THE INTEGRATION OF LIQUID AND SOLID MUON ABSORBERS INTO A FOCUSING MAGNET OF A MUON COOLING CHANNEL *

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Abstract

This report describes how one can integrate the muon absorber with the focusing coils of a SFOFO muon cooling channel [1]. The absorber material must be a low Z material that reduces the muon momentum with minimum scattering. The best materials to use for muon ionization cooling absorbers are hydrogen, helium, lithium hydride, lithium, and beryllium. Hydrogen or helium in an absorber would normally be in the liquid state. Lithium hydride, lithium, and beryllium would normally be in the solid state. This report limits the absorber materials discussed to hydrogen, helium, lithium, and beryllium. In order to achieve the same level of ionization cooling with a solid absorber as a liquid hydrogen absorber, the beta of the muon beam must be reduced more than a factor of two. This affects both the designs of the absorber and the magnet around it. Reducing the beam beta reduces the momentum acceptance of the channel. Integration of a liquid hydrogen absorber and solid absorbers with a superconducting focusing solenoid is discussed. The choice of absorber material affects the design of the superconducting focusing magnet and the superconductor that is used to generate the magnetic field.

MUON IONIZATION COOLING

Ionization cooling has been selected as a cooling method, because stochastic cooling, electron cooling and laser cooling take a long time (>1 sec) compared to the life of a muon (2.1 μs for a muon at rest). When a muon enters a material, energy is lost along the track. This means that both longitudinal and transverse momentum are lost as the muon passes through the cooling material. If the muon is re-accelerated in the longitudinal direction, the loss of transverse momentum is retained and beam cooling has been achieved. Coulomb scattering of the muon beam in the material counters the effect of cooling. If the emittance lost is greater than emittance gained due to scattering, net ionization cooling results.

An equation that describes ionization cooling can be stated as follows [2]:

$$\frac{d\varepsilon_{x,N}}{dz} = -\frac{1}{\beta^2}\frac{\varepsilon_{x,N}}{E}\left[\frac{dE}{dz}\right] + \beta_{\perp}\frac{(0.014GeV)^2}{2\beta^3 E m_{\mu} L_R} \quad (1)$$

where $\varepsilon_{x,N}$ is the muon emittance; $\beta = v/c$; E is the muon energy; $\beta_{\perp}$ is the transverse beam beta, m is the mass of a muon and L_R is the radiation length of the absorber.

The term with the minus sign on the right hand side of Equation 1 is the cooling term; the term on the right hand side of Equation 1 with the plus sign is the coulomb scattering term. For rapid ionization cooling one needs strong focusing in order to achieve a low value of $\beta_{\perp}$ and on wants to have a high value of L_R, which implies that one wants to use a low Z material for doing the cooling. In general, cooling is proportional to the number of electrons in the atom. Coulomb scattering is proportional to the number of charged nucleons in the atom squared. Thus hydrogen is the best material to use for ionization cooling. Table 1 compares the properties of a number of liquid and solid absorbers.

Table 1. A Comparison of the Properties of Various Absorber Materials

Material	**dE/dx** (MeV g-1 cm^2)	L_R (g cm^{-2})	**Density** (g cm^{-3})	**Length for 10 MeV of Absorption** (cm)	**Equilibrium Cooling Factor**
Liquid. Hydrogen	4.12	61.3	0.0708	34.28	1.000
Liquid Helium	1.94	94.3	0.125	41.24	0.524
Lithium Hydride	1.89	79.3	~0.78	6.78	0.352
Lithium	1.65	82.8	0.534	11.35	0.268
Beryllium	1.61	85.2	1.848	3.36	0.172
Aluminum	1.62	24.3	2.70	2.28	~0.05

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Table 1 compares various liquid and solid materials that can be used for muon ionization cooling. The last column in Table 1 compares the relative emittance reduction to the equilibrium value (the value where coulomb scatting exactly matches the cooling term). From Table 1, one can see that hydrogen should be twice as good as any other cooling material. This is not completely true because liquid hydrogen must in a leak tight container. Helium must also be contained.

Safety requirements dictate that a hydrogen absorber must have two sets of windows, the primary hydrogen-windows, and safety-windows. The two windows are separated by a vacuum space that is directly connected to a volume that is at least 50 times the absorber volume. Safety standards dictate that both windows must be designed to have a burst pressure that is four times the design pressure for the windows. Safety standards require the hydrogen absorber to have a design working pressure of 0.17 MPa (25 psig). If the hydrogen and safety windows are fabricated from 6061 aluminum, their thickness will be of the order of 300 μm. If an alloy in the 2090 or 2190 series can be used, the window thickness can be reduced to about 130 μm. There are two question concerning the 2090 and 2190 aluminum alloys. Can they be machined to a thickness of 130 microns and can they alloy be welded to 6061 aluminum? For an absorber that is 300 mm thick, the 6061 windows will reduce the relative cooling factor from 1.000 to 0.693. If the 2190 series of aluminum windows can be used the cooling effectiveness is increased to 0.815.

If helium is used to cool the muons, the total window thickness can go down a factor of four. The effectiveness factor for helium absorbers with 6061 and 2190 windows would be 0.447 and 0.478 respectively. Testing an absorber with liquid helium is an option in an experiment such as MICE [3], but the use liquid helium absorber are limited by the transfer of heat from the absorber to a cooling medium of two-phase liquid helium [4]. Table 2 compares the thermal conductivity k and the available ΔT for heat transfer out of the absorber for five candidate absorber-materials [5]. The product of ΔT and k is the heat transfer potential for the absorber. The higher this product the better. In general, a helium absorber is not viable for a high power cooling channel or a ring cooler.

Of the materials shown in Table 1, only lithium hydride is questionable in its application for absorbers. Lithium hydride is not as reactive as lithium, but it produces more hydrogen when it reacts with water. Lithium hydride generally comes in pellet form, which can be a safety hazard. Lithium hydride melts at 680 C decomposes at about 745 C. Lithium hydride would be difficult to handle in the molten state. It also may be difficult to encase lithium hydride in aluminum because of its tendency to form lithium-aluminum-hydride. Pellets of lithium hydride have poor thermal conductivity. The thermal conductivity is variable depending on the hydroxide content. Lithium hydride should not be ruled out without more study, but it has not been included in the list of absorber materials shown in Tables 2 and 3.

Lithium and beryllium both appear to be viable materials for ionization cooling. Lithium must be encased to prevent oxidation and reaction with water. Thin aluminum windows (say 50 μm) can protect the lithium absorber from the air. The case around the absorber can carry coolant for the absorber. (Oil is a recommended coolant for lithium.) Lithium in the molten state (melting T = 180.5 C) can be used as an absorber. Molten lithium is used in lithium lenses, which cool the beam while reducing the beam beta.

Beryllium, while toxic in the form of dust, can be handled safely in block form. The melting temperature of beryllium is 1553 K (1278 C), which means that radiation cooling is an option for many absorbers. Water-cooling pipes can be attached a copper sheath around a beryllium absorber. No absorber windows are needed.

The use of solid absorbers is only attractive if one can reduce the transverse beam beta $\beta_\perp$. A strong focusing solenoid is needed to reduce the beam beta in a solid absorber. A small beta in one part of a cooling cell implies that there will be a large beam beta in another part of the cooling cell. The large beam beta in another part of the cooling cell (such as the RF cavity iris) will limit the momentum acceptance of the cooling channel. This suggests that the use of solid absorbers would be more attractive in later cooling stages of a cooling channel.

COOLING IN MICE

The proposed Muon Ionization Cooling Experiment (MICE) allows one to compare the cooling performance of various absorber materials. The predicted cooling for the MICE channel with an average momentum of 200 MeV/c and a beam beta of 420 mm in the absorber is shown in the first column of Table 2. The MICE channel cooling channel cools far from the equilibrium emittance. This is apparent when one compares hydrogen and helium cooling. Note: the beam beta in the MICE channel is too large for any cooling to occur with an aluminum absorber. MICE should be able to demonstrate cooling using hydrogen, helium, and low Z solid absorbers.

Table 2. A number of Material Parameters For Five Absorber Materials

Material	**MICE Cooling Factor** (%)	**k** ($W\ m^{-1}\ K^{-1}$)	**ΔT** (K)
LH_2	-12.9	~0.113	~5.0
LHe	-11.0	~0.029	~0.7
Li	-9.5	85.9	~120
Be	-6.0	218	>800
Al	+13.4	236	>400

Table 3. Focus Coil Current Density, Focus Coil Peak Induction, and the MICE Channel Momentum Acceptance as a function of Beam Beta at the Absorber Center

$\beta_\perp$ (mm)	Focus Coil J (A mm^{-2})	Coil B_p (T)	Δp/p (±%)
420	107	6.27	25
255	127	7.44	20
160	141	8.26	17
103	156	9.14	14
55	177	10.37	8

Average muon momentum = 200 MeV/c

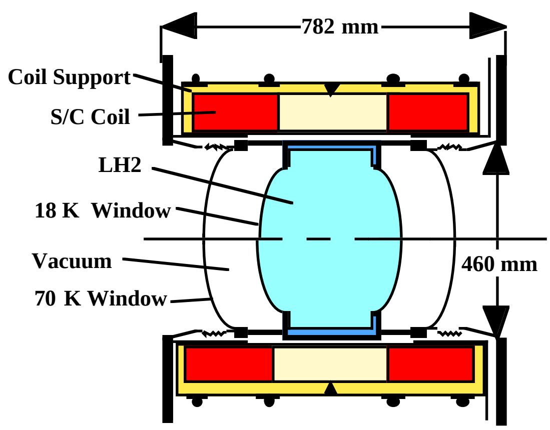

Figure 1. A Cross-section of a MICE Focusing Magnet around a Liquid Hydrogen Absorber

Simulations of the MICE channel have been made for various cases where the beam beta is changed in the absorber [6]. Table 3 shows the MICE focusing coil current density and peak induction in the windings for various values of the absorber beam beta for a muon beam with an average momentum of 200 MeV/c. The final column shows the momentum acceptance of the MICE channel as a function of beam beta at the center of the absorber within the focusing magnet.

Since the MICE coils shown in Figure 1 are made from niobium titanium, the average coil current densities and peak induction in the windings shown in Table 3 are not realistic for beam betas less than 250 mm. In order to do the lowest beam beta experimental cases in MICE, the average momentum of the MICE beam must be reduced. The case where the transverse beam beta is 55 mm, will have an average beam momentum of 140 MeV/c.

Figure 2 illustrates how one might modify the MICE magnets so that solid absorbers can be used. Figure 2 shows a niobium tin insert magnet installed in the niobium titanium MICE coils. The current density in the niobium tin winding can be as high as 150 A mm^{-2}, for a peak induction in the niobium tin coil as high as 11 T.

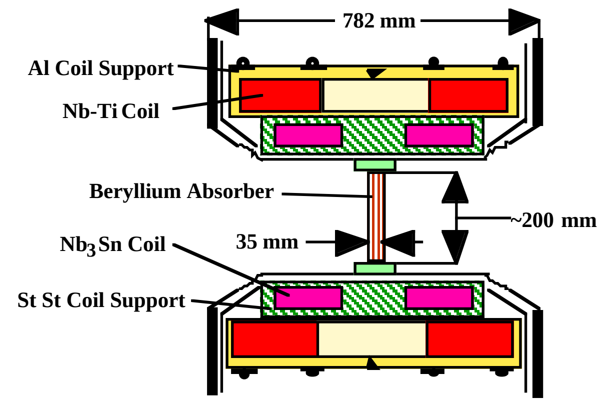

Figure 2. A Cross-section of the MICE Focusing Magnet with a Nb_3Sn Insert Coil and a Beryllium Absorber

Figure 2 illustrates the kind of magnet design that must be considered in order to utilize solid absorbers in the later stages of a muon cooling channel, where a lower momentum acceptance can be tolerated.

CONCLUDING COMMENTS

Hydrogen is the best material to use for ionization cooling of muons. The use of liquid hydrogen is advised in the first stages of a muon cooling channel or ring cooler. Solid absorbers can be used to effectively cool muons, provided one is willing to operate the focusing magnets at higher fields and tolerate a lower momentum acceptance. The focusing magnet around the absorber can be smaller than the magnet proposed for the level II study and MICE. The inner focus coils will probably have to be made from niobium tin.

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