6D COOLING SIMULATIONS FOR THE MUON COLLIDER*

Pavel Snopok and Gail Hanson, University of California, Riverside, CA, USA

Abstract

The RFOFO ring is considered to be one of the most promising six-dimensional cooling channels proposed for the future Muon Collider. It has a number of advantages over other cooling channels, but also certain drawbacks. The injection and extraction, the absorber overheating, and the bunch train length are among the main issues. A number of simulations of a possible solution to these problems, the RFOFO helix, commonly referred to as the Guggenheim channel, were carried out and their results are summarized. The issue of the RF breakdown in the magnetic field is addressed, and the preliminary results of the simulation of the lattice with magnetic coils in the irises of the RF cavities are presented.

INTRODUCTION

In a Muon Collider design the muon beam 6D phase space volume must be reduced several orders in magnitude in order to be able to further accelerate it and inject it into the storage ring. Ionization cooling is currently the only feasible option for cooling the beam within the muon lifetime ($\tau_0 = 2.19\ \mu s$). The RFOFO ring [1, 2] is one of the feasible options currently under active investigation along with other designs [3–5]. The RFOFO ring provides a significant reduction in the six-dimensional emittance in a small number of turns with a relatively low particle loss factor. However, the design of the injection and extraction channels and kickers is very challenging, and this ring could not be used as is, because the bunch train is too long to fit in the ring. Both problems would be removed in the RFOFO helix, also known as the Guggenheim channel [6]. In addition, utilizing the helix solves another important problem, namely, the overheating in the absorbers.

RFOFO RING LAYOUT AND PARAMETERS

The most important parameters of the original RFOFO design can be found in [1, 2]. They are also summarized here in Table 1 and compared to the parameters of the Guggenheim channel. The layout of the RFOFO ring is shown in Fig. 1. The results of particle tracking through the RFOFO channel in the code G4Beamline [7] are used as the point of reference while comparing the RFOFO and Guggenheim channel efficiencies.

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Table 1: RFOFO and Guggenheim parameters

	RFOFO	Guggenheim
RF frequency, [MHz]	201.25	201.25
RF gradient, [MV/m]	12.835	12.621
Maximum axial field, [T]	2.77	2.80
Pitch, [m]	0.00	3.00
Pitch angle, [deg]	0.00	5.22
Circumference, [m]	33.00	32.86
Radius, [mm]	5252.113	5230.365
Coil tilt (wrt orbit), [deg]	3.04	3.04
Average momentum, [MeV/c]	220	220
Reference momentum, [MeV/c]	201	201
Absorber angle, [deg]	110	110
Absorber thickness on beam axis, [cm]	27.13	27.13

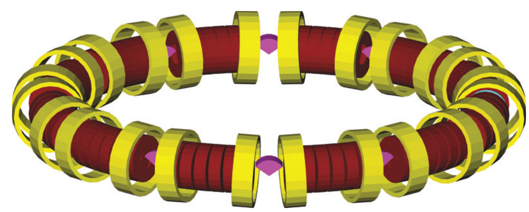

Figure 1: Optics of the RFOFO ring

GUGGENHEIM LAYOUT AND SIMULATION RESULTS

The layout of the Guggenheim channel to a large extent repeats the one of the RFOFO ring, except for the three meters of separation between the layers of the helix. As a result, the circumference of the helix has to be slightly smaller than that of the ring to keep the arclength of one revolution intact. Fig. 2 shows the 5-turn layout which has been simulated. Along with the unshielded case with all the magnetic coils of all layers contributing to the magnetic field guiding muons, another scheme has been considered: with shielding between individual layers. Both layouts include safety windows around absorbers and Be windows in the RF cavities. The simulation details can be found in [8]. Here we only show the transmission (Fig. 3), the six-dimensional emittance reduction (Fig. 4), and the merit factor (Fig. 5) as functions of the number of turns. Here merit factor $M = \frac{\varepsilon_{6D}(0)}{\varepsilon_{6D}(s)}\frac{N(s)}{N(0)}$, $\frac{\varepsilon_{6D}(0)}{\varepsilon_{6D}(s)}$ is the six-dimensional emittance reduction factor, $\frac{N(s)}{N(0)}$ is the transmission, and s is the arclength at which the merit factor is being calculated. In all figures muon decay and various stochastic processes are taken into account. The solid line is used for the RFOFO ring, which serves as a reference, the dashed line is the Guggenheim channel with shielding between layers and no windows in absorbers or RF cavities (the idealized Guggenheim, the performance of which should not differ significantly from the RFOFO ring, which

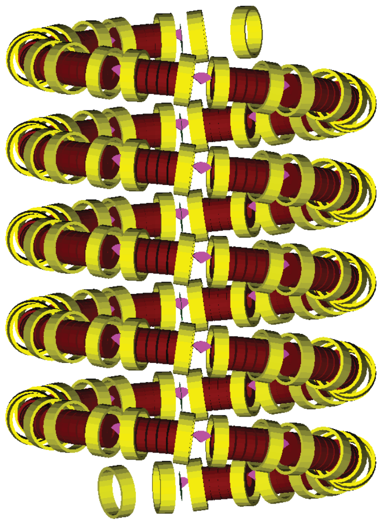

Figure 2: 5-layer Guggenheim (RFOFO helix) layout

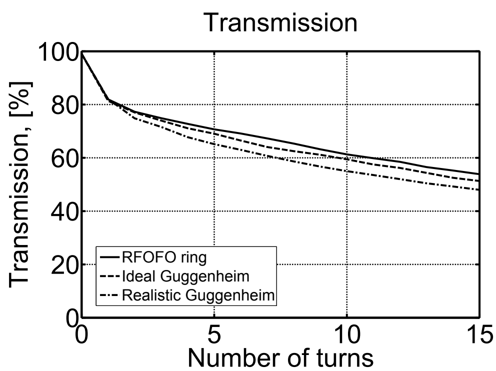

Figure 3: Transmission (number of particles in the beam after a number of turns).

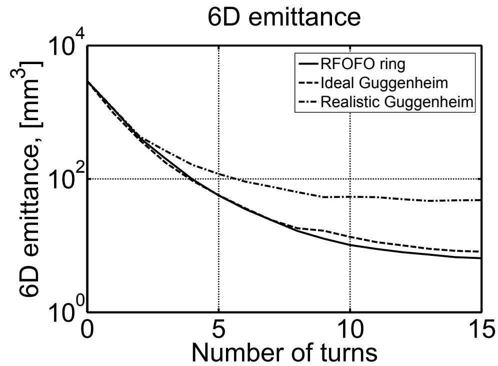

Figure 4: Six-dimensional emittance.

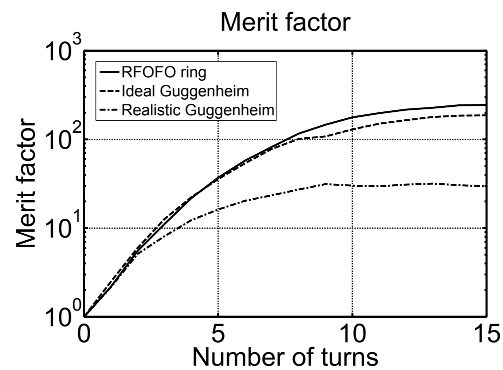

Figure 5: Merit factor (inverse ratio of six-dimensional emittances multiplied by transmission).

is indeed the case), and the dash-dotted line is for the realistic Guggenheim with shielding between layers and windows in both absorbers and RF cavities. Figures clearly demonstrate significant six-dimensional cooling; however, the performance of the cooling channel is seriously affected by the use of absorber and RF windows. These results are in agreement with earlier studies for the RFOFO ring [1].

RF BREAKDOWN AND NEW LATTICE ADDRESSING THIS ISSUE

Various studies suggest that the presence of the magnetic field might disrupt the performance of RF cavities by causing breakdown [9]. Thus, it was proposed to consider an alternative layout of the cooling channel, the so-called magnetically insulated scheme [10]. The concept itself consists of two components: a) moving the solenoidal coils from over the RF cavities into the irises; and b) shaping the RF cavities such that the walls of the cavities are predominantly parallel to the magnetic field lines, which hopefully solves the problem of the breakdown. First results of the simulation of such a layout are presented here. The current layout (Fig. 6) does not include specifically shaped RF cavities; instead a simplified pillbox geometry is used. If further simulations justify the use of the layout in terms of transmission and six-dimensional emittance reduction, the next step will be to import RF cavity shapes from Poisson/Superfish into G4Beamline for simulations.

Figure 6 shows that the new cooling ring has 12 cells with three RF cavities in each and four solenoidal coils in the irises. These coils bear currents with the following densities: 63 A/mm^2, 45 A/mm^2, -45 A/mm^2, -63 A/mm^2. The circumference of the ring is 30.72 meters. The idea of tipping the solenoids, similar to the RFOFO ring concept, is employed in this layout to generate an average vertical magnetic field of 0.136 T providing necessary bending (Fig. 7). Solenoid axes are tipped 4.9° above or below the orbital midplane depending on the direction of the current. The centers of the solenoids are displaced radially outward from the reference circle by 21 mm to minimize the integrated on-axis radial field, thus, vertical beam deviations. This technique allows to save 2% of the beam that would be lost if there was no offset. The fact that the solenoids are tipped leads to the reduction in the amount of space available for the RF system; hence, the energy gain per cell is limited to 7.1 MeV/c, which, in turn, limits the angle of the

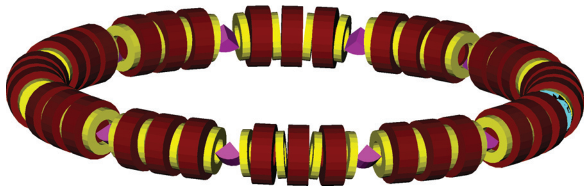

Figure 6: New cooling channel layout with magnetic coils in the irises of the RF cavities

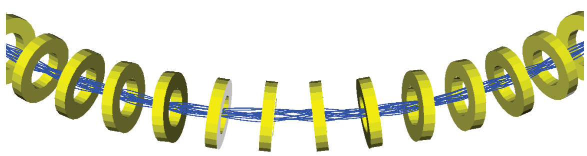

Figure 7: Solenoid axes are tipped 4.9° above or below the orbital midplane depending on the direction of the current.

wedge absorber to approximately 90°.

Figure 8 illustrates the difference between field components for the original RFOFO design and the new design with coils in irises. Since there are four coils per cell, all field profiles have more complicated shapes; however, the magnitudes are similar. The peak in the longitudinal field is still approximately 3 T, the radial component is more pronounced, but still small compared to both the vertical and the longitudinal components. The vertical component is everywhere positive providing an average bending field of 0.136 T.

Preliminary simulation results with magnetic fields only suggest that the transmission is 90% with no decay and no stochastic processes and 65.4% with decay and stochastic processes after 15 turns in the ring (461 m). These results are consistent with tracking results in the RFOFO ring or Guggenheim helix with RF and absorbers turned off. The effect of RF cavities and absorbers on the lattice with magnetic coils in the irises requires further study.

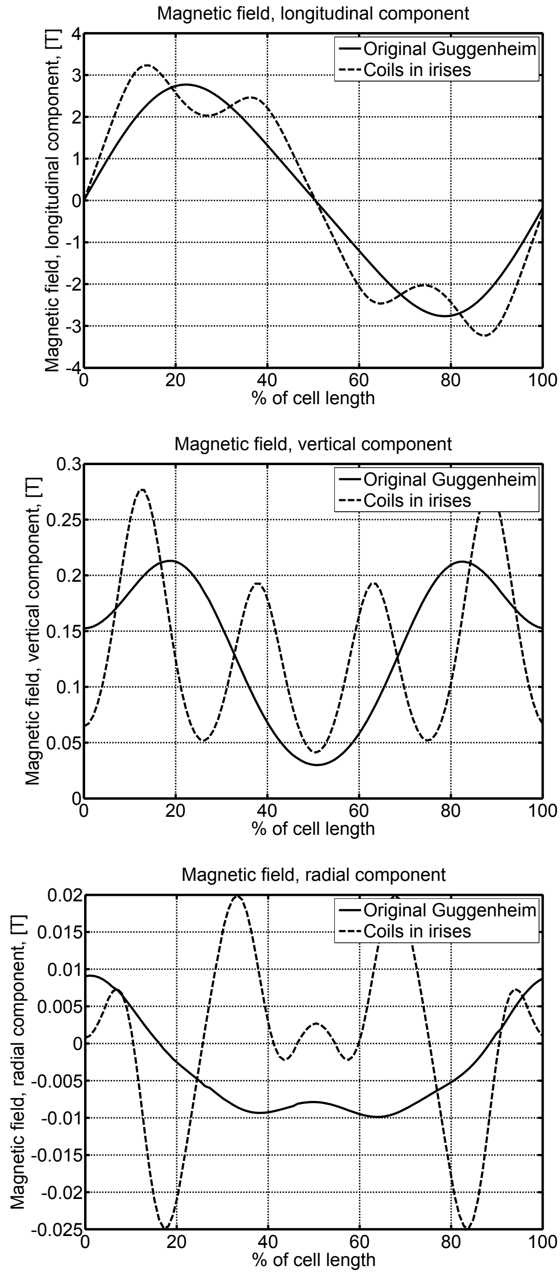

Figure 8: Magnetic field comparison between the RFOFO ring (or Guggenheim, fields are very similar) and the new layout, one cell shown.

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