MUON COOLING IN A RACETRACK FFAG USING SUPERFLUID HELIUM WEDGE ABSORBERS

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Abstract

A fixed field alternating gradient (FFAG) lattice with racetrack-shape has been proposed to cool muon beams. The ring has straight sections with FFAG magnets. Wedge absorbers using superfluid helium and RF cavities are installed to the straight section. This paper describes the first result of simulation study and R&D status of the superfluid helium wedge absorber.

INTRODUCTION

The 6D-emittance reduction of a muon beam is essential for future neutrino factories and muon colliders. Ionization cooling was proposed to achieve a quick muon cooling, since the muon lifetime is 2.2 μs in its rest frame. The emittance reduction in the muon ionization cooling is achieved by repeated channels of an absorber and an RF cavity [1]. In order to demonstrate this cooling method, the MICE is in preparation at Rutherford Appleton Laboratory (RAL) [2]. A long muon cooling channel is necessary to achieve a required emittance reduction for a neutrino factory and a muon collider. Such channels need a high cost of construction. A cooling section using a ring (ring cooler) would be more cost-effective than that consists of straight channels, since a number of RF and absorbers would be reduced. Some designs for the ring cooler have been proposed [3]. These designs, however, have some issues must be solved: injection/extraction and its kicker system, effects of windows for absorbers and RFs.

The study in this paper is the first attempt to design a ring cooler using the following ideas:

- racetrack FFAG ring and
- superfluid helium wedge absorbers.

The racetrack FFAG can be realized by new ideas of a straight beamline consists of FFAG type magnets, which was proposed recently by Y. Mori and S. Machida, *et.al.* [7]. These ideas bring new possibilities to design of the scaling type FFAGs such as dispersion suppressing section in a FFAG ring and an enough space to install devices for kicker systems. New ideas with the racetrack FFAG are actively discussed for example in the PRISM task force [4] and FFAG workshops [5]. FFAG as a muon ring cooler is not well studied yet. Papers by H. Schönauer report the study on ionization cooling in Japan's FFAG-based neutrino facility [6]. However, there is no other papers on the muon ionization cooling in FFAGs.

A typical absorber material proposed in the muon cooling channels is liquid hydrogen, since it has the lowest multiple scattering due to its lowest Z and sufficient ionization loss. Since the liquid hydrogen is an explosive material, its mechanical and engineering design and cooling of the liquid hydrogen are very finicky [8]. On the other hand, helium has no explosion risk and the second lowest Z of any materials. For the superfluid helium, there are more advantages as the absorber material: a lower pressure than the liquid hydrogen and a high thermal conductivity. All of these properties would make the absorber design easier than that with the liquid hydrogen. A thinner absorber window can be used, and a cooling system for the absorber material can be simpler, for instance.

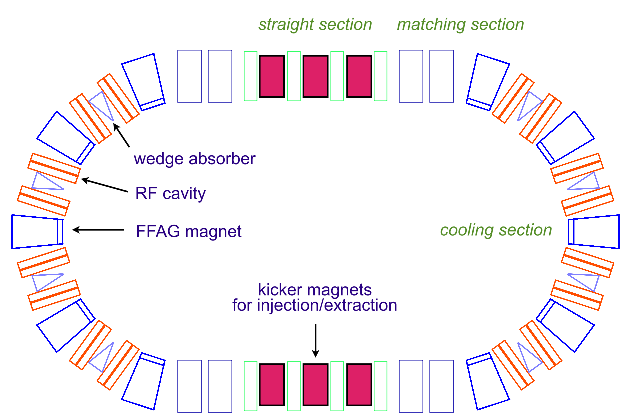

Figure 1: Concept of the muon ring cooler with a racetrack FFAG.

CONCEPT OF RACETRACK FFAG COOLER

Figure 1 illustrates a concept of the muon ring cooler with a racetrack FFAG. The ring is designed as a scaling type FFAG, since it can achieve a large transverse acceptance and a large momentum acceptance simultaneously. The ring consists of three sections: arc sections for the cooling, which has RF cavities and wedge absorbers; straight sections, which have an enough space to install kicker magnets for injection and extraction; and matching sections between the arc section and the straight section.

Zero-chromaticity and large momentum dispersion in a

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scaling FFAG would enable effective longitudinal cooling with wedge absorbers. Choosing cooling parameters carefully, 6-D cooling would be possible in this racetrack FFAG cooler.

MUON COOLING IN PRISM-FFAG BASED LATTICE

As the first step of study for the racetrack FFAG cooler, muon cooling in a FFAG ring cooler based on the PRISM-FFAG [9] lattice have been studied. Figure 2 shows a ring used in this study. Parameters for the ring are summarized in Table 1. A set of lattice parameters of the PRISM-FFAG ring is used for this study except for the central momentum of the muon beam and the magnitude of magnetic field. The central momentum is 308 MeV/c, since the momentum region of 200-300 MeV/c is suitable for the ionization cooling. Magnetic fields of FFAG magnets are calculated by Opera-3d. The beta function and dispersion function are shown in Fig.3 and Fig.4, respectively. This ring cooler lattice would show a possibility of PRISM-FFAG type FFAG ring as a muon ring cooler and can be considered as a racetrack FFAG without straight sections: an ultimate case of the racetrack. Eight set of four RF cavities and four liquid hydrogen wedge absorbers is installed to the ring as shown in Fig.2. Parameters of the RF cavities and the absorbers are listed in Table 2. The opening angle of the wedge absorbers is adjusted to achieve the minimum momentum spread of the muon beam after 15 turns in the ring. A muon beam is injected to the ring at the point A in Fig.2. The beam eminence at the injection point is summarized in Table 3. The g4beamline [10] is used as a tracking code in this study. The beam information is recorded at the point A at every turn until the 15th turn.

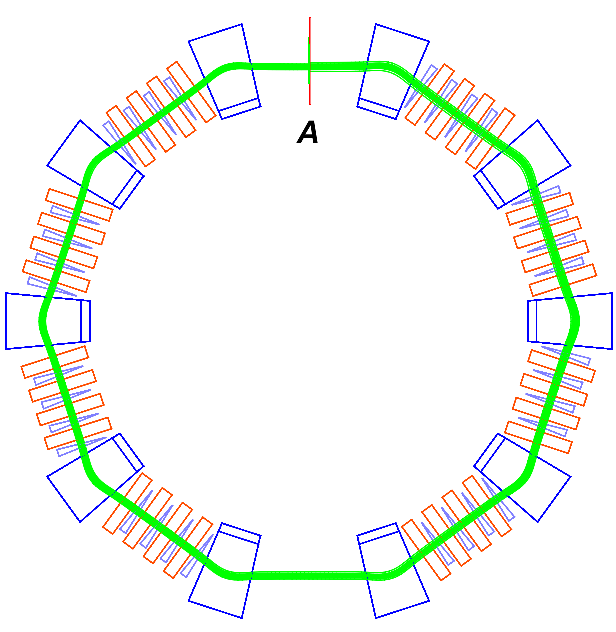

Figure 2: A PRISM-FFAG based lattice for muon ionization cooling used in this simulation study.

Table 1: Parameters of the PRISM-FFAG based lattice for muon ionization cooling.

Circumstance (m)	38
Number of cells	10
Field index k	4.6
F/D ratio	6.0
Maximum field (T)	1.6
Central momentum (MeV/c)	308
Magnet type	DFD triplet
Magnet aperture	H:100 cm × V: 30 cm
Horizontal tune	2.73
Vertical tune	1.58

Table 2: Parameters of the RF cavities and the absorbers.

Circumstance (m)	38
Total number of cells	10
Cell with RF cavities and absorbers	8
Central momentum P_0 (MeV/c)	308
Number of wedge absorbers per cell	4
Wedge thickness on r_0 for P_0(cm)	8.672
Wedge opening angle (degree)	3.86
Absorber material	LH_2
Number of cavities per cell	4
Cavity length (cm)	28.75
RF gradient (MV/m)	8.709

Table 3: Beam emittance of the injected muon beam.

E_0^{kin}	220	MeV
P_0	308	MeV/c
σ_x	4	cm
σ_{p_x}	15.4	MeV/c
$\sigma_{x'} = \sigma_{p_x}/P_0$	0.05	
$\varepsilon_x^{norm} = \beta\gamma\sigma_x\sigma_{x'}$	0.582	cm
σ_y	4	cm
σ_{p_y}	4.6	MeV/c
$\sigma_{y'} = \sigma_{p_y}/P_0$	0.015	
$\varepsilon_y^{norm} = \beta\gamma\sigma_y\sigma_{y'}$	0.175	cm
σ_{cT}	8	cm
σ_T	0.2667	ns
σ_{dE}	20	MeV
σ_{p_z}	21.1	MeV/c
$\varepsilon_L^{norm} = \beta\gamma\sigma_{cT}(\sigma_{p_z}/P_0)$	1.591	cm
$\varepsilon_{6D} = \varepsilon_x^{norm}\varepsilon_y^{norm}\varepsilon_L^{norm}$	0.16	cm^3

Figure 5, 6, and 7 show the tracking results of horizontal, vertical, and longitudinal phase space, respectively. No emittance reduction was observed in every phase space in this study, although the momentum spread was converted to the time spread as shown in Fig.7. The number of survived muon at each turn was quickly reduced as shown in the figures. These results would be caused by a large beta func-

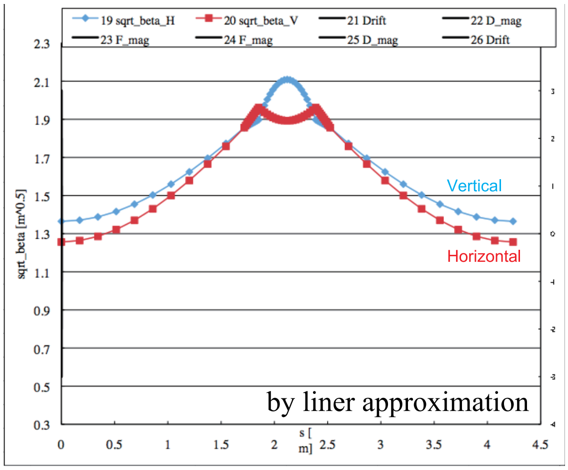

Figure 3: Beta function of the PRISM-FFAG based lattice.

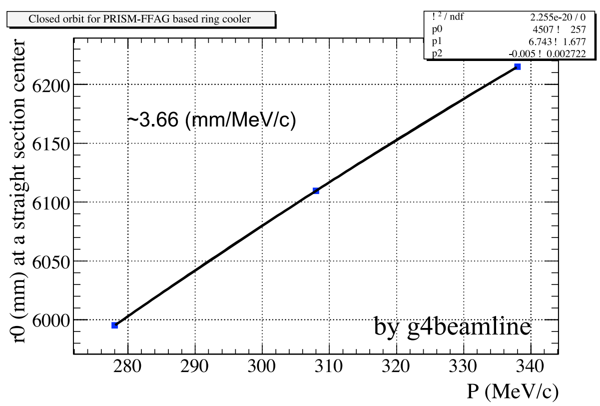

Figure 4: Dispersion function of the PRISM-FFAG based lattice.

tion of this lattice: $\sqrt{\beta}$ [$\sqrt{m}$]=1.25 for horizontal and 1.37 for vertical at the center of straight sections and probably improper parameters of RF and absorbers. In order to improve the cooling efficiency, much detailed studies will be performed. Using this system, cooling tests with a heater in the absorber will be carried out in the coming year.

R&D ON SUPERFLUID HELIUM WEDGE ABSORBER

The superfluid helium is safer than liquid hydrogen as an absorber material for the muon cooling and has a high thermal conductivity, which is useful to reduce heat from the muon beam. A superfluid helium absorber, however, is never developed yet so far. A cryostat and a prototype of the wedge absorber for superfluid helium have been constructed in KEK. Figure 8 is a picture of the prototype wedge absorber.

SUMMARY AND FUTURE PROSPECTS

A new muon ring cooler using a racetrack FFAG and wedge absorbers with superfluid helium have been proposed. Its R&D has just been started. As the first attempt, the PRISM-FFAG based lattice was studied. The lattice with the RF and absorber parameters in Table 2 was, however, not suitable for a ring cooler. Possible causes are large beta functions, not enough acceptance, and improper parameters of RF and absorbers. In order to improve the cooling efficiency, much detailed studies will be performed. A new lattice for the ring cooler must be designed. Then matching and straight section including a kicker system for injection and extraction will be studied to complete a racetrack FFAG ring cooler. A cooling test of a superfluid helium wedge absorber will be performed soon.

ACKNOWLEDGEMENT

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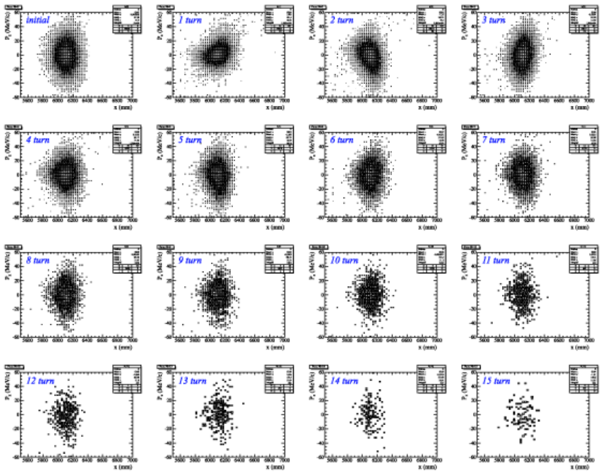

Figure 5: Tracking result: Vertical phase space.

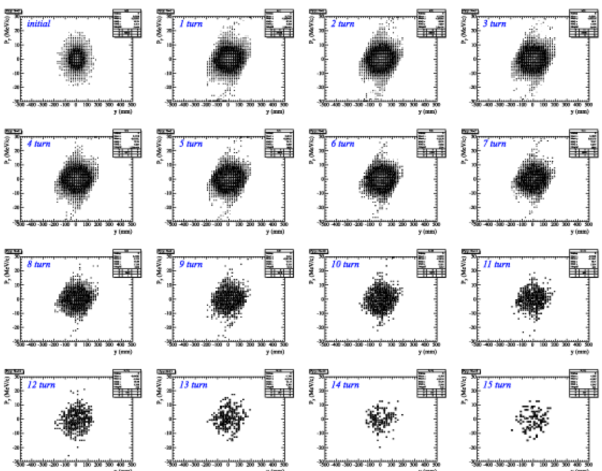

Figure 6: Tracking result: Horizontal phase space.

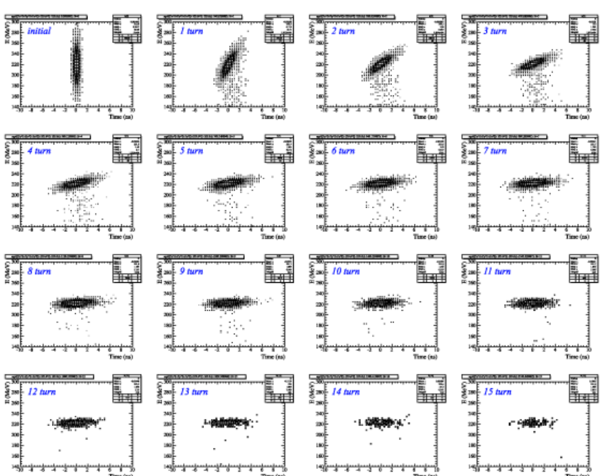

Figure 7: Tracking result: Longitudinal phase space.

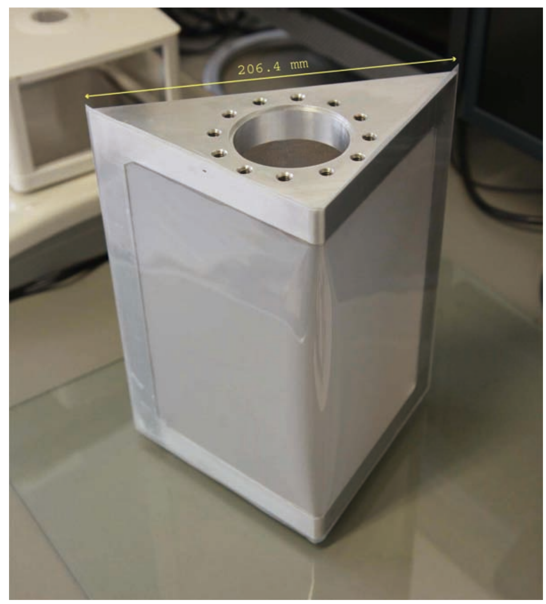

Figure 8: Container of the first prototype of the Superfluid Helium Wedge Absorber.