MUON COOLING CHANNELS FOR A MUON COLLIDER

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Abstract

Ionization cooling channels for a muon collider are designed. In the status report[1], high field solenoids and high rf gradients, such as 15T and 31T alternating cooling channels with 36MV/m, were presented for the coolings of middle and final sections of the muon collider, respectively. We present the possibilities of cooling channels which use lower field solenoids and lower rf gradients than the alternating solenoid channles. For these purposes, a 6T Super-FOFO, a 6T Super-FOFO without the bucking coils and a 10T RFOFO cooling channels are designed. It is shown that the 6T Super-FOFO and 6T Super-FOFO without the bucking coils cooling channels can be considered as a replacement for the 15T alternating cooling channel. It is shown that the 10T RFOFO can be considered as a replacement for the 31T alternating cooling channels.

1 INTRODUCTION

The design of an efficient and practical cooling system is one of the major challenges for the muon collider complex. Indeed, realization of a cooling channel, even without a true muon beam, is one of the critical technology demonstrations. A more robust cooling scenario would add credibility to the collider concept. Results presented here do not yet achieve this goal, since they are restricted to transverse cooling. They do, however, indicate that transverse cooling may be easier to achieve than previously thought.

The status report contained two simulation examples of transverse cooling for a HIggs factory. One example is towards the end of of a full cooling sequence and uses 15T alternating solenoids. Another example, using 31T alternating solenoids, is for the final cooling in the Higgs factory. In the alternating solenoid lattices, the direction of the fields in the magnets alternates from one cell to the next. The rf is centered around the minimum magnetic field and the liquid hydrogen absorber is located at a high field region inside the solenoid.

We simulated these examples by using a 6T Super-FOFO, a 6T Super-FOFO without bucking coils and 10T RFOFO channels. In these cooling channels, minimum magnetic field is at a maximum in the midpoint of the liquid hydrogen. The required rf gradients are lower than in the alternating channels, but resulting in the comparable cooling performances with the alternating channels.

Figure 1 shows coil configurations of designed cooling channels which are considered in this report. We do not have any correlation between energy and transverse amplitude. All simulations were performed using ICOOL version 1.89.

2 SIMULATION RESULTS

2.1 6T Super-FOFO Cooling Channel

The mimimum values of the beta function and the B_z field occur at the midpoint of an absorber, here 8cm long. The 6T Super-FOFO channel has total absorber length of 15.5cm per 1m channel. For comparison, the 15T alternating channel has absorbers for 36cm and 32cm per 1m channel.

The uncorrelated Gaussian initial beam distribution is generated with transverse and longitudinal emittances of 1390 mm-mrad transverse and 0.988 mm, respectively. The initial momentum (Pz) of the beam was 190MeV/c.

The magnetic field that was used in the 6T Super-FOFO simulations is seen in Figure 2(a), where the magnetic field B_z is plotted for as a function of propagation length z for 5m, or, equivelently here, 5 cells. Figure 2(b) shows the beta function β_x for 5 cells. Figure 3 shows the decrease in transverse(x) normalized emittance as a function of distance along the channel. There is transverse cooling by a factor of 0.65 in the x phase space. Longitudinal normalized emittance showed the increase by a factor of 1.43 (not plotted here). The longitudinal emittance in this Super-FOFO channel has about a 60% lower increase than in the 15T alternating channel. The Super-FOFO channel provides 6D cooling by a factor of 0.63, compared to the better cooling factor of 0.4 in the 15T alternating channel. Of course the cost of a 6T Super-FOFO solenoid is perhaps 4 times less than a 15T solenoid of the same length, so the cooling section can be a bit longer (to achieve the same degree of cooling) and still be very much less expensive.

The rf gradients (20MV/m) used in the simulation is lower than the 15T alternating channel (36 MV/m). Used rf frequency is 805MHz. Table-1 gives the initial and final beam parameters in the 6T Super-FOFO channel. It shows that the rms beam size σ_x and the rms bunch length σ_z are increased by factor of 0.78 and 1.2, respecively.

Table 1: Beam parameters in 6T Super-FOFO Cooling Channel of 20m

Parameters	**Units**	**Initial**	**Final**
particles tracked		1000	989
transverse emit.(x)	mm-mrad	1388	907
longitudinal emit.(z)	mm	0.988	1.414
6D emittance($\times 10^{-12}$)	$(m - rad)^3$	2197	1383
rms bunch length(σ_z)	cm	1.56	1.89
rms beam size(σ_x)	cm	0.94	0.74

2.2 *6T Super-FOFO without Bucking Coils*

The coil placement is the same with the Super-FOFO without bucking coils. It produces a magnetic field B_z on axis, as plotted for 5 cells in Figure 4(a). Figure 4(b) shows the beta function β_x along the axis for 5 cells. Figure 5 shows the decrease in transverse(x) normalized emittance as a function of distance along the channel. The cooling is by a factor of 0.64 in the x transverse phase space. From the slope of the curve we note that the linear rate of cooling is maintained, and limits to the cooling performance need further investigation. Longitudinal normalized emittance showed the increase by a factor of 1.4 (not plotted here). The cooling channel shows 6D cooling by a factor of 0.65. This value is comparable to the case of the 6T Super-FOFO channel.

The rf parameters are the same parameters with the case of the 6T Super-FOFO. Table-2 shows the initial and final beam parameters in the 6T Super-FOFO channel without bucking coils of 20m. It shows that the rms beam size σ_x and the rms bunch length σ_z are increased by factor of 0.79 and 1.22, respectively.

Table 2: Beam parameters in 6T Super-FOFO Channel of 20m.

Parameters	**Units**	**Initial**	**Final**
particles tracked		1000	985
transverse emit.(x)	mm-mrad	1388	893
Longitudinal emit.(z)	mm	0.968	1.416
6D emittance($\times 10^{-12}$)	$(m - rad)^3$	2162	1405
rms bunch length(σ_z)	cm	1.55	1.90
rms beam size(σ_x)	cm	1.0	0.79

2.3 *10T RFOFO Cooling Channel*

A 10T RFOFO channel is designed for the final section cooling. The uncorrelated Gaussian initial beam distribution is generated with 550 mm-mrad transvese and 0.71 mm longitudinal emittances. The initial beam momentum (Pz) is 120MeV/c.

Figure 6(a) plots the magnetic field B_z along the axis for 5 cooling cells and Figure 6(b) shows the beta function β_x along the axis for 5 cells. Figure 7 shows the decrease in transverse(x) normalized emittance as a function of distance along the channel. The system provides cooling by a factor of 0.6 in the x transverse phase space. Longitudinal normalized emittance showed the increase by a factor of 1.4 (not plotted here). The 6-D normalized emittance the decrease by a factor of 0.61. This value is comparable to the cases of the 31T alternating channel.

The rf gradients of 26MV/m used in the simulation is lower than 31T alternating solenoid channels with 36MV/m. Used rf frequency is 605 MHz. Table-3 reports the initial and final beam parameters. It shows that the rms beam size σ_x and the rms bunch length σ_z are increased by factor of 0.79 and 1.78, respecively.

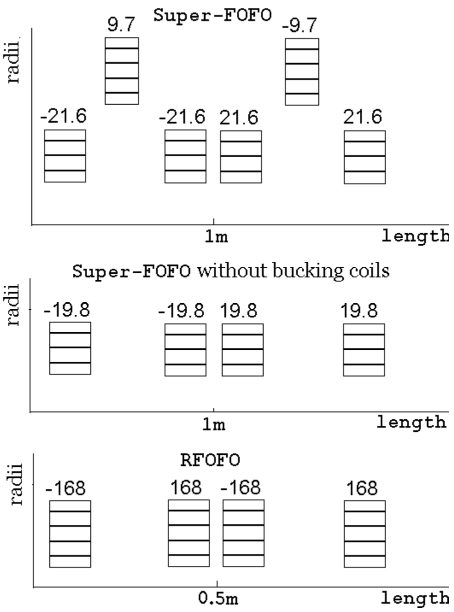

Figure 1: Coil configurations of cooling channels. Numbers correponds to current density(A/mm^2)(Here, factor of has to be multiplied in numbers of current density in cases of Super-FOFO and Super-FOFO without bucking coils), each solenoid is modelled with current sheets. In Super-FOFO channel large solenoid is 33.6cm long, with 2.42$\times 10^6 A/m$ for each current sheet. Small solenoid is 18.9cm long, with 4.6$\times 10^5 A/m$ for each current sheet. In Super-FOFO without bucking coils solenoid is 33.6cm long, with 2.22$\times 10^6 A/m$ for each current sheet. In RFOFO channel solenoid is 12.6cm long, with 5.3$\times 10^6 A/m$ for each current sheet.

3 SUMMARY

ICOOL simulations of a 6T Super-FOFO, a 6T Super-FOFO without bucking coils and a 10T RFOFO cooling channel are performed for the middle section and final section coolings of the muon collider. The optimization of parameters for those cooling channels show that lower focusing magnetic fields and lower rf gradients can be used, as compared to the alternating solenoid options in the status report.

The 6T Super-FOFO channel without bucking coils shows comparable performance with the 6T Super-FOFO channel. The 6T examples show about 1% particle losses, 40% longitudinal emittance growths and 20% rms bunch lengthening. The 6T examples do not achieve the same cooling rate, as the 15T solenoid case, but it requires less rf and should be easier to build.

The 10T RFOFO, with a lower muon energy than in the 31T alternating solenoid example, achieves comparable performance with the 31T alternating channel. RFOFO

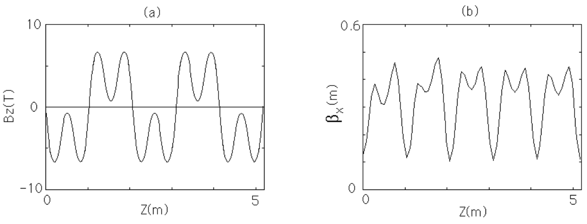

Figure 2: (a) Magnetic field (Bz) $vs.$ Z(m); (b) beta function β_x $vs.$ Z(m) in a 6T Super-FOFO channel which has a 103cm long cell

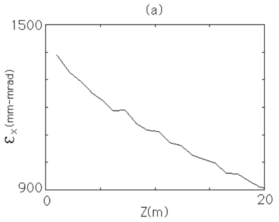

Figure 3: x-dimensional emittance $vs.$ Z(m) in 6T Super-FOFO channel

channel shows about 6% particle losses and 90% longitudinal emittance growth. Simulation studies show that a 6T Super-FOFO and a 6T Super-FOFO without bucking coils can be considered as an replacement for the 15T alternating solenoid cooling reported in the status report, while the 10T RFOFO can be considered as replacement for the 31T alternating solenoid final cooling section.

Table 3: Beam parameters in 10T RFOFO Channel of 20m

Parameters	Units	Initial	Final
particles tracked		1000	938
transverse emit.(x)	mm-mrad	550	327
longitudinal emit.(z)	mm	0.71	1.38
6D emittance($\times 10^{-12}$)	$(m - rad)^3$	280	170
rms bunch length(σ_z)	cm	1.61	2.87
rms beam size(σ_x)	cm	4.3	3.4

REFERENCES

[1] Eun-San Kim, ICOOL simulation of muon ionization cooling, Mucool notes 44, 1999.

[2] Status of Muon Collider Reserach and Development and Future Plans, C.M. Ankenbrandt, et al., Phys. Rev. Special Topics: Accelerators and Beams, Vol 2,081001 (1999).

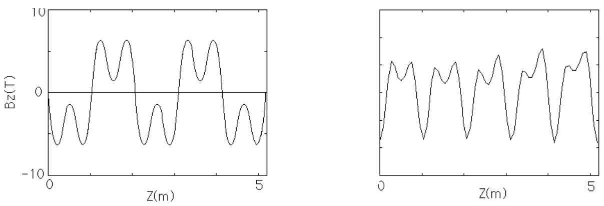

Figure 4: (a) Magnetic field (Bz) $vs.$ Z(m); (b) beta function β_x $vs.$ Z(m) in 6T Super-FOFO channel without bucking coils which has a 103cm long cell

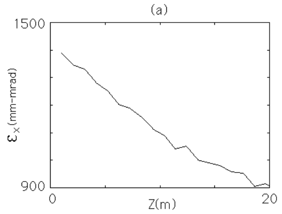

Figure 5: x-dimensional emittance $vs.$ Z(m) in 6T Super-FOFO channel without bucking-coil

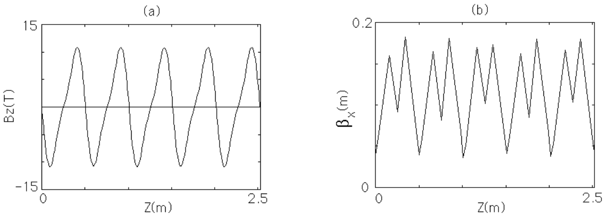

Figure 6: (a) Magnetic field (Bz) $vs.$ Z(m); (b) beta function β_x $vs.$ Z(m) in 10T RFOFO cooling channel which has a 50.456cm long cell.

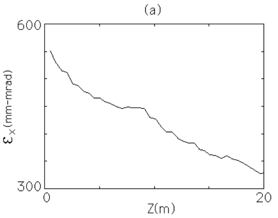

Figure 7: x-dimensional emittance $vs.$ Z(m) in 10T RFOFO channel