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Superconducting Magnets for a Muon Collider

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The existence of a muon collider will be dependent on the use of superconducting magnets. Superconducting magnets for the $\mu^- \mu^+$ collider will be found in the following locations: the $\pi^- \pi^+$ capture system, the muon phase rotation system, the muon cooling system, the recirculating acceleration system, the collider ring, and the collider detector system. This report describes superconducting magnets for each of these sections except the detector. In addition to superconducting magnets, superconducting RF cavities will be found in the recirculating accelerator sections and the collider ring. The use of superconducting magnets is dictated by the need for high magnetic fields in order to reduce the length of various machine components. The performance of all of the superconducting magnets will be affected the energy deposited from muon decay products.

1 . INTRODUCTION

The proposed muon collider[1-5] consists of the following components: 1) a 10 GeV proton source that generates about 1.5×10^{15} protons per second, 2) a target section that produces and captures pions, 3) a section where the pions decay to muons that are phase rotated to compact bunch, 4) a muon cooling section where the muon emitance is reduced three orders of magnitude, 5) several rings to accelerate muons to 2 TeV, 6) the collider ring, and 7) the detector. Superconducting magnets will be found in all of these sections except for the proton source.

This report describes the superconducting solenoids in the pion capture system around the target. A brief description of the solenoids needed in the phase rotation and the muon cooling sections is presented. Dipole and quadrupoles for the recirculating accelerator rings and the collider ring are also described. This report does not include any discussion about superconducting magnets that are part of the detector system around the collider collision point.

A muon decays to two neutrinos and electron or positron (depending on the charge state of the original muon). Roughly forty percent of the muon energy ends up in the decay electron or positron. The energy in the electron or positron can be deposited in various parts of the muon collider and its subsystems. The problem of muon decay is at its worst in the collider ring, but it is a problem for superconducting magnets and RF cavities throughout the muon collider subsystems.

Muons have a life time that is dictated by its energy. The mean life of a muon at rest is about 2.197 μs. At the collider full energy the of 2 TeV, the muons will have a mean life of 41.6 ms. This means that the repetition rate for the muon collider must be of the order of the muon life time in the collider ring if high colliding ring luminocities are to be maintained. In order to maintain a luminocity of 10^{35} cm^{-2} s^{-1} in a collider ring with a $\int$* of 3 mm at the collision point, over 1.2×10^{14} muons per second must be created and stored in a ring with 7 T bending magnets. The collider ring must have two bunches (one of each charge state) of 2×10^{12} muons per bunch at a repetition rate of 30 Hz in order to have the desired luminocity at the collision point.

2. CAPTURE AND DECAY SOLENOIDS

Pion capture solenoids with capture central inductions of 28 tesla and 22 tesla are described in this report Both of these capture solenoids are hybrid magnets with water cooled Bitter type solenoids inside of superconducting solenoids. The length of the capture solenoid system is determined by the type of target used to produce the pions. The capture solenoids described here are assumed to have a low Z (beryllium or carbon) targets within them.

The superconducting solenoids are graded. The outer coils are low field niobium titanium coils; the inner coils that operate at high field would be made from niobium tin. Both of the superconducting capture solenoid coils would be cooled to 1.8 K by a refrigerator. Both versions of the capture solenoid magnet system include a transition section where the central induction is reduced from the capture induction to the decay channel and phase rotation channel induction of 7.0 tesla. The warm bore diameter is 300 mm at 7 tesla in both options. The final three meters of the capture solenoid is the start of the 7 tesla muon decay channel.

The water cooled bitter solenoid absorbs 2 MW of the 5 MW beam energy deposited on the target at the center of the capture solenoid system. The thickness of the water cooled bitter magnet must be at least 225 mm so that little of the proton beam energy ends up in the 1.8 K superconducting solenoids Downstream from the capture solenoid, the inner wall must be heavy and water cooled in order to reduce the energy from the target that is deposited in the 7 T magnets. Table 1 compares the two capture solenoid designs that have been studied.

The superconducting coils for the 28 tesla capture solenoid are based on the cable in conduit superconducting coils that the National High Magnetic Field Laboratory[6] is using for their 45 tesla hybrid magnet system. The water cooled Bitter magnet is longer and has a larger bore diameter than the Florida State magnet system. The projected power numbers in Table 1 reflect the longer water cooled solenoid length. A magnet inner bore of 150 mm used for the 28 tesla capture solenoid will capture pions with a transverse momentum of 314 MeV/c. Figure 1 shows a cross-section of the 28 tesla solenoid.

TABLE 1 Parameters for High Field and Low Field Capture Solenoids

Parameter	High Field Magnet	Low Field Magnet
Total Length of Solenoid System (mm)	5000	5000
Cryostat Outer Diameter (mm)	1850	1120
Niobium Titanium Capture Solenoid OD (mm)	1650	920
Niobium Titanium Capture Solenoid Length (mm)	1200	1000
Niobium Tin Capture Solenoid OD (mm)	1080	650
Niobium Tin Capture Solenoid Length (mm)	1000	1000
Water Cooled Bitter Coil OD (mm)	610	350
Water Cooled Bitter Coil Bore Diameter (mm)	150	180
Water Cooled Bitter Coil Length (mm)	900	900
Decay Channel Diameter (mm)	300	300
Transition Region Length (mm)	600	800
Decay Channel Length (mm)	3000	3000
Capture Solenoid Total Central Induction (T)	28.0	22.0
Superconducting Solenoid Central Induction (T)	14.6	14.2
Water Cooled Solenoid Central Induction (T)	13.4	7.8
Decay Solenoid Central Induction (T)	7.0	7.0
Total Magnet System Stored Energy (MJ)	150.7	51.1
Superconducting Magnet Stored Energy (MJ)	124.9	45.6
Power Required for the Water Cooled Solenoid (MW)	27.4	10.8
310 K Cooling Required for the Magnet System* (MW)	32.0	15.4
Total Mass of the Superconducting Magnets (Metric Tons)	26.0	16.6

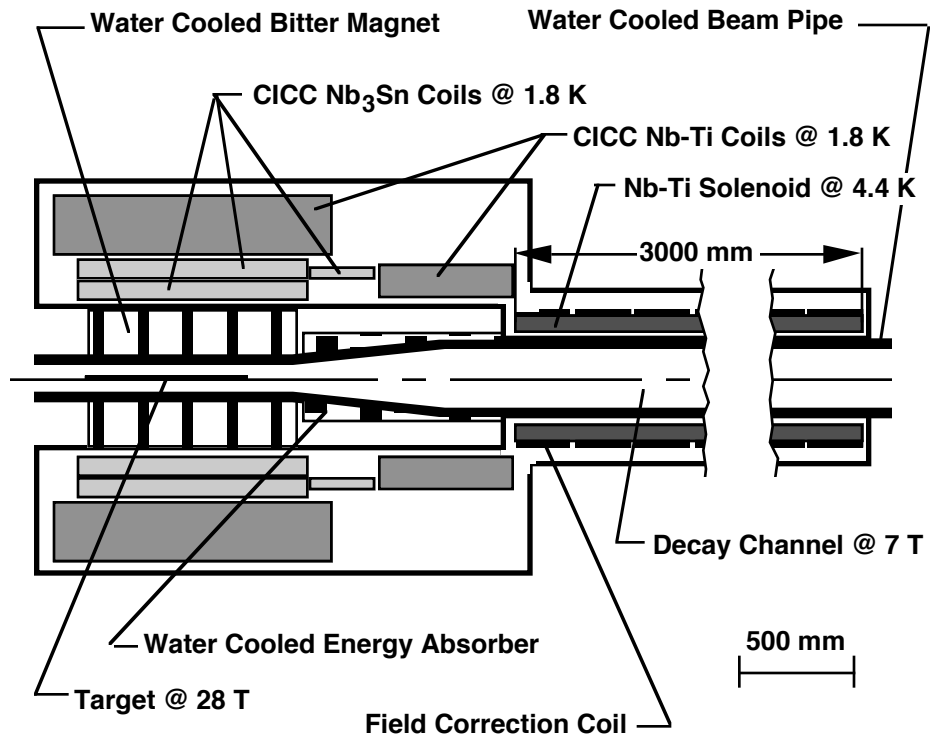* includes the water cooling required for the beam energy into the target

Water Cooled Bitter Magnet

Water Cooled Beam Pipe

CICC Nb$_3$Sn Coils @ 1.8 K

CICC Nb-Ti Coils @ 1.8 K

Nb-Ti Solenoid @ 4.4 K

3000 mm

Decay Channel @ 7 T

Water Cooled Energy Absorber

500 mm

Target @ 28 T

Field Correction Coil

Figure 1 A Cross-section of a 28 T Hybrid Capture Solenoid using CICC Coils

Water Cooled Bitter Solenoid

Water Cooled Beam Pipe

Nb$_3$Sn Coils @ 1.8 K

Nb-Ti Coils @ 1.8 K

Nb-Ti Solenoid @ 4.4 K

3000 mm

Decay Channel @ 7 T

Target @ 22 T

Field Correction Coil

500 mm

Water Cooled Energy Absorber
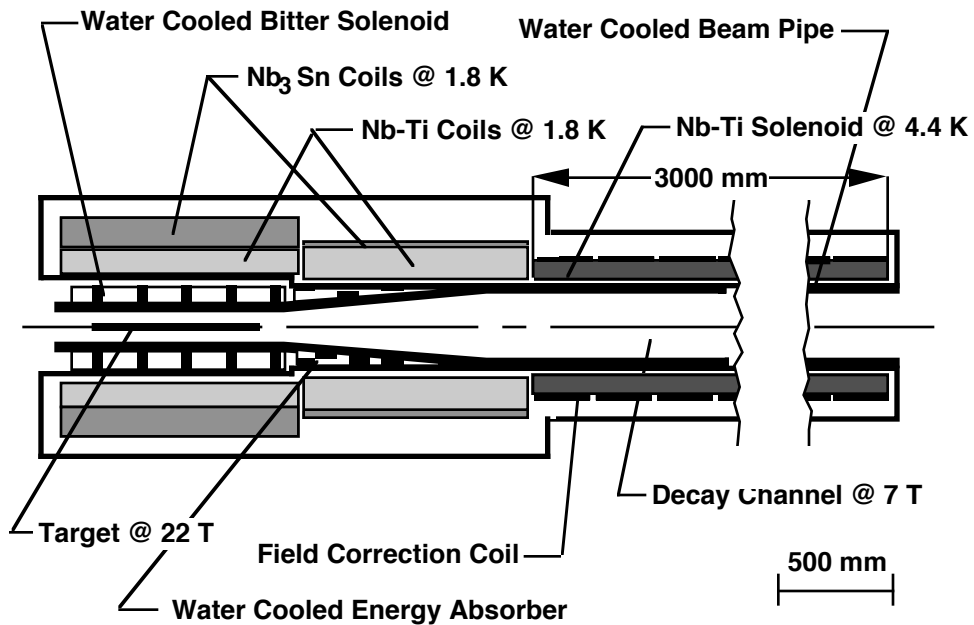
Figure 2 A Cross-section of a 22 T Hybrid Capture Solenoid using Bath Cooled Coils

The superconducting coils for the 22 tesla capture solenoid are based on the bath cooled superconducting coils that the Francis Bitter Magnet Laboratory[7] is using for their 35 tesla hybrid magnet system. The water cooled Bitter magnet is longer and has a larger bore diameter than the MIT magnet system. The projected power numbers in Table 1 reflect this. A magnet inner bore of 180 mm was used for the 22 tesla capture solenoid. This magnet will capture pions with a transverse momentum of 296 MeV/c. (See Figure 2 for a cross-section view.)

The theoretical capture efficiency of the 22 tesla solenoid is somewhat lower than the capture efficiency of the 28 tesla solenoid. In either case, there are problems with the water cooled Bitter solenoid section. Bitter solenoids typically have a life time that is limited by a combination of high current densities fatigue, and corrosion. The high radiation environment only makes matters worse.

The length of the decay channel between the capture solenoid and its transition section to 7 tesla is determined by the type of system used to phase rotate the pions and muons coming from the target. If a system using RF cavities is used for phase rotation, it is desirable that the RF cavities be located as close to the target as possible. The decay of the pions to muons would occur simultaneously with phase rotation. If an induction linac is used for phase rotation, a 150 meter long muon decay channel is desirable in order for the muon beam to be spread out over a length of about 30 meters. The number of muons in the channel will reach its peak about 150 meter down stream from the target.

A 150 meter long decay channel could be built from ten 15 meter long 7 tesla solenoid sections that have a warm bore of 300 mm. Table 2 shows the basic parameters of a 150 meter long decay solenoid magnet system. The length of each magnet in the section is dictated by the quench parameters of the magnets. For 15 meter long magnet sections, the nominal superconductor plus matrix current density should be about 75 amperes per square millimeter. The warm bore tube wall thickness (assumed to be water cooled copper) is set at 25 mm. Figure 3 shows a schematic cross-section of a decay solenoid unit.

TABLE 2 Pion Decay Solenoid Parameters

Parameter

Length of Channel (m)	150
Number of Units	10
Length per Unit (m)	15
Solenoid Cryostat OD(mm)	~700
Nb-Ti Coil OD (mm)	530
Nb-Ti Coil ID (mm)	380
Warm Bore Diameter (mm)	300
Bore tube Thickness (mm)	25.4
Central Induction (T)	7.0
Operating Temperature (K)	~4.4
Cold Mass per Unit (metric tons)	17.8
Total Mass per Unit (metric tons)	23.0
Stored Energy per Unit* (MJ)	47.5

* at the design central induction

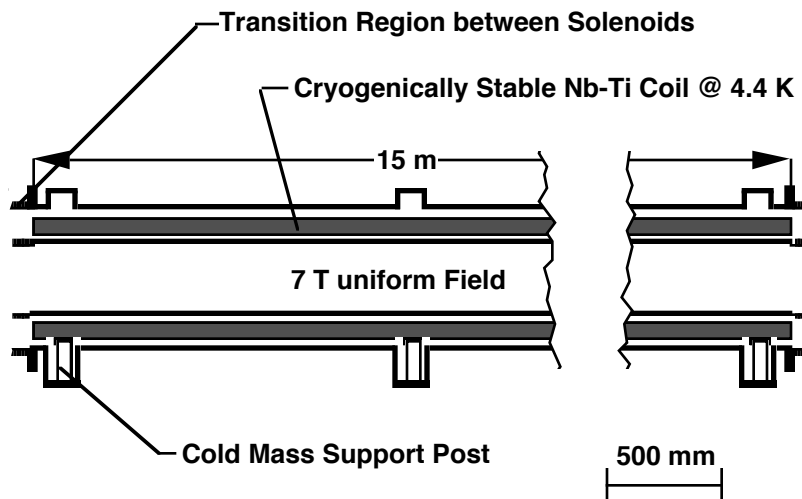
Figure 3 A Cross-section of a 7 T Decay Solenoid Section

3. PHASE ROTATION AND COOLING SYSTEM SOLENOIDS

The phase rotation magnets are string of solenoids within the RF cavities or induction linac sections. The solenoids in the string have the same polarity and they occupy at least 60 percent of the space in the string. The acceleration section gap and cryostat walls occupy the space between the coils. The coils should be designed so that the solenoidal field along the string is as uniform as possible. The average induction along the string of solenoids is the same as the induction in the muon decay channel.

When RF cavities are used for phase rotation, the phase rotation must start as soon as possible downstream from the capture solenoid. Close to the target and capture solenoid, particle flux to the walls may be a factor in the design of the superconducting magnets in the RF cavity. The length of the RF cavity phase rotation system is estimated to be somewhere near 100 meters. A schematic of the RF cavities and their superconducting magnets is shown in Figure 4. It is estimated that about 80 of these cavities would be required for phase rotation provided the phase rotation starts soon enough after the pion capture.

When an induction linac is used for phase rotation, it is desirable to have a decay drift of 100 meters or more before phase rotation is started. An induction linac phase rotation system might be 250 to 300 meters long. A couple of hundred solenoids might be required for the induction linac. Like the RF phase rotation system, the uniformity of the solenoidal field down the bore of the induction linac is of some concern. A longer solenoid length with respect to the cavity length means greater the field uniformity in the phase rotation channel.

If RF cavities are used for phase rotation, saturation of ferromagnetic materials is not an issue. If an induction linac is used for phase rotation, the magnetic flux outside of the solenoid will be concentrated within the ferrite material that is essential to the operation of the induction linac. The effect of the magnetic field on the operation of the induction linac is not known at this time.
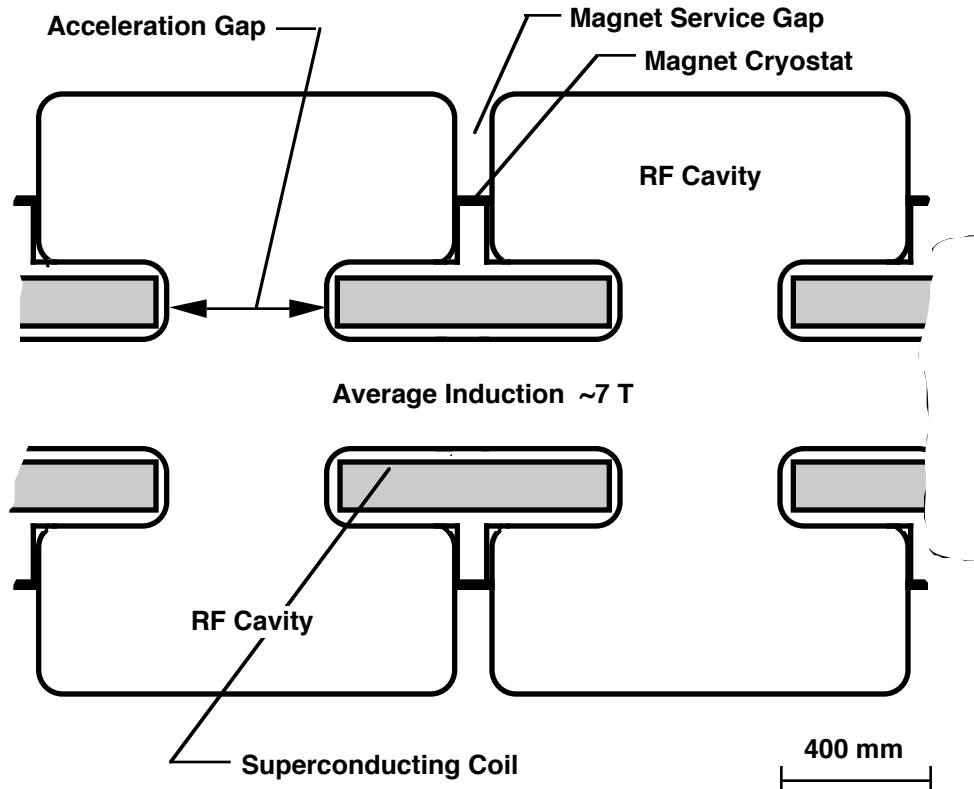

Figure 4   A Schematic View of Superconducting Solenoids within a Phase Rotation RF Cavity System

The solenoids in the muon cooling system are very different form those in the phase rotation system. The muon cooling system uses a FOFO structure. The solenoids alternate in polarity. The cooling system solenoids start at the same central induction (at their center) as the muon decay and phase rotation system. Between the solenoid is the lithium, beryllium or lithium hydride that reduces the muon momentum (in all directions). When cooling is finished in a section, the muon are accelerated back up to about 1 GeV (Longitudinal momentum is increased but transverse momentum is not increased as much.) As one moves down the cooler, the strength of the solenoids increases and their bores and spacings become smaller.

At the start of the cooling channel, the solenoid clear bore is about 600 mm. At the end of the channel the clear bore drops to about 40 mm. The central induction of the solenoids at the end of the string might be as high as 14 tesla. Figure 5 shows the cooling solenoids at the high emittance (low field) end. The cooling solenoids have alternating polarity. A radial component of field must squeeze out between the solenoid coils. The peak field in the coils can be much higher than the field along the string of solenoids. The magnetic forces on the coils want to push them apart. One can attach the coils together with a cold support, but there must be some radial access to the cooling point.

4. ACCELERATION SECTION AND COLLIDER RING DIPOLES AND QUADRUPOLES

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 recirculation rings will be separated function rings that can have up to 18 separate bores. The superconducting dipoles and quadrupoles in the bores will 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 $\int*$ at the collision point must be about 3 mm in order for the desired design luminosity of 10^{35} cm^{-2} s^{-1} to be achieved.
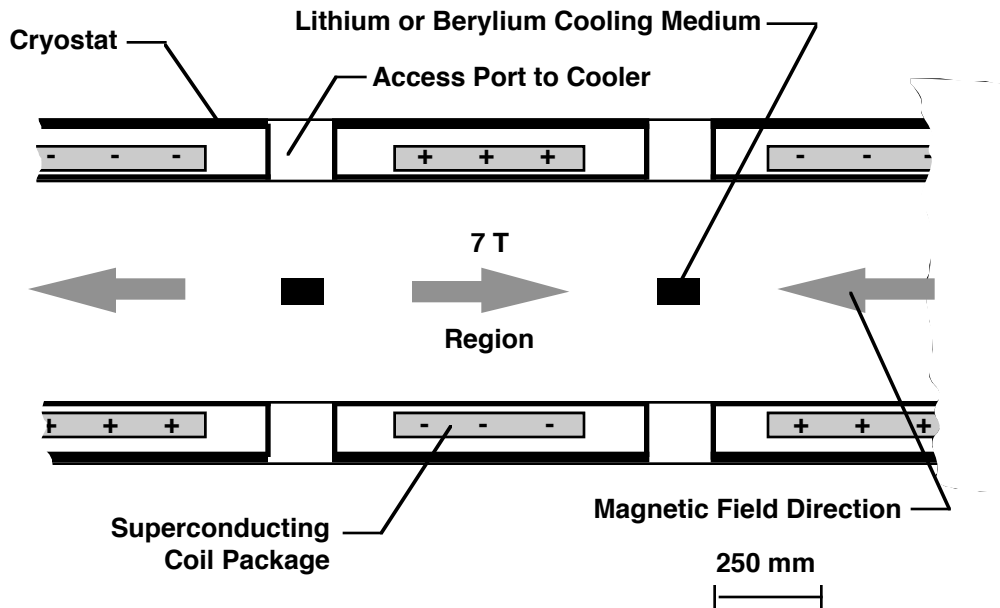

Figure 5 A Schematic Representation of Solenoids for the Muon Cooling System at the Warm End

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

$$N_d = \frac{N"L_T"E_o}{\dagger_o"(E_T"+"E_o)"c} \quad (1)$$

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_T is the length of the structure; E_T is the muon energy; E_o is the muon rest mass (E_o = 105.7 MeV); c is the velocity of light (c = 2.998 x 10^8 m s^{-1}): and $\dagger_o$ is the muon decay time constant at rest ($\dagger_o$ = 2.197 x 10^{-6} s). Equation 1 is applicable when the transit time for the muon through length L is less than the decay time constant of the muon at 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 x 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 3 presents calculations for muon decay in each of the accelerator components and the collider ring. Included in the Table 3 is the number of turns through the component and the total transit length L_T through the structure. Table 3 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 x 10^{14} muons per second (one bunch of each type with 3 x 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. (Increasing the field in the collider ring dipoles will increase the luminosity at the collision point.)

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, the beam dispersion caused by inhomogeneities of the magnetic field, and the physical size of the muon beam (say 6ß beam size from the mid plane in the vertical direction). 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 stay clear region for the decay products as far as the magnet coils are concerned is determined by the size of the region where the decay energy strikes the wall, plus the physical size of the magnet coil supports at the mid plane, plus the thickness of multilayer insulation between the coil mid plane support structure and the vacuum chamber, and the thickness of the vacuum chamber. For a 6ß vertical beam size of 5 mm, the minimum separation of the coils at the mid plane, surrounding the vacuum vessel would be about 15 mm.

Table 3 Muon Decay Parameters for Various Parts of a Muon Collider

Component	Peak Energy (GeV)	Number of turns	L_T (km)	Decay Rate (μ s^{-1})	Heating Power (kW)	Peak Heat per unit L (W m^{-1})
Linac	2	-NA-	0.12	1.938 x 10^{13}	1.37	-NA-
First Ring	20	9	1.37	0.653 x 10^{13}	2.49	4.6
Second Ring	200	18	20.13	1.088 x 10^{13}	31.9	2.5
Third Ring	2000	18	201.3	1.011 x 10^{13}	324	2.5
Collider Ring	2000	1356**	9.2	1.331 x 10^{14}	17100	~2400

* Power from e$^+$ and e$^-$, assumed to be 40 percent of the muon beam power
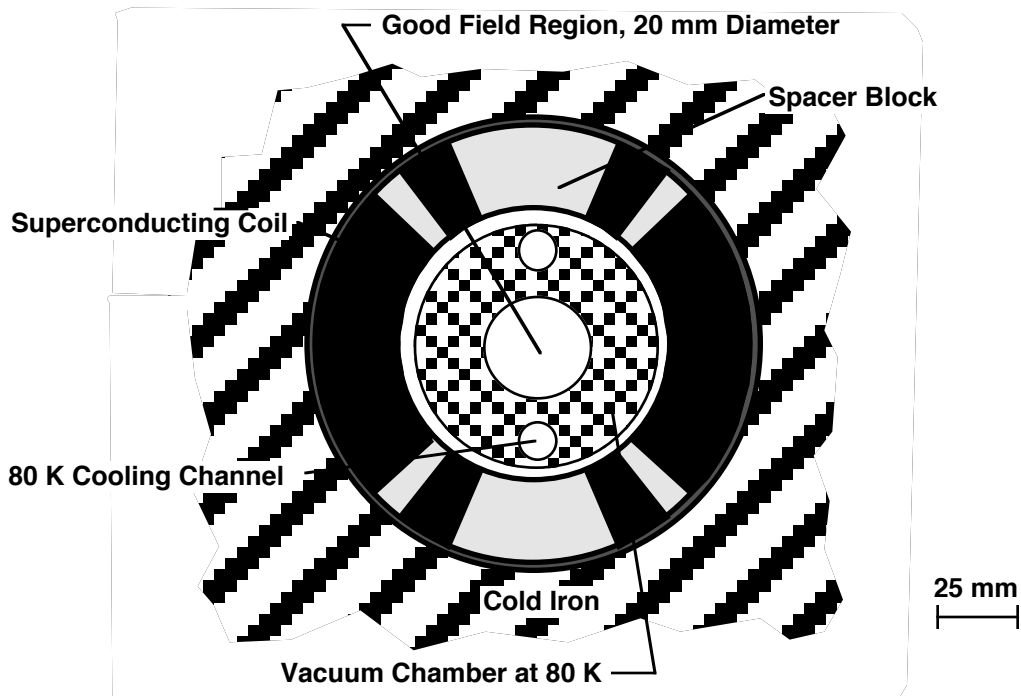** during one decay time constant of 41.6 ms

Figure 6 A Cosine Theta Dipole with a 20 mm Thick Vacuum Chamber Cooled to 80 K

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

For the four acceleration rings 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 vacuum chamber should be made from material heavy enough to reduce the energy into the 4 K region of the magnet by a factor of three to ten. The heavy vacuum chamber scatters the particles and reduces the energy deposition per unit volume in the superconductor. The temperature of the vacuum chamber can be as low as 40 K. Figure 6 illustrates how a cosine theta dipole magnet can have a 20 mm thick metal liner at 80 K that absorbs energy from the decay electrons and positrons. A bronze liner would absorb 75 percent of the decay product energy; a tungsten liner would absorb 90 percent of the energy. Acceleration section quadrupoles can have a liner similar to the dipole's liner.

For the collider ring, one can use a conventional cosine theta type of dipole provided the heavy (tungsten) vacuum chamber is thick enough to reduce the energy into the superconducting coils

about three orders of magnitude. The collider dipole warm bore is about 20 mm. The thickness of tungsten needed to reduce the heating from muon decay three orders of magnitude is about 65 mm. The cold bore of the superconducting dipole coils has to be about 160 mm for a magnet with a 20 mm bore in the liner. The heavy vacuum tube must be cooled with a fluid at room temperature. A collider ring dipole with a tungsten liner is illustrated in Figure 7. The energy from the decay products that remains is well scattered into the coils.

Another approach to building collider ring dipole magnets is to have the coils that are completely separated on the mid plane. The iron return yoke is at room temperature. The forces pulling the coil together across the mid-plane must be carried by 300 to 4 K supports. (Cold iron designs might be possible and are being studied.) 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 8 shows warm iron dipole with maximum separation between the coils. The dipole shown in Figure 8 has reasonably good field quality (about 4 parts in 10000 at a 10 mm radius).
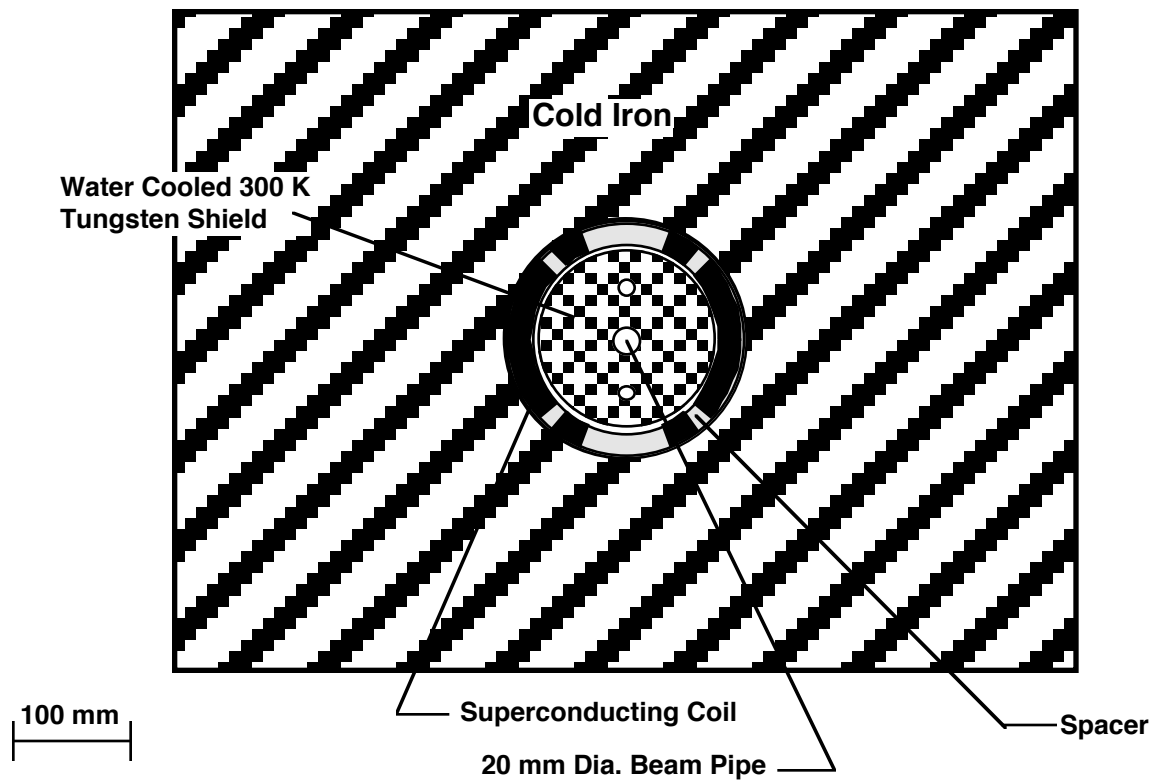
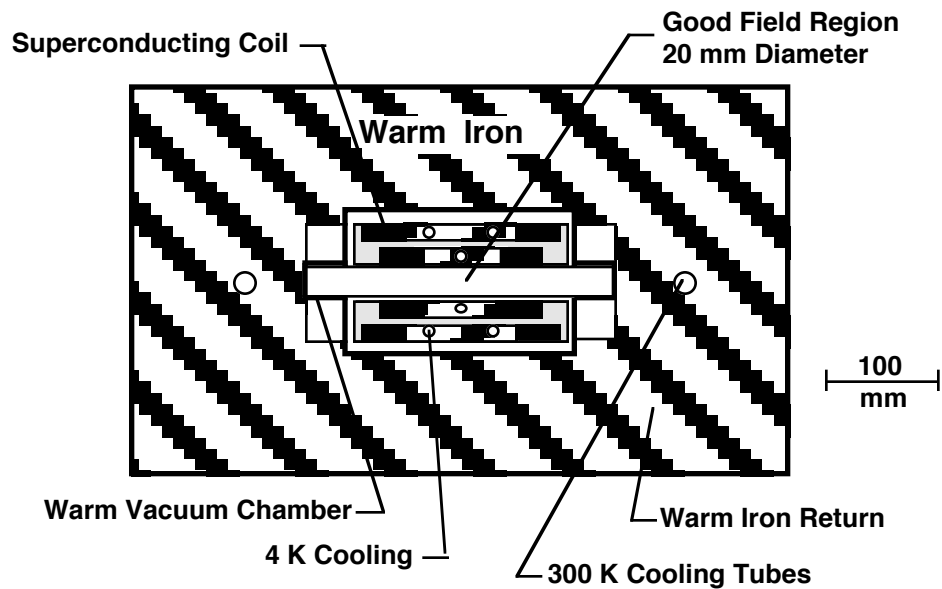Figure 7 A Cold Iron 7 T Cosine Theta Dipole with a 65 mm Thick Tungsten Liner at 300 K

Figure 8 A 7 T Warm Iron Split Dipole that will have less than 0.1 Percent of the
Muon Decay Product Power Deposited within the Superconducting Coils

The quadrupoles will have most of the decay product energy deposited on the mid plane because the decay products from the upstream dipole will end up in the quadrupoles. Decay products produced in the quadrupoles will end up on both the horizontal and vertical axes. One problem with quadrupoles and sextupoles is that mid plane coil separation has a worse affect on field quality than it does in a dipole. A second problem with quadrupoles and sextupoles is that the coil radius has a strong effect on the gradient one can get in the bore of the magnet.

Quadrupoles in the acceleration sections of the muon collider can have a vacuum chamber similar to the dipoles, but the design gradient must be reduced. It is unattractive for the quadrupoles and sextupoles in the collider ring to be split on the mid plane. It is also very unattractive for the vacuum chamber to be 65 mm thick. It appears to be desirable that cell quadrupoles and sextupoles for the collider ring be conventional. For a collider ring good field aperture diameter of 20 mm, quadrupole gradients of 100 to 120 T m^{-1} are possible using conventional water cooed magnets. Extra water cooling is required to absorb the energy from the decaying muons.

5 . ACKNOWLEDGMENT

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