# SHIELDING THE MUON COLLIDER INTERACTION REGION

C.J. Johnstone and N.V. Mokhov*
Fermilab, P.O. Box 500, Batavia, IL 60510, USA

*Abstract*

One of the most serious technical problems in the design of a 2-TeV muon collider arises from muon decay. With $2 \times 10^{12}$ muons in a 2-TeV bunch, $2 \times 10^5$ $\mu \rightarrow e\nu\tilde{\nu}$ decays occur per meter. Immersed in strong magnetic fields, the induced electromagnetic showers deposit about 2 kW/meter in the storage ring; far surpassing the heat load capacity of cryogenic systems. Yet a more problematic background is the intense, highly directional, neutrino flux generated by the decays. This background does not respond to conventional shielding techniques; in fact the total radiation dose from neutrino interactions is worsened in the presence of shielding. The work presented here will discuss methods to reduce or compensate for the severe decay backgrounds and radiation produced in a very high-energy muon collider.

## 1 INTRODUCTION

There has been strong interest in a high-energy high-luminosity $\mu^+\mu^-$collider project [1] based on the physics potential of such a machine which is beyond or complementary to what can be accomplished at $e^+e^-$and hadron colliders. However, there remain many issues to be examined in such a machine, especially technical ones. One of the most serious technical problems in the design of a muon collider arises from muon decay. With $2 \times 10^{12}$ muons in a 2-TeV bunch, there are $2 \times 10^5$ $\mu \rightarrow e\nu\tilde{\nu}$ decays per meter in a single pass through an interaction region (IR), or $6 \times 10^9$ decays per meter per second. Both the decay electrons (with an energy of about 700 GeV) and the synchrotron photons emitted by these electrons in a strong magnetic field induce electromagnetic showers in the collider and detector components. Almost 15 MW of power is deposited in the storage ring, or about 2 kW every meter. The resulting heat load to the cryogenic systems and the background levels in the collider detectors exceed the past operational experience and even the upgrade designs at hadron and $e^+e^-$colliders. In addition, the intense, directed neutrino beam generated is, in itself, a serious issue, perhaps even more so than the high radiation level from electromagnetic showers. Neutrino interactions in the soil intended to shield the collider produce unacceptable radiation levels at large distances. Since earth shielding is unavoidable, techniques have been explored which diffuse neutrino-generated radiation.

Substantial suppression of the induced background levels is critical in the concept of a muon collider and detector [1, 2]. The design of a storage ring and, in particular, an IR in such an environment is a difficult and challenging problem [3]. The merits of different approaches to solving beam-induced energy deposition issues in a muon collider IR are the subject of this paper. Calculations of the particle interactions in the lattice and detector components for a 2 TeV muon beam are performed with the MARS code [4].

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## 2 IR DESIGN PROBLEMS

The MARS studies have shown that the two quadrupoles nearest the interaction point (IP) require a minimum of 6 cm of tungsten. Even with a relaxed $\beta^* = 3$ cm IR lattice [5] a power dissipation in these quadrupoles range from 4 to 13 kW. An acceptable level is about 10 W/m so these values are too high by two orders of magnitude. The second solution, a noncosine theta magnet, does not work for the SC IR quadrupoles. Compared to the early IR design with $\beta^* = 3$ cm, the situation is much worse for a similar IR design with $\beta^* = 3$ mm even with a considered 6-cm thick tungsten liner.

In the IR adding a 6-cm liner increases the difficulty of an already problematic design, since the nonlinear attributes of the IR are strongly correlated with the strength of the final-focus quadrupoles [6]. The beam size at the quadrupole nearest the IP is only 2 cm; therefore, adding 6 cm to the aperture represents a factor of 4 decrease in the quadrupole gradient. The $\beta$-functions in the high-beta quadrupoles increase by roughly this factor, feeding an iterative effect: apertures increase further and gradients decrease correspondingly. First-order chromaticity has approximately a linear dependence on the peak $\beta$-functions, and increases proportional to the gradient reduction. Nonliearities, particularly those associated with sextupole-based chromatic correction have a much stronger dependence. Higher orders of chromaticity, for example, show an increase of about two orders of magnitude for a factor of two decrease in gradient. Therefore the net effect of a thick liner is to increase dramatically the nonlinear behavior of the IR.

## 3 REDUCTION OF HEAT LOAD

More recent designs [6] employed strong non-superconducting quadrupoles near the IP (Bitter quadrupoles), to reduce the peak $\beta$-function values and distribute the energy more evenly through the IR. The power levels, however, were still unacceptable in two of the SC quadrupoles: over a hundred Watts per meter. At this point it became clear that both active and passive shielding must be designed into the final focus system. The following calculations have been performed using the final focus and chromatic correction section shown in Fig. 1.

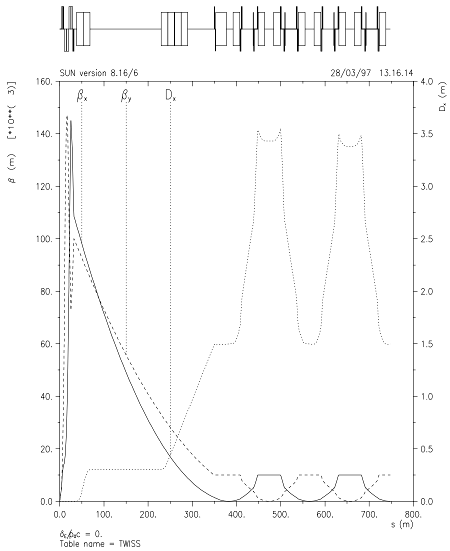


Figure 1: Horizontal (solid line) and vertical (dashed line) $\beta$-functions in the $\beta^* = 3\,\mathrm{mm}$ IR lattice. Dot-dashed line shows the dispersion.

To eliminate background particles generated outside of the IR, sweep dipoles were positioned on either side of the final focus [3]. To be effective, the sweep dipoles had to be 15 m long and superconducting with a poletip field of 8.5 T. Additionally, they had to be placed at least 1 m upstream of the elements to be protected. The sweep dipoles removed backgrounds propagating from the long drift preceeding the high-$\beta$ quadrupoles and from the arcs. In the latest design, a pair of reversed, horizontally-bending dipoles were used in order to restrain the dispersion function through the long IR drift. Otherwise, the dispersion would reach an enormous value at the end of the 150 m drift, which marks the beginning of the chromatic correction module.

In spite of the added dipoles, the heat load remained too high in most of the IR quadrupoles, in particular, the focussing and defocussing pair nearest the IP. Optically, these quadrupoles are the most significant in determining the nonlinear properties of the IR. Passive shielding was then included in the final focus to spread decay electrons (positrons) along the entire region instead of allowing them to hit apertures in the immediate vicinity of the IP. To achieve this tungsten collimators were sandwiched between all quadrupoles. Calculations indicate the collimators should be 15 cm long, with a $4\sigma$ aperture in order to fully shadow the SC quadrupoles which have a $5\sigma$ aperture. As shown in [3] combined effect of adding dipoles and collimators to the IR allowed the protective tungsten liner of all the SC quadrupoles, including the innnermost ones, to be reduced to 2 cm. Resulting power dissipation in the SC components is shown in Fig. 2 together with the results for the original lattice. One sees a drastic reduction in heat load in most critical components closest to the IP. With the thinner liner the strength reduction of the IR quadrupoles is a factor of 2 compared to the case with no liner, but it is twice as strong as the case with a 6-cm liner. The smaller liner reduced peak $\beta$-functions by about factor of two (to 150 km), and first-order chromaticities were correspondingly halved (presently -1500 in the horizontal and -2300 in vertical plane). Second and third order chromaticities fell by almost two orders of magnitude.

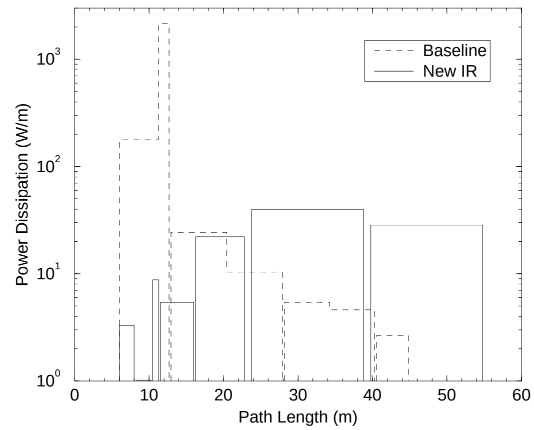


Figure 2: Power dissipation in the IR SC components.

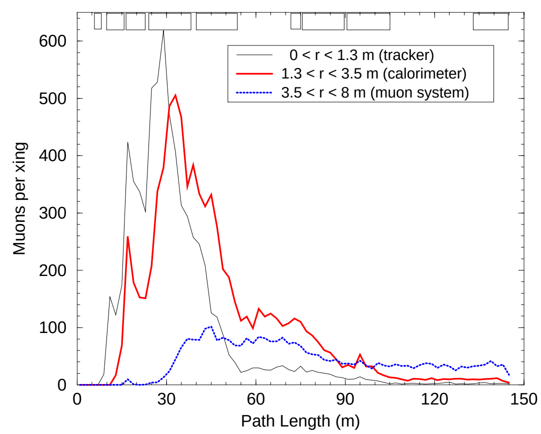


Figure 3: Number of secondary muons coming to three detector regions as a function of distance from IP of 2 TeV muon decays.

## 4 BACKGROUND REDUCTION

A careful design of the final focus system includes [3]: 1) tapered liner apertures, 2) sweep dipole magnets, 3) tungsten collimators interspersed between quadrupoles, and 4) tungsten collimators inside the detector with the aspect of two nozzles about the IP. Careful attention to the IR and shielding design has reduced the background levels significantly. In the optimum configuration, background fluxes are reduced by an order of magnitude. However, there still remains a serious problem with secondary muons, mainly

Bethe-Heitler pairs $\gamma Z \rightarrow Z\mu^+\mu^-$. Fig. 3 shows the secondary muon background distributions in three detectors caused by 2 TeV muon beam decays along the IR. One can deduce that the region, $15 \leq L \leq 90$ m, from IP is mostly responsible for high muon fluxes in the calorimeter. The results were obtained with thin shielding between the quads and dipoles, but it is clear that thick magnetized shields across the entire tunnel cross section (or even wider) will be required to bring the muon fluxes down. Another promising possibility, also studied using MARS, is the implementation of timing cuts.

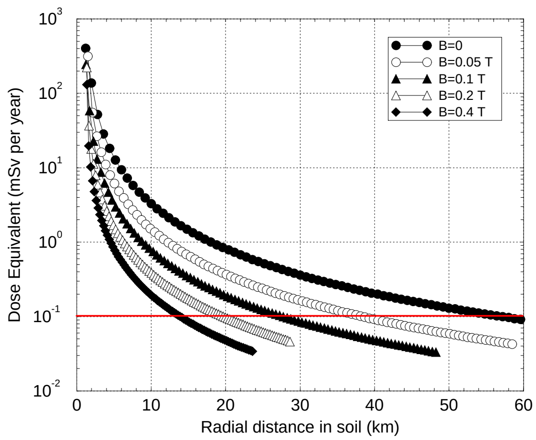


Figure 4: Neutrino induced average dose in the orbit plane *vs* distance in soil from the ring center for five values of the vertical wave field.

## 5 NEUTRINO

An intense secondary neutrino beam is created from muon decays and significant radiation levels result from neutrino interactions. The dose levels remain high even at very large distances from the collider ring [7]. Ironically, the neutrinos are not a problem in air at same distances; i.e. if the collider is left unshielded. Since the neutrino beam is highly collimated and directional – the intrinsic divergence is only 50 $\mu$rad from 2-TeV muon decay – the solution proposed here is to vary the production direction of the secondary neutrino beam. The neutrino beam is already spread in a horizontal disc by the collider dipoles. A vertical wave can be instituted in the collider ring to distribute the radiation and lower the average dose. This vertical wave should be varied in strength and phase over time to really smear the dose. MARS calculations indicate that such a floating vertical wave installed in the arc can be used to mitigate the neutrino flux by more then order of magnitude (Fig. 4). The approximately 8-m arc dipoles can be rolled by 20 mrad to achieve the desirable 200 $\mu$rad kick (B$\sim$0.2 T in Fig. 4). To avoid the complication of skewed quadrupoles, net rolls or horizontal magnetic fields are cancelled before entering quadrupoles. That is, the first dipole in a set of three is rolled 10 mrad horizontally, the next double that in the opposite direction, and the last the same amount in the original direction to almost exactly cancel coupling, vertical dispersion and amplitude effects. Reverse rolls and other time-varying changes can be instituted to reduce dose levels in all directions.

## 6 SUMMARY

The combination of $5\sigma$ aperture sweep dipoles and $4\sigma$ aperture tungsten collimators reduced not only the heat load in the SC IR elements to acceptable values, but also improved tremendously the performance of the muon collider IR through strengthed quadrupole gradients. The reduction of dissipated power is almost a factor of 2000 in some elements for the same IR design. Operationally, therefore, the beam-induced energy deposition problems in the IR appear to be resolved (if the liners and collimators are kept at room or nitrogen temperature). The backgrounds in the detector with the new IR, although reduced by a factor of 10, still require further work.

The serious problem of neutrino-generated radiation, in principle, appears to be solved by introducing a systematic, time-varying vertical wave in the collider ring to disperse this strongly-directed radiation. The lattice appears to support the concept of a vertical wave through rolled arc dipoles although detailed tracking and error studies need to be done to determine is such a configuration can be supported.

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