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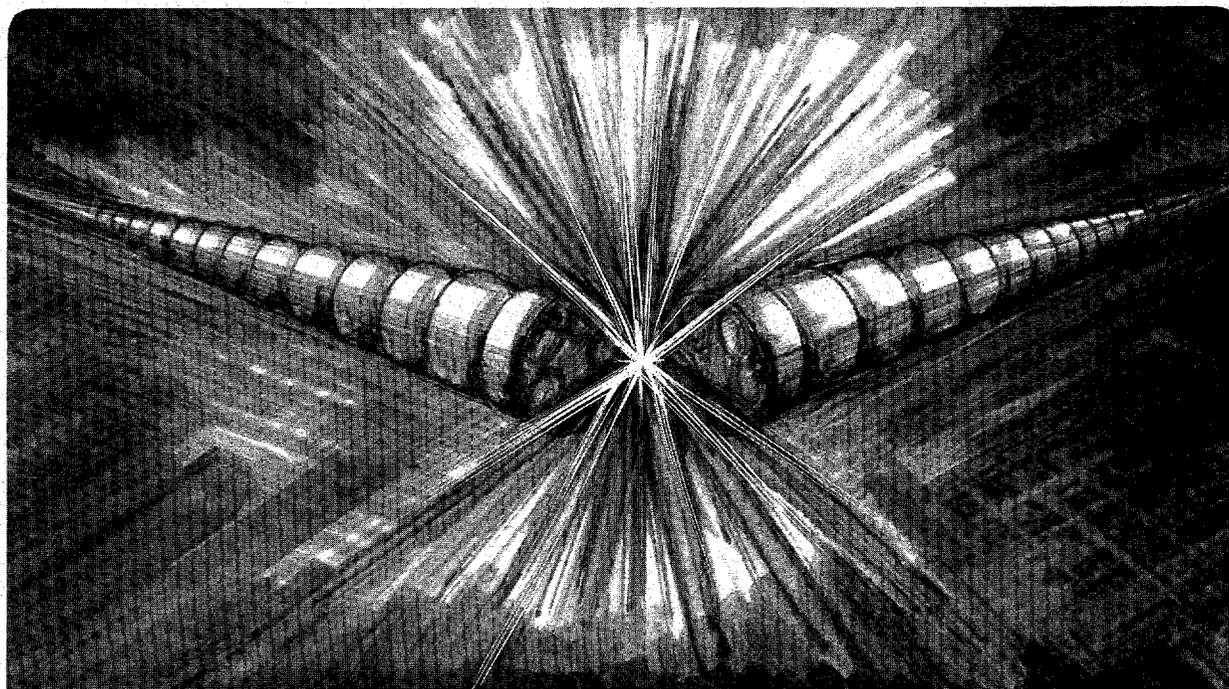
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M.A. Green

November 1995



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M.A. Green

Accelerator and Fusion Research Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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The Effect of Muon Decay on the Design of Dipoles and Quadrupoles for a Muon Collider

Michael A. Green

*E. O. Lawrence Berkeley National Laboratory
University of California
Berkeley, CA. 94720*

Abstract. The decay of muons to neutrinos and electrons can cause heating in the superconducting dipoles and quadrupoles in the muon collider acceleration rings and the colliding beam ring. The problem is particularly acute in the colliding beam ring where heating in the magnets can be as high as 2.4 kW per meter in the bending magnets of muon collider ring with 2 TeV mu plus and mu minus beams with 2.22×10^{12} particles per bunch at a repetition rate of 30 Hz. The energy deposited within the helium temperature region must be reduced at least three orders of magnitude in order for the refrigeration system to begin to keep up with the heat load. Beam heating from muon decay will require changes in dipole design from the traditional cosine theta (or intersecting ellipse) design used in the SSC magnets. Some dipole and quadrupole design options are presented in this report for both the accelerator rings and the colliding beam rings.

BACKGROUND

Muons decay after they are produced. The decay time constant for a muon at rest is 2.197×10^{-6} seconds. Muons traveling near the speed of light have a decay time constant equal to the rest decay time constant multiplied by the gamma factor. All through the processes of cooling, acceleration and storage the muons are decaying to two neutrinos and an electron or positron (depending on the charge of the muon that is decaying). The energy of the muon is split between the three particles. In our calculations, 40 percent of the muon energy is assumed to end up in electrons and positrons. The energy that ends up in the neutrinos is not of concern, but the energy that is in the electrons and positrons is of serious concern because it can end up in the superconducting elements of the machine.

The electrons and positrons will emit synchrotron radiation as they are bent by the magnetic field. The synchrotron radiation power will be deposited on the outside of the magnet on the beam orbital plane. The power that remains in the

electrons will be deposited on the inside of the magnet on the beam orbital plane. The energy from the synchrotron radiation and the electrons and positrons can have negative consequences on the superconducting magnets that are used to bend and focus the charged muons as they are accelerated and stored in the collider rings. As a result, the superconducting magnets will probably have a different design from those that are used in the Tevatron, HERA or the LHC.

MUON DECAY IN THE ACCELERATION SECTIONS AND THE COLLIDER RING

Once the muons are produced, bunched and cooled they must be accelerated quickly to the final energy of the collider. This report assumes that the final beam energy where the muons collide is 2 TeV. It is further assumed that negative and positive muons will be carried in the same accelerator structure. The muons are assumed to leave the muon cooling system at an energy 0.2 GeV. Two bunches (one with positive muons, the other with negative muons) containing 3×10^{12} muons leave the cooling section at a repetition rate of 30 Hz. Thus the assumed muon flux entering the first acceleration section is 1.8×10^{14} muons per second. In order to achieve the design luminosity for the colliding beam ring, less than one third of the muons will decay during the acceleration process. (It is not known if one muon bunch is stacked on top of the previous bunch when the design luminosity was calculated.) The remainder of the muons will decay in the colliding beam ring with a time constant of 41.6 ms (for muons at 2 TeV). About 41 percent of the muons from the previous cycle will be left when the new bunches are injected into the collider 33.3 ms after the previous bunch was put into the ring.

The system for accelerating the muons from the cooler at an energy of 0.2 GeV to a final energy of 2 TeV is assumed to contain the following components: 1) a linac to accelerate the muons from 0.2 to 2 GeV, 2) A nine turn recirculation ring with two superconducting linacs in the straight sections to accelerate the muons from 2 GeV to 20 GeV, 3) an eighteen turn recirculation ring with two superconducting linacs in the straight sections to accelerate the muons from 20 GeV to 200 GeV, and 4) an eighteen turn recirculation ring with two superconducting linacs in the straight sections to accelerate the muons from 200 GeV to their final energy of 2 TeV. The magnets for the recirculation rings will be superconducting and all of the magnet bores share a common cold iron flux return system. The collider will be a single separated function ring of superconducting magnets that carries both the negative and the positive muons. The beta star at the collision point must be about 3 mm in order for the desired design luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ to be achieved.

The number of muons that will decay in a given length L can be estimated using the following expression:

$$N_d = \frac{N L E_o}{\tau_o (E_T + E_o) c} \quad (1)$$

where N is the number of muons transported through a structure per second; N_d is the number of muon that decay in the structure per second; L is the length of the structure; E_T is the muon energy; E_0 is the muon rest mass ($E_0 = 105.7$ MeV); c is the velocity of light ($c = 2.998 \times 10^8$ m s⁻¹); and τ_0 is the muon decay time constant at rest ($\tau_0 = 2.197 \times 10^{-6}$ s). Equation 1 is applicable when the transit time for the muon through the structure of length L is much less than the decay time constant of the muon at its energy E_T .

The power available for deposition into the structure from the muon decay can be estimated using the following expression:

$$P = \sim 0.4 N_d E_{ave} e \quad (2)$$

where N_d is number of muon that decay per second (See Equation 1); E_{ave} is the average energy of the muon in the structure; e is the unit charge for the electron (muon have the same charge as an electron. $e = 1.602 \times 10^{-19}$ C s⁻¹). The factor 0.4 at the start of Equation 2 represents the assumed portion of the muon energy that ends up in the decay electrons or positrons. The remainder of the muon energy is transported to the universe by the decay neutrinos.

Table 1 presents calculations for muon decay in each of the accelerator components and the collider ring. Included in the table 1 is the number of turns through the component and the total transit length L_T through the structure. Table 1 gives an estimate of the decayed muon power that is transferred to electrons and positrons. This is the portion of the decayed muon power that can end up in the superconducting magnet system. The beam flux of μ^+ and μ^- that enters the accelerator section is assumed to be 1.8×10^{14} muons per second (one bunch of each type with 3×10^{12} muons per bunch at a repetition rate of 30 Hz). The peak bending induction in all of the rings is assumed to be 7 T.

Table 1 Muon Decay Parameters for Various Parts of a Muon Collider

Component	Energy (GeV)	Turns	L_T (km)	Decay Rate (μ s ⁻¹)	Power* (kW)
Linac	2	-NA-	0.12	1.938×10^{13}	1.37
First Ring	20	9	1.37	0.653×10^{13}	2.49
Second Ring	200	18	20.13	1.088×10^{13}	31.9
Third Ring	2000	18	201.3	1.011×10^{13}	324
Collider Ring	2000	1356**	9.2	1.331×10^{14}	17100

* Power from e^+ and e^- , assumed to be 40 percent of the muon beam power

** during one decay time constant of 41.6 ms

THE EFFECT OF DECAYED MUONS ON THE COLLIDER MAGNETS

Table 1 shows the estimated beam power that ends up in the form of decay electrons and positrons in various components of the muon collider acceleration system and the storage ring. Depending on electron positron beam power per unit length and the energy of the decay electron and positrons, the effect on various components can range from not serious to the factor that determines the design of that component. It appears that the superconducting magnets are most severely affected by the decay of the muons in the machine. The superconducting RF structure is less likely to be affected by the products of muon decay. The detectors around the collision point will be greatly affected by the muon decay products, but this report does not deal with that issue.

The Linac to Accelerate from 0.2 to 2.0 GeV

About 1.4 kW from electron and positron decay products will be deposited in the linac channel and the components downstream from the linac. The average energy of the electrons produced will be about 400 MeV. The synchrotron radiation critical energy that comes from the electrons in a string of 1.5 T bending magnet downstream from the linac will be about 160 eV. The decay electrons and positrons will probably be accelerated along with the muons in the linac. Thus, it is likely that little of the electron energy will end up in the linac RF structure. The energy from electrons will, for the most part be deposited in the string of conventional bending magnets and quadrupoles between the linac and the first acceleration ring. It is expected that the electrons, positrons and photons will be absorbed by the vacuum chamber wall.

The First Ring to Accelerate from 2 to 20 GeV

About 2.5 kW of power from electron and positron decay products will be deposited in the bending magnets and quadrupoles of the first accelerator ring. The average energy of the electrons and positrons produced by muon decay will be about 4.4 GeV. The synchrotron radiation critical energy that comes from the electrons and positrons in the 7 T bending magnets will be about 89 KeV. It is probable that the decay electrons and positrons will be accelerated along with the muons within the linacs. Therefore it is unlikely that much of the decay energy will end up in the RF structure of the linacs. The power per unit length that would be deposited within 0.65 km of magnet bore from the decay products would be about 4.6 watts per meter. From an overall refrigeration standpoint, this is not serious, but to keep the superconductor from overheating, it is desirable to absorb the decay product energy in a cooled bore tube at a temperature above 4 K. An 80 K bore tube can be designed to absorb eighty to ninety percent of the energy from the electrons, positrons and the synchrotron radiation.

The Second Ring to Accelerate from 20 to 200 GeV

About 32 kW of power from the muon decay products will be deposited in the bending magnets and quadrupoles of the second accelerator ring. The average energy of the electrons and positrons produced by muon decay will be in the range of 40 GeV. The synchrotron radiation critical energy that comes from the electrons and positrons in the 7 T bending magnets will be about 7.4 MeV. The decay electrons and positrons will be accelerated along with the muons within the linacs. Therefore, it is expected that little of the decay energy will end up in the RF structure. The power per unit length that would be deposited within 12.9 km of magnet bore from the decay products is estimated to be about 2.5 watts per meter. From an overall refrigeration standpoint, this begins to become a problem. To keep the dipole and quadrupole superconductor from overheating, it is desirable to absorb eighty to ninety percent of the decay product energy in a cooled bore tube at a temperature of 80 K or higher. If eighty to ninety percent of the decay energy is deposited at a higher temperature, the overall sizes of the helium refrigeration plants become reasonable.

The Third Ring to Accelerate from 0.2 to 2.0 TeV

About 324 kW of power from the muon decay products will be deposited in the bending magnets and quadrupoles of the third accelerator ring. The average energy of the electrons and positrons produced by muon decay will be about 400 GeV. The synchrotron radiation critical energy that comes from the electrons and positrons in the 7 T bending magnets will be about 740 MeV. The decay electrons and positrons will be accelerated along with the muons in the linacs. It is expected that little of the decay energy will end up in the RF structure. The power per unit length that would be deposited within 130 km of magnet bore from the decay products is estimated to be about 2.5 watts per meter. From an overall refrigeration standpoint, 324 kW at 4.4 K is a serious problem (by an order of magnitude given the size of the ring). In addition, one would like to reduce the beam losses into the superconductor to something around 0.3 watts per meter. A simple cooled vacuum chamber is probably not adequate for absorbing the energy from the muon decay products. One is forced to look at magnet designs where the coils are split on the mid plane so that a heavy muon decay product absorption system at 80 K or above can be installed. The quadrupoles will also have to be split on the mid plane so the muon decay product energy can be absorbed.

The Muon Collider Ring

It is estimated that about 17100 kW of power from the muon decay products will be deposited in the collider ring. Most of this energy will be deposited within the dipole and quadrupoles magnet strings. The average energy of the electrons and positrons produced by muon decay will be about 800 GeV. The synchrotron

radiation critical energy that comes from the electrons and positrons in the 7 T bending magnets will be about 4.3 GeV. The power per unit length that would be deposited within 7 km of magnet structure from the decay products is estimated to be about 2400 watts per meter. This is unacceptable from the total helium refrigeration required and the energy deposition per unit volume in the superconductor of the magnets. From both standpoints, the energy deposited into the 4 K region of the magnets should be reduced by more than three orders of magnitude. One is forced to look at dipole and quadrupole magnet designs where the coils are split on the mid plane so that the electrons, positrons, and synchrotron gamma rays can be moved away from the cold regions of the magnet into an energy absorption system at 300K that is capable of removing 17.1 MW of thermal energy. The long straight sections in the collider ring will also see some of the muon decay products. The muon decay products are a serious problem for the detectors.

SUPERCONDUCTING DIPOLE AND QUADRUPOLE DESIGNS FOR THE MUON COLLIDER RINGS

The size of the region where the decay electrons, positrons and synchrotron radiation strike the wall of the vacuum chamber is determined by the vertical emittance of the beam, and the beam dispersion caused by inhomogeneties of the magnetic field. The stay clear region for the decay products as far as the magnet coils are concerned is determined by the size of the region where most of the decay energy comes from (two or three sigma beam size from the mid plane in the vertical direction), the physical size of the magnet coil supports at the mid plane (This depends on the structure, but the minimum size is about 1 mm.), and the minimum thickness of multilayer insulation between the coil mid plane support structure and the warm parts of the vacuum chamber that absorbs the energy from the muon decay products (3 mm is a minimum sort of number). The field quality has a larger effect than beam emittance on the size of the fan of muon decay products from the beam. If the field within the dipole is good to 1 part in 1000, the decay product fan angle from the mid plane is about 1 milliradian. The minimum separation of the magnet, coils at the mid plane, surrounding a warm decay energy absorber will be about 12 mm for a magnet that has an inner coil radius of 30 mm.

The design of the dipoles and quadrupoles is dependent on the percentage of the muon decay product energy that can be deposited within the 4 K mass of the dipole. For low energy decay products, such as those from the first acceleration ring, all but ten percent of the muon decay product energy will be deposited in the beam vacuum chamber. As the energy of the muon decay product increases, the depth where the energy is deposited increases. Thus muon decay product energy absorption has to extend further along the mid plane of the dipole before there is only ten percent of the decay product energy left to be deposited at 4 K. The extra mass needed to absorb decay product energy at some point will impact the superconducting coils at the magnet mid plane. The magnets of the collider ring, where only one tenth of one percent of the decay product energy can end up in the 4 K region, must have an

open structure to allow the decay product energy to be absorbed in a water cooled structure that is at or near room temperature

At least three design approaches for can be considered for the superconducting dipole magnets in the various rings for the muon collider:

- 1) For first acceleration ring (perhaps the second ring as well), a conventional cosine theta dipole design can be employed with a warm vacuum chamber that has a cooling system to remove the energy from the muon decay products. The temperature of the vacuum chamber can be as low as 80 K. This type of magnet does not require coils that are split on the mid plane because at least eighty percent of the decay product energy can be removed within the vacuum chamber. Figure 1 illustrates this type of magnet concept with a cooled vacuum chamber in the bore.
- 2) For the second and third acceleration rings a design with the coils split on the mid plane should be pursued. In this instance, most the energy from the decay products can not be absorbed in the vacuum chamber unless it extends into the space between the coils and perhaps beyond into the iron return yoke. The iron around the superconducting coils could still be cold, but alternative methods for supporting the mid plane forces between the upper and lower coils must be found. Since it is allowable for ten to fifteen percent of the energy from the muon decay products to be absorbed in a 4 K structure, a cold bridge structure between the coils to carry force across the mid plane can be considered. The remainder of the muon decay product energy must be removed at 80 K or above. Figure 2 illustrates a dipole magnet of this type.
- 3) The collider ring must have coils that are completely separated on the mid plane. The iron return yoke, in all probability, must be at room temperature. The forces pulling the coil together across the mid-plane must be carried by 300 to 4 K supports. The coils must be separated so that less than 0.1 percent of the energy from the muon decay products ends up in the superconducting coils or its surrounding support structure that is at 4 K. The rest of the muon decay product energy ends up in the water cooled vacuum chamber and water cooled iron at the mid plane. Figure 3 illustrates the design of a dipole with maximum separation between the coils. The dipole shown in Figure 3 has reasonably good field quality (about 4 parts in 10000 at a 10 mm radius).

The quadrupoles mirror the dipoles on the mid plane because the decay products from the upstream dipole will end up in the quadrupoles and most of the decay products produced within the quadrupoles will travel along the mid plane of the magnet. The quadrupoles may have some energy deposition from the decay products along the vertical line of symmetry. In general, the energy of the decay products deposited in this region will represent less than one percent of the energy deposited along the mid plane. Mid plane coil separation has a worse affect on field quality in a quadrupole or sextupole than it does in a dipole.

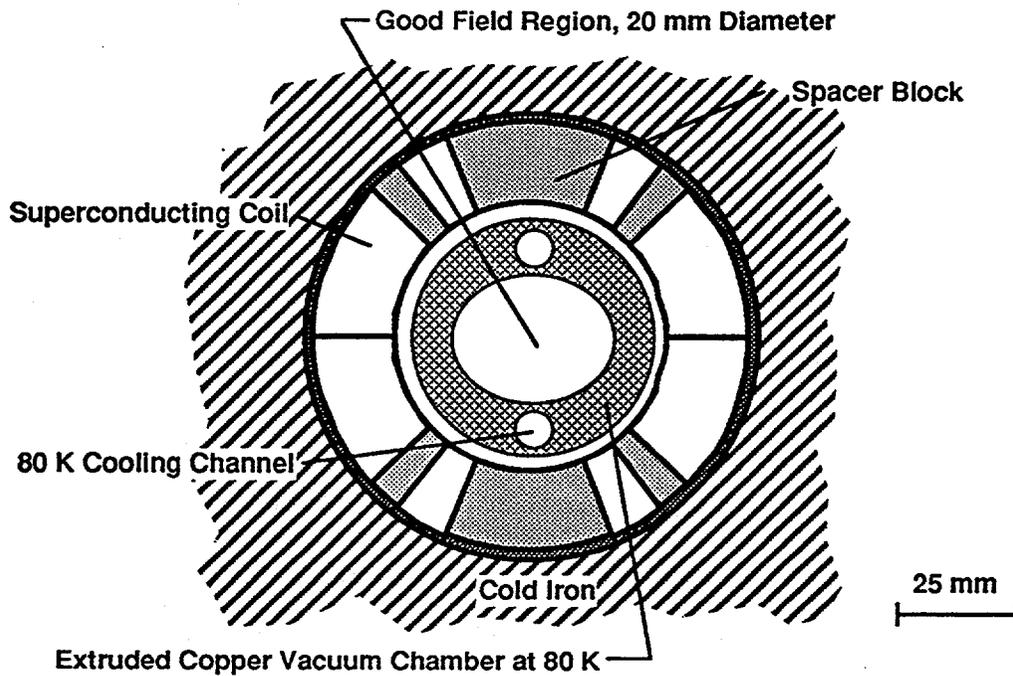


Figure 1 The Dipole Coils, Cold Iron and 80 K Vacuum Chamber for the Low Energy Accelerator Sections of a Muon Collider

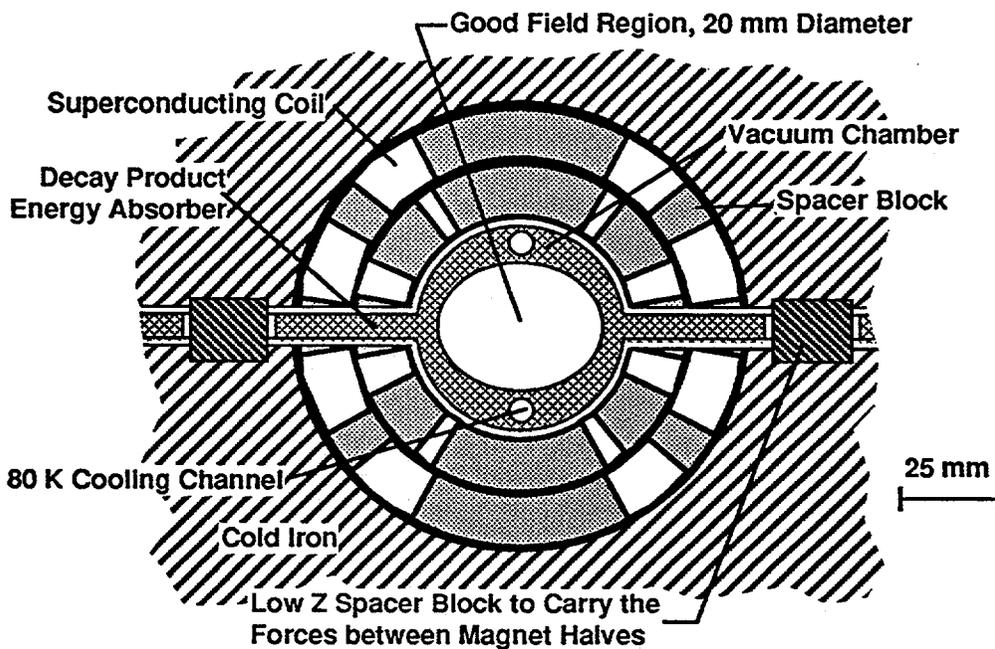


Figure 2 The Dipole Coils, Cold Iron, Vacuum Chamber and Decay Energy Absorbers for the high Energy Accelerator Sections of a Muon Collider

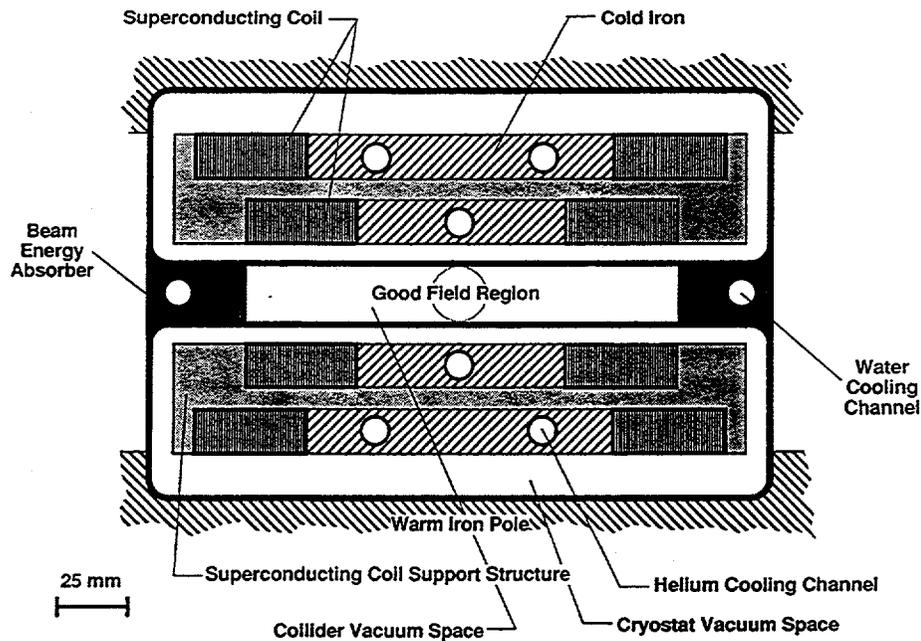


Figure 3 A warm Iron Dipole with Superconducting Coils for the Muon Collider Ring
(Less than 0.1 percent of the decay energy ends up in the 4 K region.)

CONCLUDING COMMENTS

The decay of the muons will deposit energy in the form of electrons, positrons, and photons in all of the superconducting magnets in the collider. Within the collider dipoles and quadrupoles, the decay energy will be deposited along the acceleration plane (the mid plane of the magnets). The region where the muon decay energy is deposited will be only a few millimeters wide. How one deals with the energy from the muon decay products depends on the muon energy and the muon residence time in the magnet structure.

The accelerator sections of the muon collider have a muon residence time that is from 5 to 8 percent of the muon decay time constant. It is estimated that 26 percent of the muons will decay between the muon cooling system and the entry of the muons into the collider ring. The amount of energy in the decay products is about ten times the energy that is allowed to be deposited in the superconducting magnets of the three acceleration sections. At low energies the penetration distance for the decay products is relatively short. The dipole and quadrupole superconducting coils can be on the mid plane if less than ten percent of the muon decay product energy ends up in that region. As the energy of the muon decay products increases, the penetration distance will also increase. The extra mass needed to attenuate the muon decay product energy begins to impact on the superconducting magnet coils. The dipole and quadrupole coils must be moved off of the mid plane. The coil geometry

changes if one is to maintain the field quality required in the bending and focusing elements. The magnet shown in Figure 2, has the cold upper and lower magnet halves completely separated. A physical connection between the upper lower parts of the magnet is achieved by using low atomic number (density) supports between the two cold halves. Up to ten percent of the muon decay product energy can be absorbed within these interconnect members.

The amount of energy deposited by the muon decay products is highest in the colliding beam rings. The muons stay in the colliding beam storage ring until they have completely decayed. The decayed product beam power is about three orders of magnitude higher than a reasonably sized 4 K helium refrigeration system can remove from the magnet string. The muon decay product beam power per unit volume is about three orders of magnitude higher than it should be for reasonable operation of a superconducting magnet system. A collider dipole that has superconducting coils and a warm iron return yoke has been postulated for the collider ring. The 2.4 kW per meter of beam power from the muon decay products can be removed by water cooling through the vacuum chamber and the iron return yoke. The collider ring quadrupoles and sextupoles must also have warm iron. Superconducting coils are an option for the these magnets.

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