MAGNETS FOR INTERACTION REGIONS OF A 1.5×1.5 TeV MUON COLLIDER*

V.V. Kashikhin#, Y.I. Alexahin, N.V. Mokhov, A.V. Zlobin, Fermilab, Batavia, IL 60510, USA

Abstract

The updated IR optics and conceptual designs of large aperture superconducting quadrupole and dipole magnets for a 1.5×1.5 TeV muon collider and an average luminosity of 4×10^{34} cm^{-2}s^{-1} are presented. All magnets are based on the Nb_3Sn superconductor and provide the required operating fields and gradients in the given apertures with adequate margins. Special dipole coils were added to some quadrupole designs to provide small bending field and thus facilitate chromaticity correction and dilute background fluxes on the detector. Magnet parameters are reported and compared with the requirements.

INTRODUCTION

The final stage of a Muon Collider (MC) includes a compact Storage Ring (SR) with special Interaction Regions (IR) to collide two circulating muon beams. Operating conditions for a Muon Collider pose significant challenges to superconducting (SC) magnets used in the interaction regions. IR magnets have to provide high operating gradient and magnetic field in a large aperture to accommodate the large size of muon beams due to low β^* as well as the cooling system to intercept the large heat deposition from the showers induced by decay electrons.

The IR design for a 0.75×0.75 TeV MC with an average luminosity of 10^{34} cm^{-2}s^{-1} has been developed and thoroughly studied [1,2]. The next design iteration for a 1.5×1.5 TeV MC (3 TeV c.o.m.) with an average luminosity of 4×10^{34} cm^{-2}s^{-1} is being analysed [3] including the IR optics and layout. The new IR layout motivated to update the designs and parameters of large aperture SC quadrupole and dipole magnets. All the magnets require the Nb_3Sn superconductor to achieve the necessary operating parameters with the critical current margins required for a reliable machine operation.

Previous analysis [1,2] had shown that a horizontal shift of IR quadrupoles by ~1/10 of the aperture provides the dipole field component of ~2 T at the beam center and thus facilitates the chromaticity correction and dilutes background fluxes on the detector. The more round beams in the 3 TeV MC design does not allow for a significant shift of IR quadrupoles. Since the benefit of such a shift for detector backgrounds has not been demonstrated yet, it is not included in the present design.

There is, however, another factor which is important for a TeV-scale MC: the neutrino radiation [4]. In the nearest to the IP quadrupoles, the natural beam divergence is sufficient to spread it, but in more distant quadrupoles the additional bending field is necessary.

* Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy
# vadim@fnal.gov

Such bending field can be generated by special dipole coils. This paper reports the updated IR magnet designs and parameters, and compares them with the new optics requirements.

Table 1: MC Storage Ring Parameters

Parameter	Unit	Value
Beam energy	TeV	1.5
Circumference	km	4.5
Momentum acceptance	%	±0.5
Transverse emittance, ε_N	π·mm·mrad	25
Number of IPs		2
β^*	cm	0.5

IR LAYOUT AND MAGNET TARGET PARAMETERS

The parameters of Muon Collider with a c.o.m. energy of 3 TeV and an average luminosity of $4\cdot10^{34}$ cm^{-2}s^{-1} are summarized in Table 1 [3]. The IR layout consistent with these parameters and vertical/horizontal beam size variations in the IR magnets are shown in Fig. 1.

The final focus of muon beams in the new IRs is provided by the quadrupole triplets formed by nine quadrupole magnets Q1-Q9. The number of different apertures increased to 6 with respect to [1] to follow the beam sizes more closely. The IR quadrupoles are divided into short (~2-2.6 m) magnets to provide the necessary space for the tungsten masks in between.

The bending dipole B1, placed immediately after the final-focus triplet, generates a large dispersion function at the location of the sextupole nearest to the IP to compensate for the vertical chromaticity. It is composed of ~6 m long coils with tungsten masks in between.

The IR magnet design parameters are summarized in Table 2. The aperture of the magnets is determined by the following criterion: $D_{x/y}=10\sigma_{max}+30$ mm.

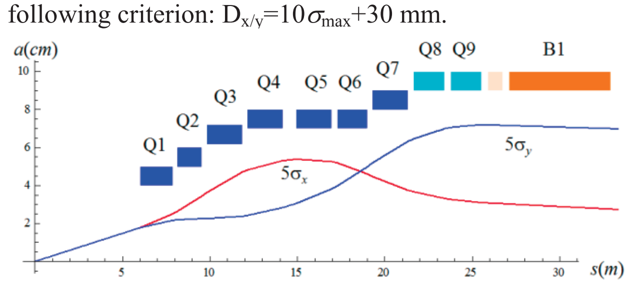

Figure 1: MC IR layout and beam size in magnets.

Table 2: IR Magnet Parameters

Parameter	Q1	Q2	Q3	Q4-6	Q7	Q8-9	B1
Apert. (mm)	80	100	124	140	160	180	180
G_{op} (T/m)	250	200	161	144	125	90	0
B_{op} (T)	0	0	0	0	0	2	8
Length (m)	1.85	1.40	2.00	1.70	2.00	1.75	5.80

Copyright © 2012 by IEEE – cc Creative Commons Attribution 3.0 (CC BY 3.0) — cc Creative Commons Attribution 3.0 (CC BY 3.0)

MAGNET DESIGNS AND PARAMETERS

The level of magnetic fields in the MC IR magnets calls for the Nb_3Sn superconductor, which has the most appropriate combination of the critical current density J_c, critical temperature T_c, and critical magnetic field Bc_2. Multifilament Nb_3Sn strands are commercially produced at the present time in sufficiently long pieces.

The magnet coils are based on the multistrand Rutherford cables. The Nb_3Sn strand and cable parameters used in this study are summarized in Table 3. Both cables are made of the same strand. Larger Cable I is used for the main quadrupole coils Q1-Q9. Smaller Cable II is used for the auxiliary dipole coils in Q8-Q9 and possibly in the other quadrupoles.

The coil cross-sections of all IR magnets described below were optimized by ROXIE code [5] to achieve a good field quality in the area occupied with the beams.

Table 3: Cable Parameters

Parameter	Cable I	Cable II
Number of strands	40	6
Strand diameter (mm)	1.0	1.0
Cu/nonCu ratio	1.0	1.0
SSL J_c(12T, 4.2K) (A/mm^2)	3000	3000
Cable mid-thickness (mm)	1.81	1.76
Cable keystone angle (deg)	0.9-1.0	0.9
Cable width (mm)	20.59	3.03
Cable insulation (mm)	0.20	0.20

Geometrical field harmonics for the IR quadrupoles Q1-Q9 are presented in Table 5. The accelerator field quality is achieved within 2/3 of the corresponding coil aperture (shaded areas in Fig. 2).

The quadrupole coils operate at a high level of Lorentz forces. Stress management in the azimuthal direction can be done by splitting the coils into several blocks separated by supporting elements that will reduce the coil efficiency and consume a part of operating margin.

Table 4: IR Quadrupole Parameters at 4.5 K

Parameter	Q1	Q2	Q3	Q4-6	Q7	Q8-9
Aperture (mm)	80	100	125	140	160	180
B_{max} coil (T)	14.1	14.3	14.5	14.7	14.8	15.2
G_{max} bore (T/m)	308	249	202	182	161	127
G_{op} bore (T/m)	250	200	161	144	125	90
G_{op} / G_{max} bore	0.81	0.80	0.80	0.79	0.78	0.71
L (mH/m)	2.4	3.3	5.0	6.1	7.7	9.1
E at G_{op} (MJ/m)	0.7	0.8	1.1	1.2	1.4	1.1
F_x at G_{op} (MN/m)[#]	2.1	2.2	2.5	2.7	2.8	3.3
F_y at G_{op} (MN/m)[#]	-2.7	-2.8	-3.1	-3.2	-3.4	-2.4

[#] totals per 1[st] octant.

Table 5: Geometrical Harmonics at R_{ref} (10^{-4})

Parameter	Q1	Q2	Q3	Q4-6	Q7	Q8-9
R_{ref} (mm)	27	33	42	47	53	60
b_6	0.06	-0.02	0.03	-0.02	0.01	0.00
b_{10}	-0.54	0.02	0.03	-0.00	0.01	0.01
b_{14}	1.16	0.54	0.70	1.02	0.73	0.64

Large-aperture IR Quadrupoles

According to Table 2, the IR needs quadrupoles with six different apertures and nominal gradients. The cross-sections of these IR quadrupoles are shown in Fig. 2, and the magnet design parameters are summarized in Table 4.

The IR quadrupoles are based on a 2-layer shell-type coil and a cold iron yoke separated from the coils by a 10 mm spacer. All the designs use the same Cable I with the parameters shown in Table 3. As can be seen, all the magnets operate at less than 81% of the short sample limit (SSL) at 4.5 K. If necessary, an extra ~10 % margin can be gained by operating the IR quadrupoles at 1.9 K. The quadrupole apertures shown in Table 4 provide adequate space for the beam pipe, annular helium channel and the elliptical inner absorber (liner).

The 80-mm Q1 and 160-mm Q7 in Table 2 have parameters similar to Q1 and Q3-Q5 used in IR doublets of the 0.75×0.75 TeV MC [1]. As per Table 4, using the larger cable allows increasing the operating margin of the 80-mm and 160-mm quadrupoles at 4.5 K by 10-15 %.

IR Dipole

The dipole aperture is determined by the vertical beam size with an additional space for the cold beam pipe and helium channel and increases in 3 TeV MC from 160 mm to 180 mm. The horizontal beam size is only ~60 mm. It allows fitting 4-5 mm thick slightly asymmetric beam absorber in the aperture, like in MC arc magnets [6].

The cross-section of IR dipole based on a 2-layer shell-type coil is shown in Fig. 2 and the parameters are summarized in Table 6.

As mentioned earlier, it is not planned to add dipole coils to Q1-Q7 so far. If further studies of detector backgrounds show benefit of bending dipole field in Q1-Q7, it can be added following a similar design approach.

In Q8-Q9 such field is necessary to spread the neutrino radiation flux; it is created by the special dipole coils. The cross-section of 2 T dipole coil is shown nested around the main quadrupole coils Q8-Q9 in Fig. 2. The dipole coil consists of a single-layer winding made of the Cable II described in Table 3.

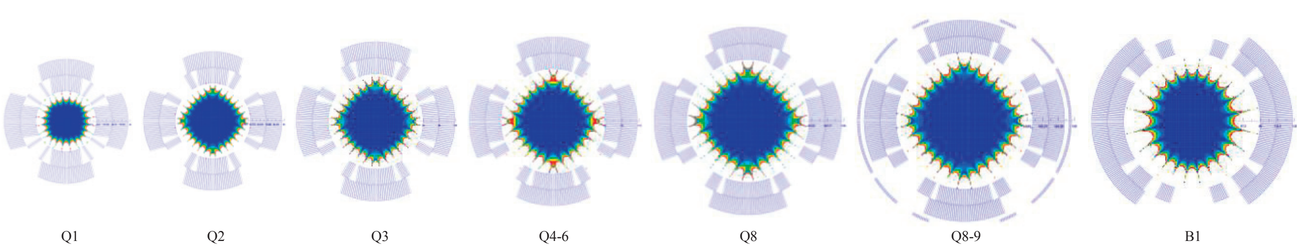

Figure 2: Coil cross-sections.

ISBN 978-3-95450-115-1

Copyright © 2012 by IEEE – cc Creative Commons Attribution 3.0 (CC BY 3.0) — cc Creative Commons Attribution 3.0 (CC BY 3.0)

Table 6: IR Dipole Parameters at 4.5 K

Parameter	Q8-9 dipole	B1
Aperture (mm)	276	180
B_{max} coil (T)	12.00	15.80
B_{max} bore (T)	2.69	14.27
B_{op} bore (T)	2.0	8.0
B_{op} / B_{max} bore	0.74	0.56
Inductance at B_{op} (mH/m)	11.60	25.07
Stored energy at B_{op} (MJ/m)	0.14	8.71
F_x at B_{op} (MN/m)[#]	0.7	2.6
F_y at B_{op} (MN/m)[#]	-1.1	-1.2

[#] totals per 1st quadrant.

The coil cross-section was optimized to operate at large margin (less than 75% of SSL) to avoid coil quenching and simplify their protection and have a good dipole field quality. The parameters of the 2 T dipole coil are shown in Table 6. The maximum fields for the dipole and quadrupole coils include the combined field of both coils at 100 % of the SSL.

The IR dipole design based on the cable parameters listed in Table 3 provides the maximum field in the aperture of 14.3 T at 4.5 K, which corresponds to ~56 % of the SSL. The maximum field in the coil is as high as 15.8 T. As in the case with the IR quadrupoles, using larger than the previously considered cable [1] allows increasing the maximum field by 1.8 T. Some fraction of the large operating margin in the B1 dipole magnets can be used to increase the space between magnets occupied by the tungsten masks.

Similar to the quadrupole magnets, the stress level in the B1 dipole is high. It would require the stress management in the azimuthal direction as well.

Geometrical field harmonics for the B1 dipole and 2 T nested dipole in the Q8-9 are presented in Table 7. The accelerator field quality is provided within 2/3 of coil aperture (shaded area in Fig. 2) which is consistent with the expected beam size in B1 dipoles.

Table 7: Geometrical Harmonics at R_{ref}=60 mm (10^{-4})

Harmonic #	Q8-9 dipole	B1
b_3	0.02	0.08
b_5	0.05	-0.01
b_7	0.17	-0.42
b_9	0.01	-1.02

CONCLUSION

Coil cross-sections for the IR magnets of a 1.5×1.5 TeV MC with an average luminosity of 4×10^{34} $cm^{-2}s^{-1}$ have been considered. The coils are based on the Nb_3Sn Rutherford type cable and designed to operate at 4.5 K, while provide the necessary gradients and fields in the given apertures with adequate margins. The coil cross-sections were optimized to achieve a good field quality in the area occupied with the beams. Special dipole coil was added to the quadrupole designs to provide ~2 T bending field and thus facilitate chromaticity correction and dilute background fluxes on the detector.

All the magnets have large horizontal and vertical Lorentz force components. The coils need adequate mechanical support to minimize the turn motion and limit stresses in the cables. Practical solutions to this problem, the study and optimization of magnet operating margins and other parameters will be done during the short model R&D phase.

The energy deposition and radiation calculations along with detector background studies and machine-detector interface optimization are underway for these new IR regions with the proposed magnet parameters.

REFERENCES

[1] Y.I. Alexahin et al., "Muon Collider Interaction Region Design," Physical Review Special Topics - Accelerators And Beams 14, 061001 (2011).

[2] N.V. Mokhov et al., "Muon Collider Interaction Region and Machine-Detector Interface Design," Fermilab-Conf-11-094-APC-TD (2011), MOODN6 paper at PAC2011.

[3] Y. Alexahin, E. Gianfelice-Wendt, "A 3 TeV Muon Collider Lattice Design," TUPPC041, these proceedings.

[4] N.V. Mokhov, A.V. Van Ginneken, in Proc. ICRS-9, Tsukuba, 1999, J. Nucl. Sci. Techn., pp. 172-179 (2000).

[5] S. Russenschuck, "ROXIE - A Computer Code for the Integrated design of Accelerator Magnets," EPAC98, Stockholm, June 1998.

[6] V.V. Kashikhin et al., "High-Field Combined-Function Magnets for a 1.5×1.5 TeV Muon Collider Storage Ring," THPPD036, these proceedings.

Copyright © 2012 by IEEE – cc Creative Commons Attribution 3.0 (CC BY 3.0) — cc Creative Commons Attribution 3.0 (CC BY 3.0)