DYNAMICS OF DECAY ELECTRONS AND SYNCHROTRON RADIATION IN A TEV MUON COLLIDER*

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Abstract

The decay electrons (and positrons) in a TeV muon collider present major challenges as heat loads to the superconducting magnets and as sources of Bethe-Heitler muon pairs that form streaming backgrounds in the detectors. If the dipoles are configured so as to accommodate a vacuum gap extending in the horizontal midplane between the coils, it is possible to channel both the decay electrons and the synchrotron radiation out of the magnet and intercept them at significant angle at the exit aperture. In this way both the heat load and the muon halo problems are mitigated.

1 MUON DECAY IN A MUON COLLIDER

Ankenbrandt *et al.* [1] summarize the design of a proposed TeV muon collider. In a well-optimized muon collider, ~half of the muons will decay during each store. Each muon decay produces an electron and two neutrinos, with a 3-body spectrum in which they share the muon's energy. The energy E of the decay electron can take any value $0 < E < E_\mu$. The maximum transverse momentum in the decay is $p_\perp \sim m_\mu/3 = 35$ MeV/c. This $p_\perp$ is small compared to the angular divergence from the beam emittance, so each electron is born traveling in the same direction as its parent muon but with a fraction $x = E/E_\mu$ of its energy (Everything in the following discussion applies equally of course to $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$).

Now consider the motion of the decay electron as it continues in the collider lattice. It is bent with a radius of curvature $R = x R_\mu$, towards the inside of the ring from the equilibrium orbit of the muons. If the collider lattice dipoles were constructed in the conventional fashion, with a central aperture flanked by coils, the electrons would soon strike the wall of the vacuum tube and produce an energetic electromagnetic cascade in the superconducting coils of the magnet. This cascade would deposit a lot of heat in the coil: assuming 3×10^{13} μ/s delivered to the ring, 2 TeV beam energy, half of the muons decaying, and one third of the decay energy in the electrons, heat power **P =** 1.6 MW would be deposited, mostly in the superconducting magnets! Scenarios with water-cooled tungsten liners have been suggested, but do not solve the problem.

The decay electrons also radiate intense synchrotron radiation. When an electron of 1 TeV travels in a dipole field of 10 Tesla energy, it radiates 150 GeV/m! It radiates ~½ of its energy within the length a single dipole. Furthermore the critical energy radiated by a 1 TeV electron (the most probable energy of each radiated photon) is 6 GeV! Such photons produce energetic showers when they contact the beam tube, contributing about as much heat to the dipoles as the electrons themselves.

2 REMOVE THE WALLS!

We have developed a design for the arc dipoles, in which a slot is opened between the top and bottom halves of the dipole coil and the vacuum enclosure is extended out into the midplane to a distance of ±20 cm from the beam axis. A quadrant of the dipole is shown in Figure 1. The field strength is constant within the muon beam region, then decreases and reverses as shown in Figure 2.

The motivation in this design is to permit decay electrons and synchrotron radiation to traverse the length of a dipole without striking any surface. At each end of each dipole, the electrons and photons would be absorbed at room temperature, eliminating the cryogenic heat load.

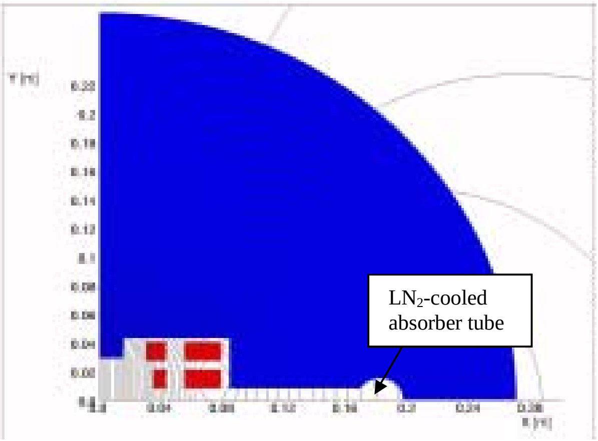

Figure 1. Quadrant of the slot dipole.

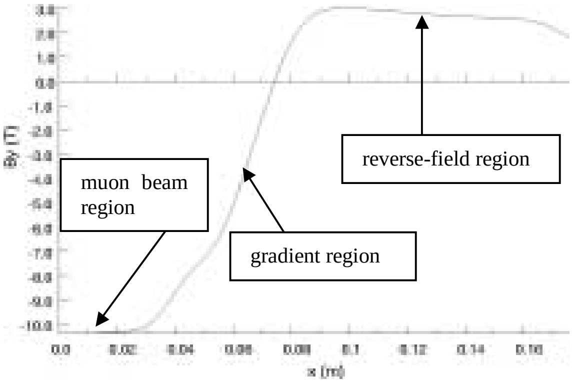

Figure 2. Field strength *vs.* x within the slot region.

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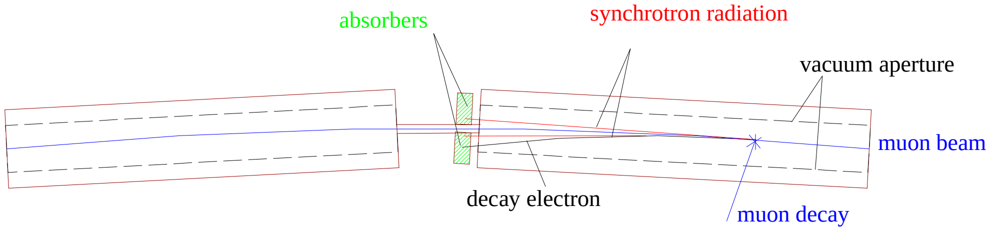


Figure 3. Schematic showing two dipoles and trajectories of the muon beam (blue), decay electrons (red), and synchrotron photons (green).

At each end of the dipole, the vacuum aperture would constrict from a 40 cm wide slot to the ~3 cm radius beam tube needed to pass the muon beams. Flanking this constriction, room-temperature absorbers would absorb decay electrons and synchrotron.

3 DYNAMICS OF ELECTRONS AND PHOTONS IN THE SLOT DIPOLE

The dynamics of the electrons and photons is a consequence of the field distribution shown in Figure 2. As a decay electron deflects towards the inside of the ring, it enters the region between the coils where the field decreases to zero. This gradient region focuses the electron horizontally (and defocuses it vertically). The electron will oscillate horizontally about an equilibrium orbit. The location of the equilibrium x_0 is a function of the electron momentum: $x_0 \sim 3$ cm for $E \sim E_\mu$; $x_0 \sim 7$ cm for $E \sim 0$.

3.1 Vertical defocusing limits dipole length

The decay electron is defocused vertically:

$$\frac{d^2 y}{ds^2} = (eG/E)y \qquad (1)$$

where $G \sim 250$ T/m is the gradient in the coil region. The invariant emittance for a TeV muon collider is $\varepsilon = 50\ \pi\ 10^{-6}$ m. Assuming a lattice function $\beta \sim 70$ m, the beam size in the arc dipoles is $\sigma_y = \sqrt{\beta\varepsilon/\pi\gamma} = 0.4$ mm, and the divergence is $\theta_y = \sqrt{\varepsilon/\pi\beta\gamma} = 6\ \mu$rad. Starting from these parameters, the distance after decay where a decay electron would reach the top (bottom) of the slot ($y_s = 1$ cm) is

$$S = \sqrt{E/eG}\,\ell n\left(y_s/\sigma_y\right) \qquad (2)$$

As discussed below, the electron energy decreases rapidly by synchrotron radiation for energies ~TeV, reaching a plateau at ~200 GeV. Detailed modeling of the vertical displacement shows that the decay electrons reach the slot surface y_s at an arc length $S = 7.5$ m. This sets the limit to the length of arc dipoles that can transport all decay electrons to the absorber without interception on the slot side walls.

3.2 Dynamics of energy loss and focusing

We have modeled the motion of decay electrons, including the energy loss from synchrotron radiation and the deflection in the magnetic field $B_y(x)$. The energy E, position (x,y), and angle θ_x as a function of arc length s following the location where the muon decays were calculated for each of a variety of decay electron energies. The results are presented in Figure 4.

The first feature to note from these results is that, for electron energy $E \geq 500\,GeV$, the electron loses energy rapidly from synchrotron radiation, arriving at an energy ~200 GeV, below which value energy loss is slow. Synchrotron radiation power is quadratic in electron energy:

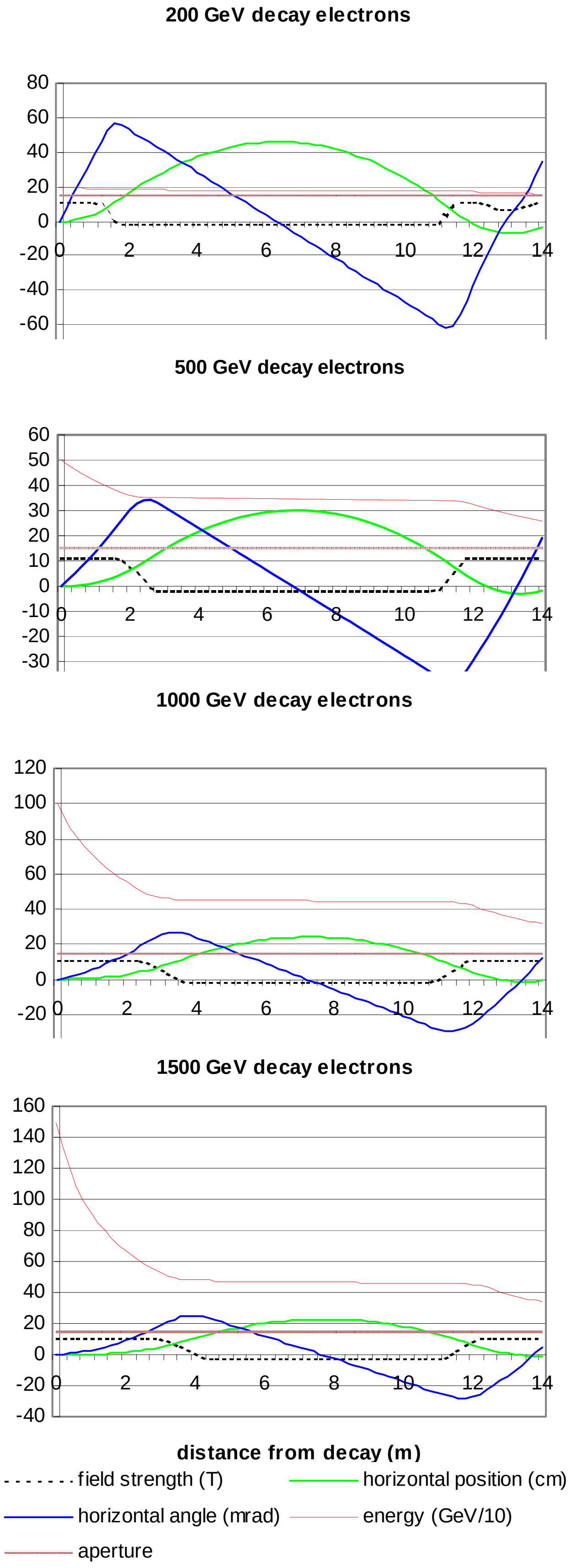
$$P = \frac{2e^6c^2}{9\varepsilon_0 (mc^2)^4} E^2 B^2 \qquad (3)$$

Energy loss is so rapid for high-energy electrons that they reach an asymptotic energy of ~200 GeV in ~3 m path length. This has the beneficial effect that almost all electrons of high energy will have degraded to ~200 GeV before they are intercepted, so that any Bethe-Heitler $\mu^+\mu^-$ pairs will have a soft spectrum and be more easily shielded.

The second feature to note is that all electrons reach the horizontal aperture limit $x_a = 18$ cm at which a liquid nitrogen-cooled absorber is located, and they reach this aperture within the length of one dipole (7 m). Decays originating near the end of one dipole will pass through the muon beam tube at the end and continue into the next dipole. Such decay electrons will evolve through the next dipole's focal guide and be absorbed either on the LN_2 absorber tube at x_a or on the water-cooled absorbers at the end of that next dipole.

The third feature to note is that there is a correlation between angle and displacement: if electrons are intercepted either at the end of the dipole or when they reach a displacement x_a, they have an angle >20 mrad to the direction of the beam axis. This has the consequence that any Bether-Heitler pairs produced in the interactions of decay electrons will be born at sufficient angle that they cannot be magnetically transported along the magnet lattice.

It remains to estimate the share of energy (electrons and photons) that is absorbed on the end absorbers, compared to that which is absorbed on the LN_2 – temperature tubes. We source electrons with equal weight along the muon beam, and with the 3-body spectrum of μ decay (see Figure 4). We source synchrotron light according to Eq. 3, and follow the light along line-of-sight trajectories. We sum the energy that is intercepted on the LN_2 tubes (x_a) and the energy that is intercepted on the end absorbers.



200 GeV decay electrons

500 GeV decay electrons

1000 GeV decay electrons

1500 GeV decay electrons

Figure 4. Transport of decay electrons through the slot dipole.

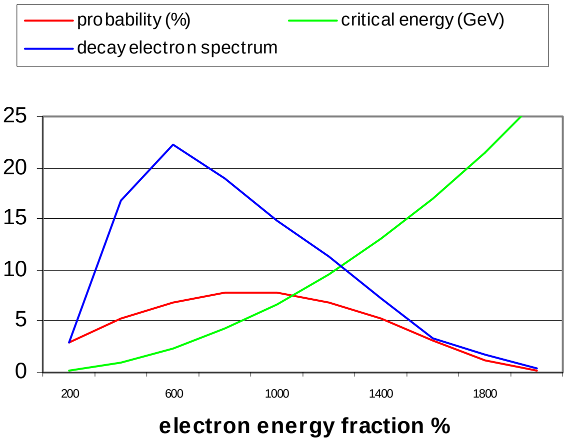


Figure 5. Fraction of energy absorbed on LN$_2$ tubes, and critical energy, *vs*. electron energy.

Figure 5 shows the decay spectrum, the critical energy of photons, and the probability that energy is intercepted on the LN$_2$ absorber tubes, as a function of electron energy E. **f =** 6% of all decay electron energy is absorbed on the LN$_2$ absorber tubes (the balance is absorbed on the end absorbers). The total power absorbed on the LN$_2$ tubes is then **fP** = 100 kW. This heat power requires ~1 MW of refrigeration power to remove at room temperature, a modest power budget for a TeV muon collider.

4 CONCLUSIONS

The slot dipole makes it possible to transport 94% of all decay electrons and associated synchrotron light photons onto room-temperature absorbers located between adjacent dipoles. The balance of energy is absorbed on LN$_2$ – temperature tubes within the dipole, so that heat is not deposited on the LHe- temperature surfaces of the dipoles.

Lastly the decay electrons are degraded by light emission to ~200 GeV before being absorbed, andare aabsorbed when they are deflected at angles >20 mrad. As a result Bethe-Heitler $\mu^+\mu^-$ pairs are soft in energy and dechanneled from transport along the lattice.

For these reasons the slot dipole offers a solution to two of the difficult challenges for the design of the arc lattice of a multi-TeV muon collider.

5 REFERENCES

[1] C.M. Andenbrandt *et al.*, “Status of muon collider research and development and future plans”, Phys. Rev. Special Topics **2**, 81001 (1999).