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A HYBRID SIX-DIMENSIONAL MUON COOLING CHANNEL WITH GAS FILLED CAVITIES.*

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Abstract

A muon collider requires single, intense, muon bunches with small emittances in all six dimensions. This can be achieved in a ionization cooling channel that consists of periodically inclined solenoids of alternating polarity, dense absorbers placed inside the solenoids and rf cavities between them. We discuss a novel idea to integrate high-pressure gas-filled rf cavities in a 6-didemsional muon cooling channel. The scheme we describe is a hybrid approach that uses high-pressure gas to avoid cavity breakdown, along with discrete Lithium Hydride absorbers to provide the majority of the energy loss. We show that the channel performs as well as the original vacuum rf channel while potentially avoiding degradation in rf gradient associated with the strong magnetic field in the cooling channel.

INTRODUCTION

Ionization cooling [1] involves passing a magnetically focused beam through an energy absorber, where the muon transverse and longitudinal momentum components are reduced and through rf cavities, where only the transverse is restored. After some distance, the transverse components compress to the point where they come to equilibrium with the heating caused by multiple coulomb scattering.

Sufficient longitudinal cooling requires emittance exchange, in turn, requires the introduction of a beam bend that creates dispersion, a correlation between the orbit energy of a particle. There are two approaches to achieve emittance exchange. One is by using a wedge absorber where the beam is dispersed across a wedge of absorbing material such that high momentum particles lose more energy [2]. The alternative technique is based on energy loss dependence on path length in a continuous absorber [3]. The former requires normal conducting cavities operating in vacuum while the latter incorporates rf cavities filled with dense hydrogen gas.

There are a few challenges in designing ionization cooling channels based on vacuum rf technology. For instance, there is now considerable experimental evidence that the performance of a normal conducting cavity degrades markedly when the cavity is immersed in a strong axial magnetic field [4]. Unfortunately, this is precisely the configuration proposed for ionization cooling of muons. For example, the last cooling stages require 650 MHz rf cavities to operate at gradients > 25 MV/m within a magnetic field that exceeds 5 T. Interestingly, recent studies using a cavity filled with high-pressure (HP) hydrogen gas show no degradation in maximum gradient in this configuration [5, 6]. For this reason it seems prudent, to begin investigating the technical aspects of implementing HP rf in a 6D cooling channel.

In this study we design and simulate a rectilinear channel [7] with the purpose to cool the 6D phase-space of a muon beam. In order to mitigate the possible problems in high magnetic fields we investigate a novel hybrid approach that uses gas-filled pressurized cavities and compare its performance against the conventional vacuum rf channel. With aid of numerical simulations we show that a rectilinear channel with gas filled cavities not only maintains a transmission comparable to a vacuum rf based technology channel, but also it achieves a notable 6D emittance reduction by three orders of magnitude.

COOLING CONCEPT

The overall layout of the channel is shown in Fig. 1. The lattice consists of a sequence of identical cells with two or four solenoids in each cell with opposite polarity to provide transverse focusing. The coils (yellow) are not evenly spaced; those on either side of the absorber are closer together in order to increase the focusing at the wedge absorber (magenta) and thus minimizing the beta function at that location. The relative amount of cooling can be adjusted by changing the opening angle and transverse location of the wedge. A series of rf cavities (dark red) are used to restore the momentum along the longitudinal axis. The dispersion necessary for emittance exchange is provided from the bend field generated by tilting the axes.

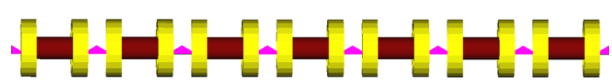

Figure 1: Conceptual drawing of a rectilinear channel

The channel in Fig. 1 is tapered meaning that parameters such as cell length, focusing strength progressively change from stage to stage based on the emittance reduction rate and transmission. The required lattice parameters are summarized in more detail in Table 1. Figure 2 shows the transverse beta function versus momentum for the stages in Table 1. Notice that the region over which the momentum is non zero becomes progressively smaller implying a reduction in momentum acceptance as the beam moves towards the late stages. For instance, while the momentum acceptance is above 90 MeV/c at the first stages, it drops below 70 MeV/c for the last four stages. From beam dynamics point of view this is not a problem since each stage is designed to provide a

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momentum acceptance that is at least 4 times higher than the sigma of the beam. Since the average momentum of the incoming beam is expected to be in the 200-210 MeV/c range, all stages are designed to provide a central momentum equal to 200 MeV/c. Notice that, for each stage, the beta at central momentum becomes progressively smaller to ensure that the cooling emittance is always above the equilibrium emittance.

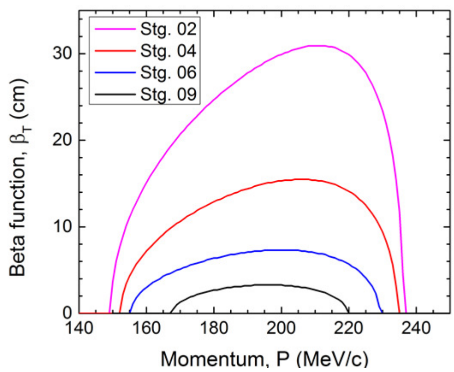

Figure 2: Momentum acceptance for different stages along the channel.

Figure 3 shows the axial magnetic field at the cavity edge for each cooling stage. While the field remains below 6 T on the first 4 stages it reaches 10 T at stage 7. The field drop on stages 8 and 9 is due the shorter cavities used for those stages.

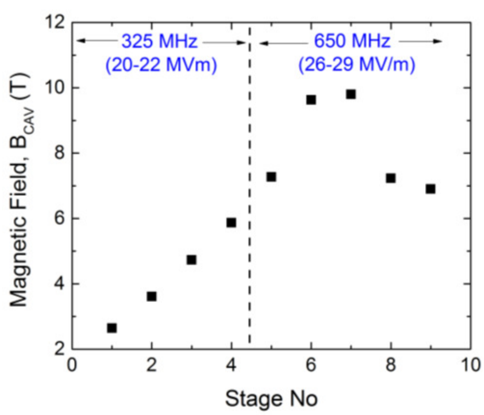

Figure 3: Axial magnetic field at the cavity edge for each cooling stage.

COOLING WITH GAS FILLED CAVITIES

There are key differences between an HP rf cooling channel and "standard" (vacuum rf) channel. In the HP rf channel [3], the energy loss is distributed throughout the channel, rather than localized at discrete absorber regions. Moreover, the loss medium is gaseous rather than liquid or solid, which makes containment more of a challenge. While the addition of high-pressure hydrogen to the rf cavity likely increases the maximum allowable gradient it is difficult to increase the energy loss correspondingly in a gas-filled system.

We propose here an alternative, hybrid approach to convert the conventional vacuum rf 6D cooling channel [9] to an HP rf version. Since our primary purpose is to avoid degradation of the cavity gradient to high magnetic field we use only enough gas to accomplish this task for the nominal gradient of 28 MV/m at 650 MHz. Based on the measurement in Ref. 6 at 805 MHz, we expect that a pressure of 34 atm at room temperature will be satisfactory. Eventually this parameter needs to confirmed in both 325 MHz and 650 MHz scenarios. At our specified pressure to compensate for the energy loss in the gas we slightly reduce the length of the absorber on axis. A conceptual design of a cooling cell for stage 2 is shown in Fig. 4.

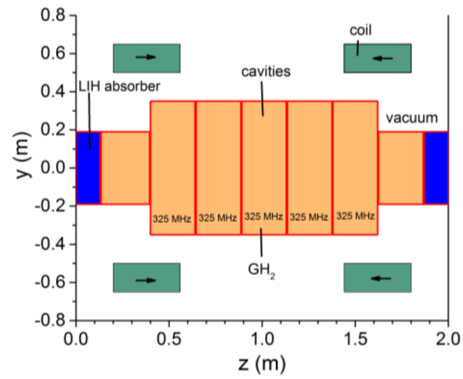

Figure 4: Schematic illustration of a hybrid channel cell with gas filled cavities for stage 2.

The performance of the cooling channel was simulated using the ICOOL code [8]. The code includes all relevant physical processes (e.g. energy loss, straggling, multiple scattering, muon decay). The absorber material was lithium hydride for all stages. The input beam in the simulations has a normalized transverse emittance of 5.10 mm and a normalized longitudinal emittance of 10.02 mm, while the average longitudinal momentum is 208 MeV/c. Those parameters closely resemble the baseline distribution of a muon beam before the final 6D cooling sequence of a Muon Collider [1]. We tracked 56,000 particles and included muon decay. The emittance evolution is shown in Fig. 5. After a distance of 515 m the 6D emittance has fallen by a factor of 1000 with a transmission of 35%. At the end of the channel, the transverse and longitudinal rms normalized emittances are 0.31 mm and 1.6 mm, respectively.

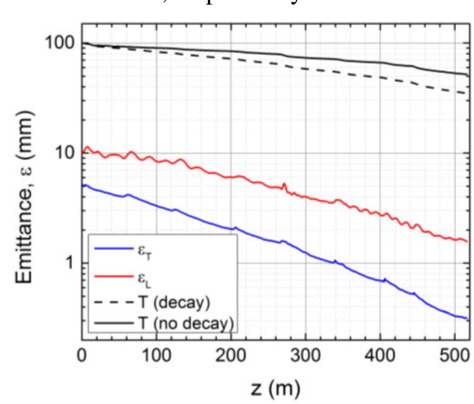

Figure 5: Cooling performance of a hybrid channel that uses LiH absorbers and gas filled cavities.

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Table 1: Main lattice parameters of a tapered rectilinear channel wth gas filled cavities. All stages are using LIH absorbers. The pressure is fixed at 34 atm, at room temperature.

Stage	Cell length [m]	rf freq. [MHz]	rf grad. [MV/m]	rf #	rf Length [cm]	Absorber type	Coil tilt [deg.]	Wedge angle [deg.]
1	2.750	325	19.0	6	37.6	LIH	0.90	30
2	2.000	325	20.0	5	40.0	LIH	0.90	30
3	1.500	325	20.0	4	34.3	LIH	0.80	40
4	1.270	325	22.0	3	19.6	LIH	0.90	40
5	0.995	650	26.0	6	20.1	LIH	0.60	50
6	0.806	650	26.0	4	18.64	LIH	0.65	60
7	0.806	650	26.0	4	14.36	LIH	0.65	90
8	0.806	650	28.0	4	15.65	LIH	0.60	120
9	0.806	650	29.0	4	13.49	LIH	0.55	120

The lattice cooling efficiency is defined as the rate of change of the 6D emittance divided by the change of muons. The Q factor compares the rate of change of emittance to the particle loss and under ideal conditions should remain the same (constant) through the lattice. In conventional lattices Q starts off small due to losses from initial mismatching, then rises to a large value and finally falls as the emittance of the beam approaches its equilibrium value. Figure 6 shows the evolution of Q along our hybrid 6D cooling channel. A glance at Fig. 6 indicates the importance of tapering as the cooling rate remains relatively flat with a maximum value (Q≈7). The blue line corresponds to an equivalent channel that uses vacuum rf cavities with LiH absorbers in every stage. It is worth noting that both vacuum rf and HP rf channels achieve the same performance. This suggests that our hybrid approach is not degrading the cooling efficiency relative to the pure vacuum solution, thus making it a very promising choice.

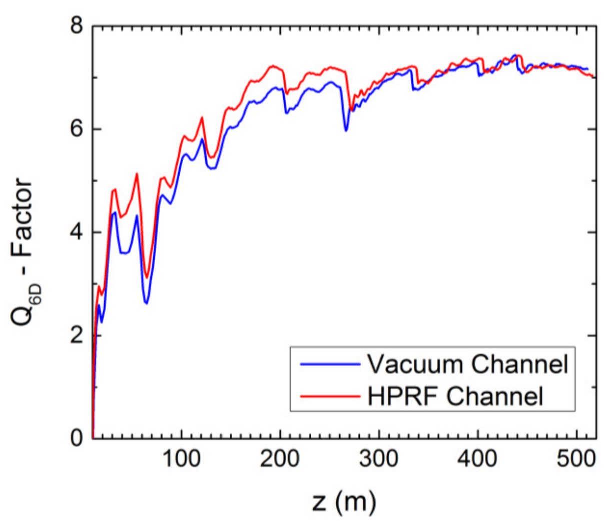

Figure 6: Quality factor, Q versus z for a channel with vacuum and gas-filled rf cavities. Both channels achieve same cooling efficiency along the channel.

CONCLUSIONS

We described a cooling technique that simultaneously reduces all six phase-space dimensions of a charged particle beam. We have discussed a possible scheme of using a hybrid approach wherein gaseous Hydrogen provides protection against cavity operational problems and LiH absorbers are the primary source of energy loss medium. With the aid of numerical simulations, we showed that a high pressure rf channel not only achieves the same transmission as conventional designs, but also maintains its performance through the channel resulting in a notable 6D emittance decrease by more than 3 orders of magnitude. Motivated from the recent experimental studies that demonstrated that a high-pressure gas-filled cavity can operate in a multi-tesla field without degradation, we believe that the hybrid concept presented here can be a promising approach to ionization cooling channels for muon based applications. Further studies accessing the engineering feasibility need to be initiated.

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