Some Options for the Muon Collider Capture and Decay Solenoids

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Abstract. This report discusses some of the problems associated with using solenoid magnets to capture the secondary particles that are created when an intense beam of 8 to 10 GeV protons interacts with the target at the center of the capture region. Hybrid capture solenoids with inductions of 28 T and a 22T are described. The first 14 to 15 T of the solenoid induction will be generated by a superconducting magnet. The remainder of the field will be generated by a Bitter type of water cooled solenoid. The capture solenoids include a transition section from the high field solenoid to a 7 T decay channel where pions and kaons that come off of the target decay into muons. A short 7 T solenoidal decay channel between the capture solenoid system and the phase rotation system is described. A concept for separation of negative and positive pions and kaons is briefly discussed.

BACKGROUND

A muon collider must have a number of different subsystems in order for the muons to collide at 2 TeV. The subsystems include: 1) a rapid cycling conventional accelerator that accelerates two bunches of about 5 x 10^{13} protons to 8 to 10 GeV at a repetition rate of 30 Hz., 2) a fixed target to produce pions and kaons from the protons, 3) a capture solenoid system to capture the particles that come from the target, 4) a decay and phase rotation channel that produces bunched muons, 5) a muon cooling channel that reduces the muon emittance from 0.025 m to 3 x 10^{-5} m at an energy of 0.2 GeV, 6) several stages of acceleration from 0.2 GeV to 2 TeV, 7) a single collider ring for both μ^+ and μ^- at an energy of 2 TeV, and 8) a single large detector to detect the products of μ^+ and μ^- collisions.

This report deals with the capture solenoid and the decay channel solenoids up to the first RF section used to bunch the pions and muons. The fixed target located inside of a capture solenoid converts 3 x 10^{15} protons per second at 8 to 10 GeV to pions and assorted other particles that will eventually decay to μ^+, μ^-, e^+, e^- and neutrinos There will also be left over protons from the original proton beam. The role of the capture and decay channel is to capture the pions and other particles and insure their decay to positive and negative muons. It may also be desirable to separate the muons from the left over protons and electrons and positrons produced by the target and the subsequent decay processes.

The transverse momentum that can be captured by a solenoidal capture field is proportional to the solenoid central induction and the solenoid radius. One can capture particles of a given transverse momentum at any field provided the solenoid is large enough. The advantages of using a high field capture solenoid are; 1) a small solenoid diameter and 2) a transfer of transverse momentum to longitudinal momentum when the field is reduced going into the decay solenoid. A transverse momentum of about 300 MeV/c can be captured by a 28 tesla solenoid with a radius of 75 mm. The process of reducing the induction from 28 to 7 tesla reduces the transverse momentum by about a factor of two. This means that a decay channel with 7 tesla solenoids will have a radius of about 150 mm.

High field solenoids (even those with a relatively small diameter) are expensive to build. For central inductions above 15 tesla, a pure superconducting solenoid is probably out of the question. For capture solenoids with a central induction above 15 tesla, the hybrid magnet with superconducting outer coils and water cooled on the inside becomes the design of choice. The water cooled solenoid inside of the superconducting solenoid uses a great deal of power. In addition water cooling has to be provided to absorb the energy from particles coming off of the target that are not captured.

If one tries to capture pions at a lower central induction, the capture efficiency theoretically goes down for a given solenoid diameter because the higher transverse momentum particles are lost. Unfortunately studies at Brookhaven and Fermi Lab have not yielded the same results in this regard(1,2). I suspect that one is comparing apples to oranges when the two studies are compared. The baseline study by Palmer uses a 28 tesla capture solenoid with a 7 tesla decay channel. Clearly other options are available for the capture and decay channels. The next section in this report describes a 28 tesla and a 22 tesla solenoid system for capturing the pions. In both cases the decay solenoids downstream are 7 tesla solenoids. The possibility of lower field capture solenoids and decay solenoids is discussed near the end of this report.

A COMPARISON OF A 28 TESLA AND A 22 TESLA CAPTURE SOLENOID MAGNETS

Capture solenoids with capture central inductions of 28 tesla and 22 tesla have been studied. Both of these capture solenoids are hybrid magnets with water cooled Bitter type solenoids inside of a 14 to 15 tesla superconducting solenoid. The superconducting solenoids are graded into low field niobium titanium outer coils and niobium tin high field inner coils. Both sets of superconducting capture solenoid coils would be cooled by a 1.8 K refrigerator. Both versions of the capture solenoid magnet system include a transition section where the central induction is reduced from the capture induction to a decay channel induction of 7.0 tesla. The warm bore diameter at 7 tesla is 300 mm in both magnet options. The final three meters of the capture solenoid is the start of the 7 tesla decay solenoid. The inner wall of this magnet section is heavy and water cooled, so the inner diameter of the niobium titanium coil is somewhat larger than it would be in subsequent decay channel magnets where the inner wall does not have to be as heavy. 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 is using for their 45 tesla hybrid magnet system(3). 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. It is assumed that a low Z temperature high melting point target will be used (for example, a beryllium target) A magnet inner bore of 150 mm was used for the 28 tesla capture solenoid. Figure 1 shows a cross-section of the 28 tesla solenoid.

The superconducting coils for the 22 tesla capture solenoid are based on the bath cooled superconducting coils that the Francis Bitter Magnet Laboratory is using for their 35 tesla hybrid magnet system(4). 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. It is assumed that a low Z target will be used A magnet inner bore of 180 mm was used for the 22 tesla capture solenoid. Figure 2 shows a cross-section of the 22 tesla capture solenoid system.

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

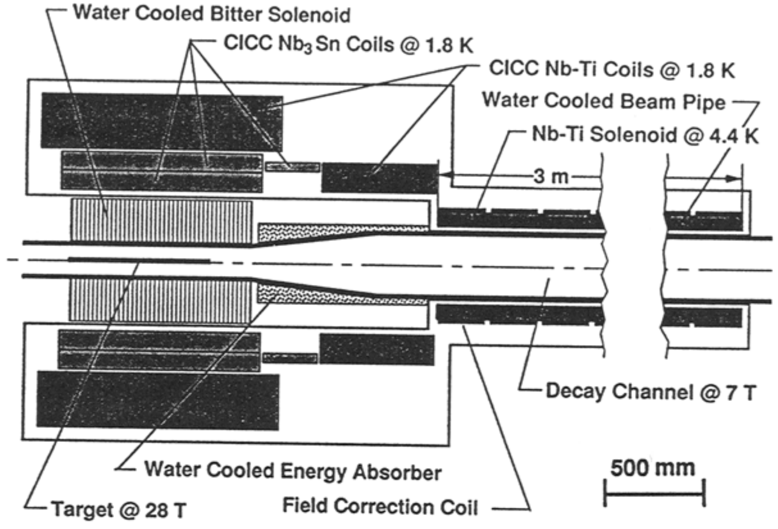

FIGURE 1 A Cross-section of a 28 T Capture Hybrid Solenoid based on the 45 T Florida State Hybrid Magnet System

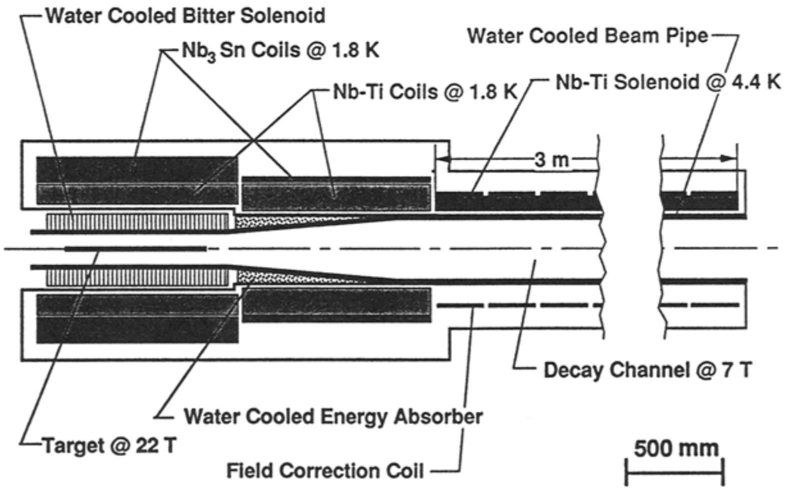

FIGURE 2 A Cross-section of a 22 T Capture Hybrid Solenoid based on the 35 T MIT Hybrid Magnet System

The theoretical capture efficiency of the 22 tesla solenoid is about 6 percent lower than the capture efficiency of the 28 tesla solenoid (from say 34 percent μ^- conversion to 32 percent conversion). The 22 tesla solenoid shown in Figure 2 should be less expensive to build than the 28 tesla solenoid shown in Figure 1. The 22 tesla capture solenoid uses less electric power and requires less cooling. However, there may be additional losses of particles in the transition section from 22 tesla to 7 tesla. The water cooled Bitter solenoid may be a problem in either case, because Bitter coils often have a limited life time. Clearly additional work is needed in order to develop a reliable water cooled insert magnet for the capture solenoid magnet system.

THE 7 TESLA PION DECAY SOLENOIDS

Once the fragments from the target have been captured by a capture solenoid system, many of the target fragments will decay to muons, electrons, positrons and neutrinos. The particles that come off of the target include the following: π^+, π^-, K^+, K^-, and protons. At energies below 1 GeV, the π^+, π^-, are produced in numbers that are similar to the number of low energy protons. The numbers of K^+ and K^- are about a factor of ten to thirty lower than the pions. There will be about 0.6 to 0.7 negative pions and kaons produced for every positive pion or kaon. The pions and kaon will decay to muons and electrons over a length of 150 meters or more. The electrons and positrons will form a tight spiral until they travel along the field lines with no transverse momentum.

The following conclusions result from computer simulations, done by Fermi Lab(5), of 8 GeV proton collisions with a target: 1) Copper targets about 1.5 interaction lengths long produced the highest numbers of muons. About ten percent of the beam power ends up in the target. 2) A water cooled Bitter solenoid that is 225 mm thick will reduce the power deposition into the superconducting magnet to around 5 mW cm^{-3}. This is below the quenching threshold in a well cooled magnet. 3) About 40 percent of the particles produced will be lost to the walls. Most will collide with the walls in the first 15 meters. 4) About ninety percent of the muons produced will have an energy in the range from 150 to 1200 MeV. 5) The maximum muon yield will be about 0.52 μ^+/p and 0.34 μ^-/p about 150 meters downstream from the target. The muon yield falls off slowly at longer distances.

From the Fermi Lab studies there is considerable latitude in the length of the phase rotation cavities and the distance to the first phase rotation cavity. The length of the decay channel should not be less than 75 meters. The issue of how long the decay channel should be before phase rotation is started was not addressed. Many think that phase rotation and pion decay can occur simultaneously. If there is no phase rotation in the first 150 meters and one neglects the particles with a momentum of 150 MeV/c, the bunch length will be about 30 meters. From the Fermi Lab studies it is clear that a range of capture and decay channel inductions are possible. In other words, one can capture at an induction below 28 tesla and the decay channel induction can be below 7 tesla. The minimum length of the decay channel before the first phase rotation cavity is probably about 30 meters.

There should be a short decay channel before phase rotation can take place. Table 2 presents the parameters for decay solenoid magnets that can be used in this channel. The central induction of these magnets assumed for this study is 7 tesla. The length of each magnet unit is determined by quench parameters for the magnets. The current density in the superconductor plus stabilizer matrix was nominally set to be 75 A mm^{-2} and the nominal magnet current should be 2000 A or larger. The bore tube wall (assumed to be water cooled copper) thickness was set at 25.4 mm. Figure 3 shows a schematic cross-section for a decay channel solenoid unit.

TABLE 2 Parameters for Pion Decay Channel Solenoids

Parameter	
Total Length of the Channel (m)	>30
Number of Solenoid Magnet Units	>2
Nominal Length for Each Solenoid Unit (m)	15
Solenoid Cryostat Outer Diameter (mm)	~700
Niobium Titanium Coil Outer Diameters (mm)	530
Niobium Titanium Coil Inner Diameters (mm)	380
Solenoid Warm Bore Diameter (mm)	300
Nominal Bore tube Thickness (mm)	25.4
Design Central Induction of the Solenoid (T)	7.0
Nominal Solenoid Operating Temperature (K)	~4.4
Cold Mass per Solenoid Unit (metric tons)	17.8
Total Mass per Solenoid Unit (metric tons)	23.0
Stored Magnetic Energy per Solenoid Unit* (MJ)	47.5

* at the design central induction

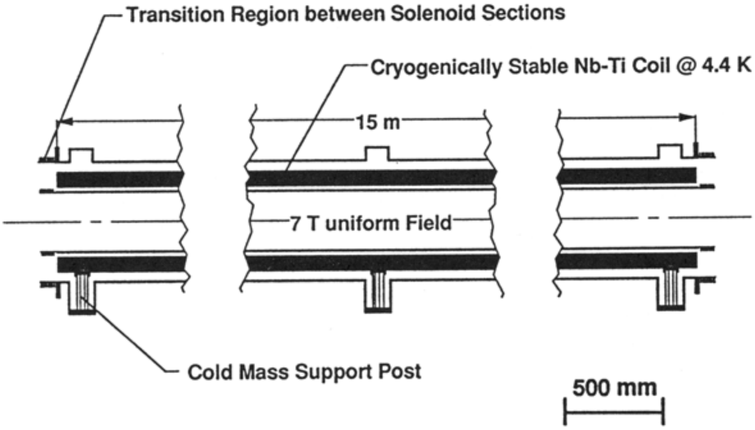

FIGURE 2 A Cross-section of a 7 T Decay Solenoid Section

DISCUSSION AND CONCLUSION

There are a number of issues that affect the efficiency and the cost of the muon production system for the muon collider. These include: 1) The capture induction affects both the cost and the efficiency of capture For constant capture efficiency, the bore of the capture solenoid must be increased as the induction of the capture solenoid decreases. 2) The type of target makes a difference. The Fermi Lab studies(1,5) suggest that the optimum material for the target is copper; the Brookhaven studies(1,2) suggest that a heavy material such as mercury is optimum. From the standpoint of power per unit mass and heat removal, a low Z material such as beryllium may be desirable. The target will define to some extent the yield and the amount of energy that is locally deposited in the superconducting magnet cryostat and the coils. Optimization of the target probably has to be done in combination with the optimization of the rest of the capture and decay system. 3) The thickness of the cryostat walls in the solenoid downstream from the target will affect the cost of the solenoids and the heating within them There is clearly an optimum wall thickness where solenoid capital cost is balanced with refrigeration cost. 4) The induction chosen for the decay channel and phase rotation channel clearly affects the cost of the magnet system. A lower central induction means larger diameter magnets, which in turn can affect the RF system for the phase rotation channel. Clearly the capture solenoid, the decay channel and the phase rotation system should be optimized as a unit.

The separation of π^+ and π^- from protons, electrons, positrons and other particles can have an effect on the overall efficiency of the injection system and the repetition rate of the collider. A method for separating π^+ and π^- was presented at the Montauk Workshop (5). This method involves the use of a curved solenoid. After the particles have been bent in the solenoid for about 10 meters, the π^+ and π^- are physically separated about 200 mm across the aperture of the solenoid. Once physical separation occurs, the bunches of π^+ and π^- have to be separated in time (and distance along the channel) so that the phase rotation RF system can act on both types of muons simultaneously. Some unusual magnet schemes have been proposed. One such magnet scheme is a cornucopia shaped magnet that has a central induction of 28 tesla at the small end of the horn and 7 to 10 tesla at the large end of the horn. All of the beam separation ideas involve larger bore solenoids if good π^+ and π^- separation is to be achieved along with a high yield of muons per proton. The cost of the cornucopia or larger bore solenoids is greater than the simple decay solenoids described earlier, If one can eliminate separate bunches of protons for the μ^+ and μ^-, the extra cost can probably be justified. The separation process for other particles coming off of the target appears to be imperfect. It is not clear where the energy from those particles will be deposited further down the decay and phase rotation channel. Should one try to get rid of the residual protons from the injector beam, and the decay e^+ and e^- before phase rotation?

From the standpoint of superconducting magnet technology, one would like to have a capture solenoid with a low central induction. A water cooled insert coil inside of the superconducting solenoid is still a good idea provided the water cooled solenoid can be made reliable enough to operate over the life of the machine. (To have to replace a radioactive water cooled solenoid during normal machine operation could be a problem.) The minimum thickness for the water cooled insert to a superconducting capture solenoid is about 250 mm (whether this insert generates part of the magnetic field or not) The optimum induction for the decay channel and the RF phase rotation channel is driven by the peak field in the phase rotation solenoids in the RF cavities and the physical size of the RF system. There is clearly a tradeoff between having to use niobium tin solenoids or a 1.8 K refrigeration system for the phase rotation magnets and having to build a larger diameter RF system. The minimum length of the drift space between the capture solenoid and the start of the phase rotation system appears to be driven by energy deposition into the walls of the decay channel. It appears that phase rotation should start as close to the capture solenoid as is practical (before the bunch length gets too large). The effect of the change in the particle gamma as it decays from a π to a μ on the phase rotation process is not clear. The separation of π^+ and π^- bunches appears to be desirable, but more study is needed.

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