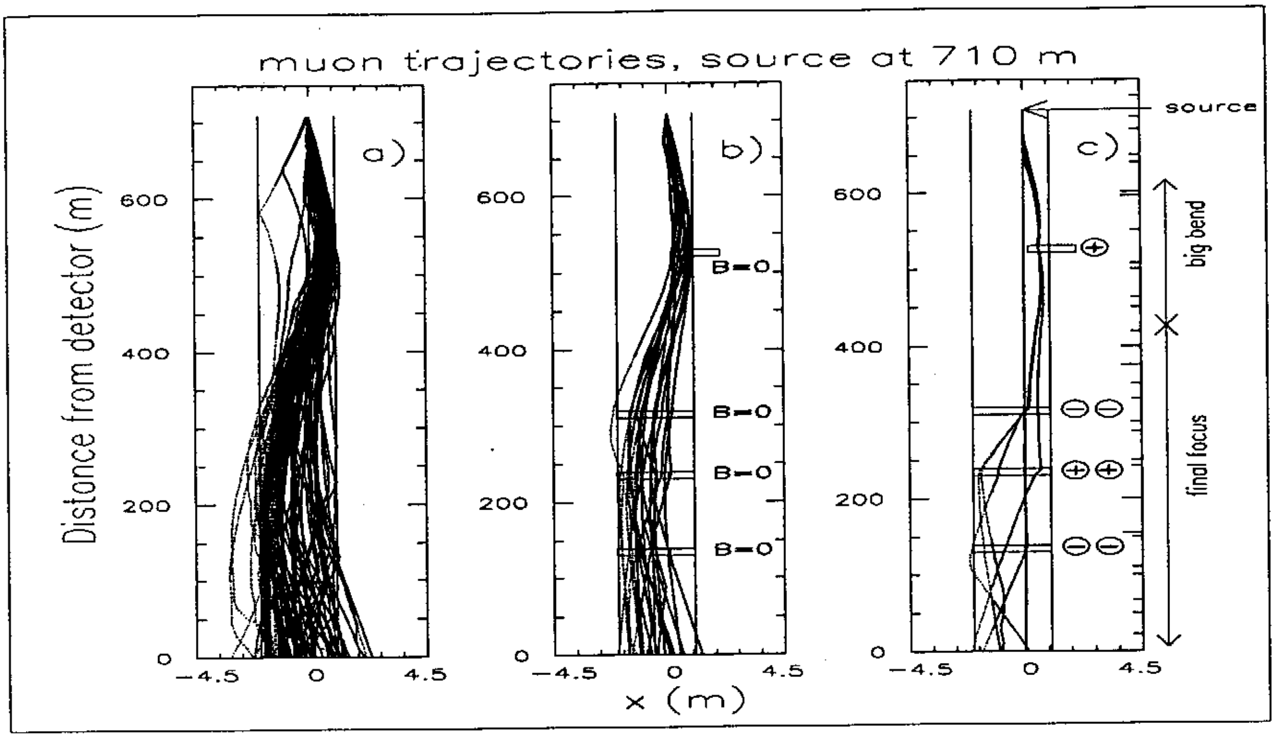

Figure 8: Tracks of muons produced 710 m upstream of the IP reaching the detector are shown for a) the standard case, b) the standard case supplemented by seven toroids without magnetic fields and c) the toroids magnetized. The symbol ⊕ means focus μ^- into the beam line whereas ⊖ means defocus μ^- particles. For clarity, the three beam line sections (collimator, big bend, final focus) are shown aligned without bending, and to avoid saturation in displaying muon tracks only a part of them is shown in a) and b).

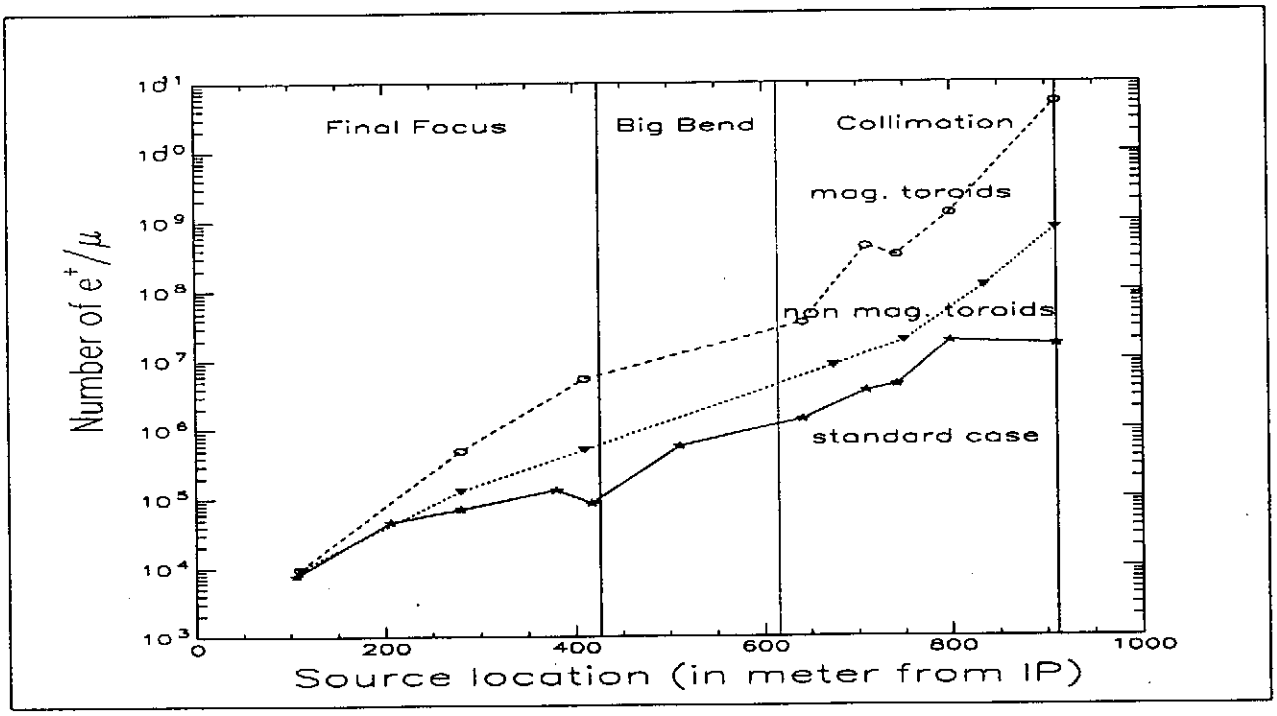

Figure 9: Number of positrons which hit the source in order to produce one muon in the detector as a function of the source location, for the standard case and for the case with seven toroids which are either magnitized or unmagnetized.

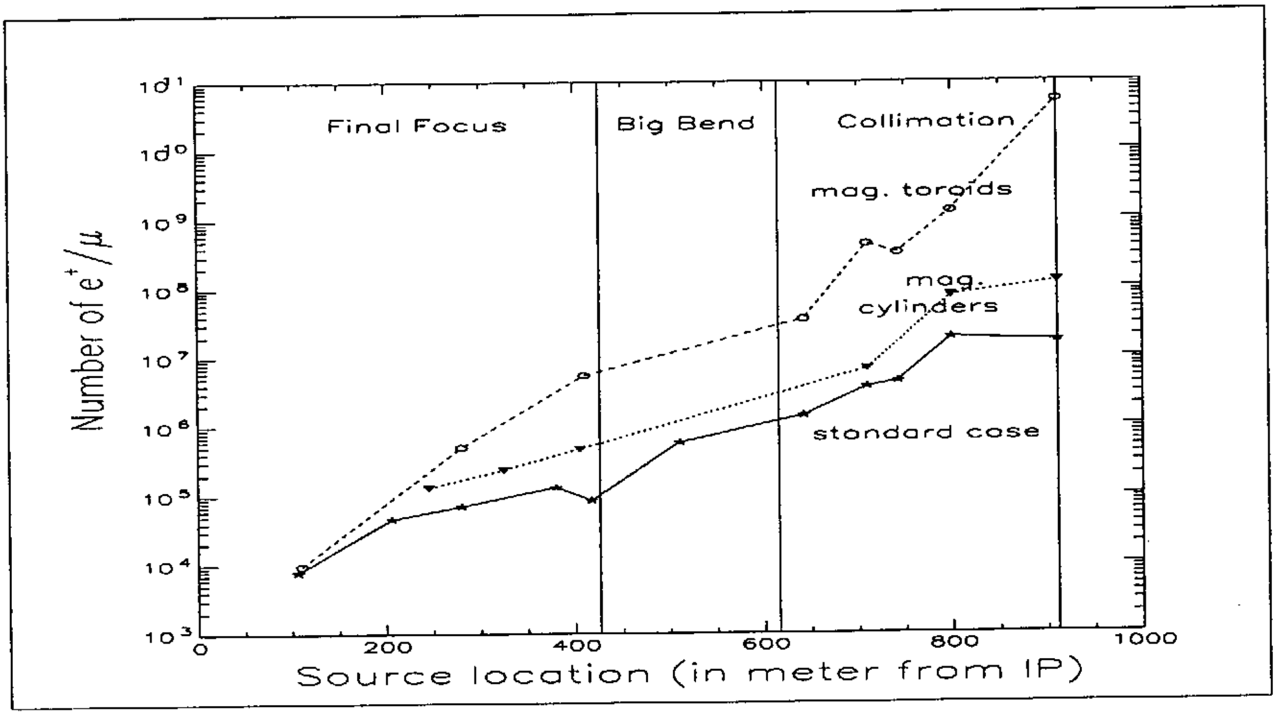

Figure 10: Number of positrons which hit the source in order to produce one muon in the detector as a function of the source location, for the standard case in comparison with the cases of magnetized iron cylinders and magnetized toroids.

then used as input for the muon production and tracking simulation programs. It is found that for the standard beam line ~5.4 10^8 primary (beam particle - collimator) interactions are needed to deliver one secondary produced muon into the detector. This indicates that muons produced in the absorber material are negligible compared with the 'directly produced' muons.

4 Summary and conclusions

Prompted by the observation of an untolerable number of muons from beam-halo collimators in the SLC final focus system and the expectation that this problem can be considerably worse in future e^+e^- linear accelerators, estimations of the muon background flux expected in a detector for the TESLA linear collider project at 500 GeV c.m.s. energy are presented. Using two independent programs, one developed at SLAC and the other at DESY-IfH Zeuthen, muons are generated mainly from the Bethe-Heitler pair production process and transported until they either range out or reach the experimental area. The results from the two calculations agree with each other as well as one can expect, taking into account the different approximations applied. This gives us confidence on the general reliability and first indications of the possible systematic uncertainties of the calculations. Various suggestions to reduce the muon background are discussed, and it is demonstrated that an appreciable reduction of the muon background can be achieved.

It is clear that suppression of muon background has to be considered in designing the linac and the final focus system, and that there are a large number of independent parameters that determine the rate of muons reaching the detector. A few of these were considered in this note, leading to the following recommendations:

- displace the beam line off the center of the tunnel into the bending direction or, even better to the bottom of the tunnel and enclose it by concrete blocks
- minimize the tunnel radius
- bring as much absorbing material into the tunnel as possible, thereby increasing the total r.l.

The impact of the big bend on the muon flux in the detector has been verified. For the beam line proposed for TESLA, the muon flux is reduced by about one order of magnitude. An appreciable further muon reduction is obtained by prolongating the big bend tunnel by some hundreds of meters.

Magnetized iron toroids in the final focus system are very efficient in reducing the rate of muons. For a particular toroid configuration, the number of muons produced by 1% beam loss (or $5\ 10^8$ beam particles/bunch) in the collimation section is tolerable or even negligible in the detector. An alternative scheme of magnetized iron cylinders with opposite-polarity azimuthal magnetic fields close downstream of the muon sources showed a less significant impact on the muon flux. Whether such a system can compete with a toroid system can only be answered by more detailed studies, since the parameters of such a system were not optimized and, in addition, they are coupled with general beam line parameters like tunnel dimensions, source locations, source thickness, magnet sizes, beam location in the tunnel, total bend section etc.

In summary, as far as sources in the collimation section of a 500 GeV TESLA linear collider are concerned the muon background rate expected might be a priori tolerable because of the large 12 σ_x and 35 σ_y beam line acceptances, which is in favour of other e^+e^- linear collider designs. Allowing a continuous 1% beam loss is therefore a very conservative assumption and serves primarily as a reference point. Improvements by about two or more orders of magnitude of the muon rate can be achieved by e.g. a system of magnetized toroids or, after some optimization, by magnetized iron cylinders.

Acknowledgements

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