6D Cooling of a Circulating Muon Beam

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Abstract. We discuss the conceptual design of a system to reduce the 6D emittance of a circulating muon beam. This system utilizes ionization cooling to achieve 6D phase reduction of the beam. Our design is based on a hydrogen gas filled ring which incorporates optics consisting of weak-focusing dipoles and 200 MHz rf cavities which restore the ionization energy loss due to the muons traversing the hydrogen gas.

INTRODUCTION

Muon beams can be cooled by ionization cooling, in which the muons lose momentum traversing a material absorber, and regain the longitudinal momentum component traversing an RF cavity. Focusing magnets, such as solenoids or quadrupoles, contain the beam. The system can be closed into a ring by bending magnets or by tilting solenoids. A ring system provides 6D cooling, while a straight one only cools transversely. We have been investigating cooling rings with lattices composed of various combinations of dipoles and quadrupoles. The first rings designed included short liquid hydrogen (LiH_2) absorbers, but subsequently we have have investigated rings in which the energy absorbtion occurs in compressed hydrogen gas that fills the entire beam enclosure. We will briefly discuss some LiH_2 based rings, then turn to the gas-filled rings. and lastly discuss a small demonstration ring intended to validate the principle of 6D muon cooling.

DIPOLE-QUADRUPOLE RINGS WITH Li H_2 ABSORBERS

Before studying gas-filled rings, many rings were designed for cooling with short LiH_2 absorbers. Their performance was simulated with ICOOL The magnet lattices used various arrangements of dipoles and quadrupoles, or of dipoles alone with edge focusing. The main lattice objectives were to have low beta-function values in the absorbers to reduce heating, to minimize the maximum beta-function values elsewhere to obtain large acceptances and to reduce the cell lengths to increase cooling efficiency. Figure 1 shows an example of this type or ring cooler.

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1 m drift available for rf
Low □ (25 cm) at absorber
Combined function dipole simulated
Dispersion only at absorber
(allows for matching straight sections)
Cell tune ~ 3/4
Beam momentum 250 MeV/c
25 cm LiH_2 wedges
Wedge angle 20^0
rf frequency 201.25 MHz
E_{max} = 16 MV/m
Transmission 50%
Total Merit = *Transmission* x
$(e_x\, e_y\, e_z)_{initial} / (e_x\, e_y\, e_z)_{final}$ = 15

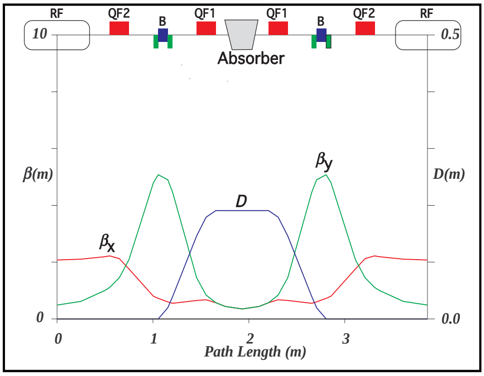


FIGURE 1. Cell of an 4-cell quadrupole-dipole ring with LiH_2absorber in the center. The 'ears' on the dipoles (**B**) indicate edge focusing.

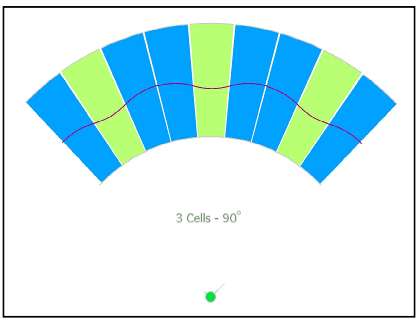
DIPOLE-ONLY GAS-FILLED RINGS

We have adopted the following approach to muon beam cooling in gas-filled rings:

Rings filled with high-pressure hydrogen gas for energy absorption.
efficient cooling (absorber everywhere)
RF breakdown voltage increased

Dipole-only, scaling lattices
compact rings
lower betamax values, high acceptances

Two types of scaling lattice rings have been investigated: Alternating Gradient Rings and Zero-gradient sector dipole **rings. Examples are shown in Figures 2 and 3.**



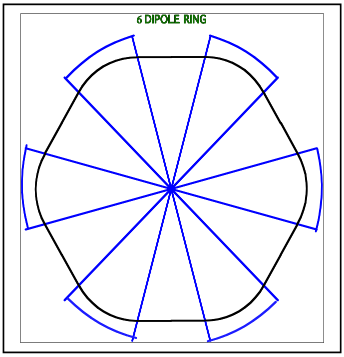
Lattice consists of alternating vertically defocusing and horizontally focusing magnets

No drift spaces between dipoles.

B_o = 2.6T and P_o = 250 MeV/c

Total merit with decay = 120

FIGURE 2. Three cells of FFAG Alternating Gradient 12 cell Ring.



Key parameters at r = 60 cm
β_x = 53 to 72 cm ; β_y = 60 to 64 cm
Dispersion = 60 to 64 cm
Circumference = 3.91 m

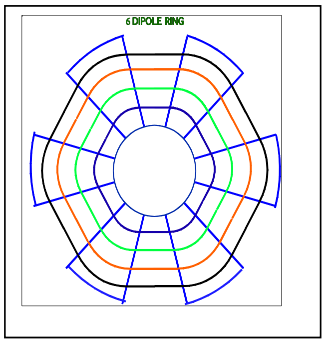
FIGURE 3. Schematic diagram of 6 cell weak focusing high-field ring.

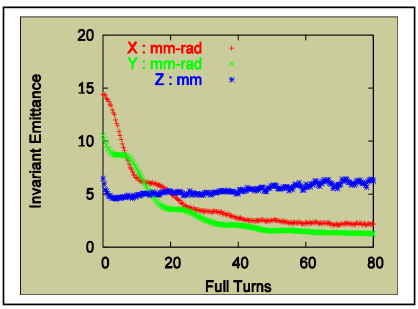
RINGS TO DEMONSTRATE COOLING

We have proceeded to make a design scenario to demonstrate 6D muon cooling with a small zero-gradient dipole ring, In order to make this demonstration economically feasible we have reduced the cooling goals to correspond to a merit factor of at least 10, and set the following design parameters:

1.8T conventional magnets, 200 MHz RF cavities, 40 Atmosphere compressed H_2
For each harmonic, the beam momentum that corresponds to the field is calculated and the cooling performance evaluated. Comparisons are made for different harmonics. It was found that 4 or 6 dipole rings and harmonic number 3 were optimum.

Harmonic 2
Circumference = 1.76 m, P_0 = 77 MeV/c
Harmonic 3
Circumference = 3.76 m, P_0 = 165 MeV/c
Harmonic 4
Circumference = 5.45 m, P_0 = 240 MeV/c





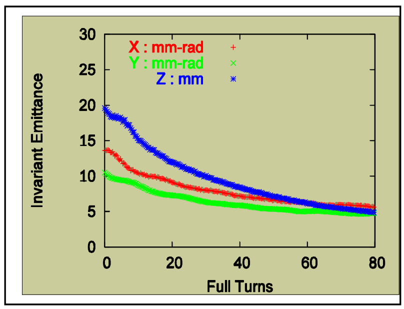
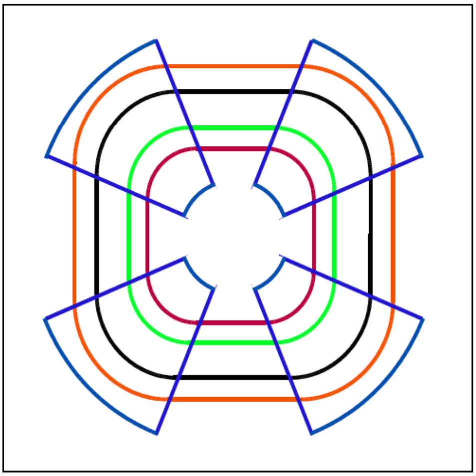


FIGURE 4. 6-dipole ring: schematic, parameters and performance for harmonic numbers 2 and 3.



Harmonic 3
Circumference = 3.76 m
P_0 = 165 MeV/c
40 Atmosphere H_2
Total Merit without decay = 20

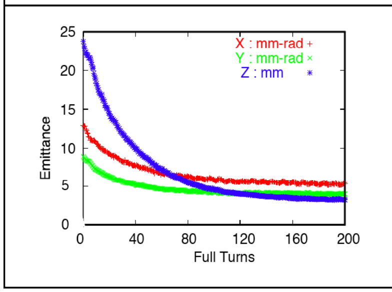
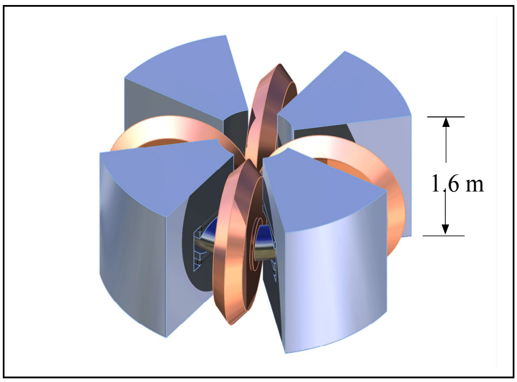


FIGURE 5. 4-dipole ring: Schematic, parameters and performance for harmonic number 3.

SMALL MUON RING FOR A COOLING DEMONSTRATION

A preliminary plan has been made to demonstrate muon cooling in a gas-filled ring. The conceptual design and parameters are shown in Figure 8.



Parameter	Value
Dipole Field	1.8 T
Number of Cells	4
Reference Momentum	172.12 MeV/c
Ring Circumference	3.81 m
X Aperture	±20 cm
Y Aperture	±10 cm
P_z Acceptance	±10 MeV/c
Minimum β_X	38 cm
Maximum β_X	92 cm
Minimum β_Y	54 cm
Maximum β_Y	66 cm
Hydrogen Gas Pressure	40 Atm @ 300¼K
RF Gradient	10 MV/m
RF Frequency	201.25 MHz
Total RF Length	1.2 m
Total Orbit Turns	100

FIGURE 6. Proposed gas-filled muon storage ring for cooling demonstration.

In order to model the fields more realistically, these have been calculated with the TOSCA code and tracking and performances obtained using the field maps generated.

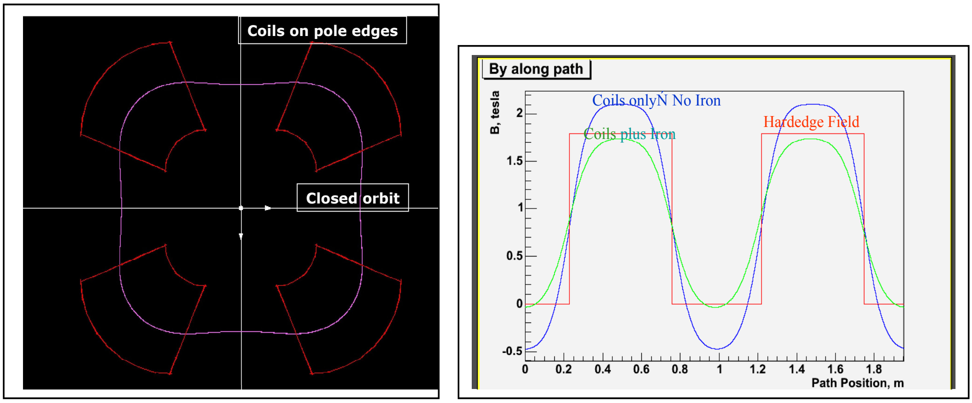


FIGURE 7. Azimuthal fields generated by TOSCA with three models.

Not surprisingly, cooling is best with the hardedge model. Studies have been made and will continue to shape the poles and coil configuration to maximize performance.

SUMMARY

- Quadrupole-dipole rings with LiH_2 absorbers require high fields for cooling.
- Dipole-only rings are more compact and thus have better cooling performance.
- Rings filled with compressed hydrogen gas with scaling lattices are promising.
- A small weak focusing ring system has been designed to demonstrate feasibility of 6-D muon ionization cooling.

ACKNOWLEDGEMENTS

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