# INTEGRATED LOW BETA REGION MUON COLLIDER DETECTOR DESIGN

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*Abstract*

Muon Colliders produce high rates of unwanted particles near the beams in the detector regions. Previous designs have used massive shielding to reduce these backgrounds, at a cost of creating dead regions in the detectors. To optimize the physics from the experiments, new ways to instrument these regions are needed. Since the last study of a muon collider detector in the 1990s, new types of detectors, such as solid state photon sensors that are fine-grained, insensitive to magnetic fields, radiation-resistant, fast, and inexpensive have become available. These can be highly segmented to operate in the regions near the beams. We re-evaluate the detector design, based on new sensor technologies. Simulations that incorporate conditions in recent muon collider interaction region designs are used to revise muon collider detector parameters based on particle type and occupancy. Shielding schemes are studied for optimization. Novel schemes for the overall muon collider design, including "split-detectors", are considered.

## INTRODUCTION

Recent advances in muon cooling schemes have increased the competitiveness of potential muon colliders, especially at higher energy[1]. Detector designs for muon colliders have lacked coverage of the particles emerging from the collision region in the forward and backward angular regions, limiting their physics potential. These regions require massive shielding, mainly due to the intense radiation produced by the decay electrons from the muon beams. Emerging technologies for instrumentation could be used to detect particles in these regions that were filled with inert material in previous designs.

## BACKGROUNDS

How well and what kind of physics can be produced with a muon collider depends on how well the backgrounds can be controlled. Most backgrounds are associated with the products of the decaying muons that get into the detector region. A 2 TeV/c muon beam, that was studied for a 4 TeV center of mass muon collider [2], with $2\times10^{12}$ μ per bunch will produce $2\times10^{5}$ decays per meter. The size of the beam related backgrounds are proportional to the number of μs in the bunch. Because the number of decays per length scales with $1/\gamma$ from Lorentz contraction and the size of a an interaction region will likely grow with $\gamma$, the number of muon decays expected in the region of the detector is approximately independent of energy. The electrons from the muon decays will not have the designed momentum of the collider ring and will either interact with the wall of the beam chamber producing electromagnetic showers or produce synchrotron radiation in regions of large transverse magnetic field. The design of a detector for a muon collider will be constrained by the necessity to reduce the electromagnetic background. The effort to minimize the backgrounds will have a strong influence on both the design of the detector and the design of the collider ring lattice in the vicinity of the intersection region.

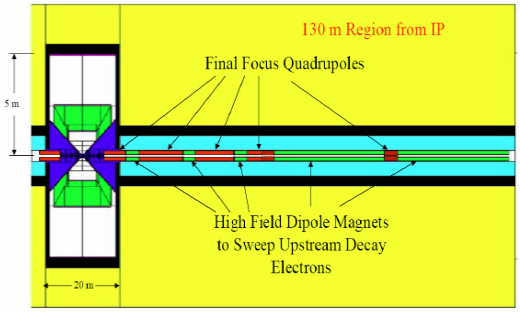

Figure 1: Sketch of the IP region and 130 meters of the final focus magnet system with quadrupoles (Q) and toroids (T). This sketch shows the geometry of the detector used in the 1996 GEANT simulation of a 2 × 2 TeV Muon Collider. The conical tungsten-filled region, shown in dark blue, was required to absorb debris from muon decays in the beams. Because of the limitations of detector technology at the time, this area was not instrumented.

Figure 1 shows a sketch of the geometry of a muon collider detector along with the final focus magnets of the collider ring, that was used in the 1996 Muon Collider Feasibility Study [3]. A number of features that were imposed on the design of the final focus region of the intersection point included:

- A conical tungsten shield surrounding the beam enclosure extending to 20º in both the forward and backward directions
- The inner surface of the shielding cone designed such that the detector does not see any surface that a decay electron can.
- The open space between the interaction point (IP) and the tungsten shielding constrained to several cm).
- The inner surface of the conical shield shaped in a sawtooth manner. to collimate the electrons in the beam and maximize the absorption of the electromagnetic showers from the electrons that graze the cone surface..

The presence of the conical shields in the forward and backward directions limits a muon collider physics reach,

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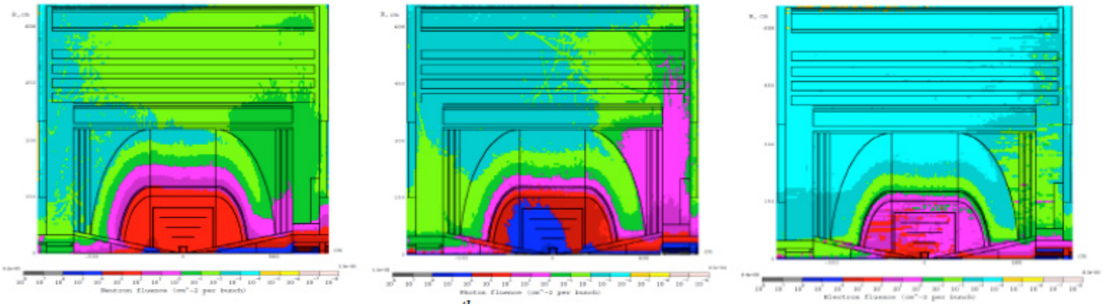


Figure 2: Muon Collider IR particle fluences in the 4th Concept Detector. Left to right: Neutron, photon and electron fluences.

With advances in particle detection and read-out technology n the years since the 1996 Muon Collider Feasibility Study, the detector coverage can be pushed into the forward region previously considered unsuitable for particle detection.

Recent efforts have been made to realistically evaluate backgrounds from muon decays inside the lattice of a collider ring. The decay length for 0.75-1 TeV muons is $\lambda_D = 4X10^6$ m. With $2e^{12}$ muons in a bunch, one has $4.28X10^5$ decays per meter of the lattice in a single pass, and $1.28X10^{10}$ decays per meter per second for 2 beams. Electrons from muon decay have mean energy of ~1/3 that of the muons. At 0.75 TeV, ~250 GeV electrons, generated at the above rate, travel to the inside of the ring magnets, and radiate considerable amounts of energetic sychrontron photons towards the outside of the ring. Electromagnetic showers induced by these electrons and photons inside the collider ring components generate intense fluxes of muons, hadrons and daughter electrons and photons. This creates high background and radiation levels both into the ring and detector. Figure 2 shows recent calculations using MARS15 model and a recent muon collider detector scheme that illustrates the challenge.

## PHOTON DETECTORS

New technology is emerging that has several advantages for the application proposed here. In particular, developments in Geiger-mode avalanche photo diodes have enabled great advances in calorimeter performance in challenging environments [5]. They are very compact and have high gain ($\sim 10^5$) and good particle detection efficiency. Furthermore they have been shown to be insensitive to magnetic fields as high as 4.4T [6] and have good (sub-nanosecond) time resolution [7], and good radiation tolerance, with no deterioration seen at 1 Mrad gamma radiation exposure[8]. The primary challenges are: thermal noise rate, non-linear response due to limited number of pixels (saturation effect), sensitivity to temperature change and cross-talk and after-pulsing.

## CALORIMETRY

Recently, detector R & D for the ILC and other future colliders has included designs of calorimeters for luminosity measurements, beam monitoring, and diagnostics[9].. Detectors for beam diagnostics using beamstrahlung photons and pairs are being considered with instrumented tungsten. Figure 3 shows examples of calorimeters currently under study for use in very far forward regions in advanced lepton colliders with large backgrounds and radiation environments. These technologies can be adapted to the similarly severe conditions of a muon collider detector extended down to lower forward angles than have been previously considered.

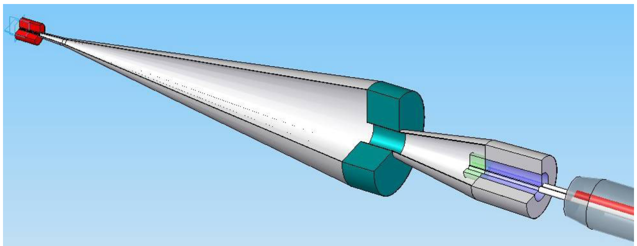
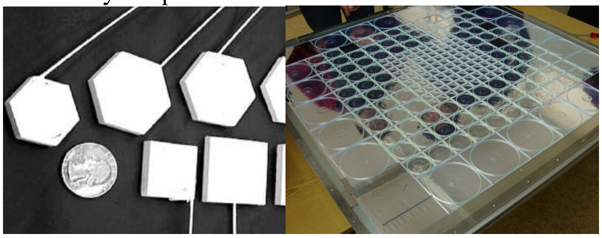


Figure 3: Illustration of conceptual forward calorimeters for luminosity (40-140 mr, shown in teal) and beam diagnostic (<40 mr, shown in blue) measurements. Advances in electronics that allow these designs can be used in a muon collider detector.

Northern Illinois University (NIU) has been involved with the design, optimization, construction, commissioning and operation of a silicon-tungsten electromagnetic calorimeter and a steel-scintillator hadron shower imager as part of the CALICE test beam program at the H6B area at CERN. The NIU group has pioneered use of arrays of plastic scintillator tiles in calorimeters.



(a) (b)

Figure 4 (a): Examples of plastic scintillator tiles for use in calorimeters made by the NIU group; (b): Array of scintillating tiles arranged on 1m x 1m plate of a prototype CALICE hadron calorimeter. The tiles are arranged as a mosaic with smaller tiles in the high rate regions and larger tiles farther away.

Using simulations to provide expected particle flux rates at different depths in the shielding cones, the sizes and arrangements of tiles that can function can be optimized.

## MACHINE-DETECTOR INTEGRATION

The development of muon collider experimental detectors must be in concert with the machine designers. This has been obvious in the past where, for examples, the length of the low beta lattice insertion of colliders has limited detector size, the distance from the IP to the nearest quad of the focusing triplet has been a compromise between the low beta value and detector coverage, or the beam halo has affected the placement of silicon vertex detectors because of background rates and sensitivity to radiation damage.

In a muon collider, this concept of machine-detector integration may be more important than in the past. An example of this concept may be understood from the excerpt below, which was taken from Fermilab's Muon Collider Task Force 5-year Plan Proposal that was submitted to the MUTAC, the technical advisory committee that advises the managements of BNL, FNAL, and LBNL on muon related research. Table 1 presents of this excerpt, three different scenarios for muon colliders described in the plan which have very different implications for detectors. (The table also has many caveats since none of the three scenarios is entirely credible, requiring devices and techniques that are not yet available.)

Table 1. Parameters for a 1.5 TeV (c.m.) muon collider.

| | LEMC | MEMC | HEMC |
|---|---|---|---|
| Avg luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 2.7 | 1.33 | 1 |
| Avg. bending field (T) | 10 | 6 | 6 |
| Proton driver rep. rate (Hz) | 6.5 | 40 | 13 |
| $\beta^*$ (cm) | 0.5 | 1 | 1 |
| Muons per bunch ($10^{11}$) | 1 | 11.3 | 20 |
| Norm. Trans. Emittance (μm) | 2.1 | 12.3 | 25 |
| Norm. Long. Emittance (m) | 0.35 | 0.14 | 0.07 |
| Energy spread (%) | 1 | 0.2 | 0.1 |
| Estimated muon survival (%) | 31 | 20 | 7 |

## CONCLUSIONS AND FUTURE PLANS

New detector designs for a muon collider will enable higher luminosity muon collider designs with more aggressive beam focusing systems for the interaction regions. The improvements to the acceptance in the forward direction expected from this project will make a muon collider more attractive in that it will be able to address a broader range of physics questions. Simulations that approximate conditions in the forward regions for contemporary muon collider design parameters are being used to specify requirements for large-scale, high-granularity instrumentation for these regions. Technological advances in particle detection make it possible to instrument a portion of the forward region of muon collider detectors , previously considered only for shielding in detector designs for muon colliders.

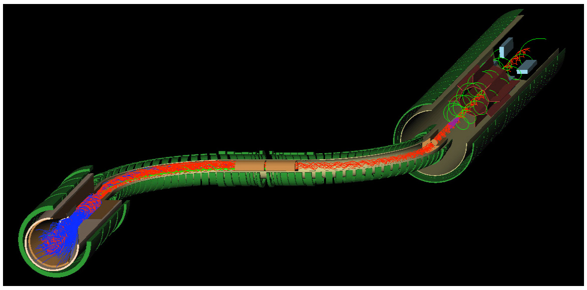


Figure 5: Illustration of beam channel and detector simulated for the proposed Mu2e experiment at Fermilab as an example of use of the G4beamline interface to Geant4. Green elements are the magnetic coils of the bent-transport and detector solenoids. Here the (blue) positive muons are seen to be absorbed in the collimator in the middle of the bent solenoid while the (red) negative muons go on to the detector. C++ programming was not required for this study

The innovation of "instrumented shielding" in the forward region with calorimetry or timing detectors for active read-out would take maximal advantage of the higher luminosity of recent muon collider designs. With better muon beam cooling and more aggressive beam focusing systems, the physics reach of these machines will be extended.

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