A NEW LATTICE DESIGN FOR A 1.5 TeV CoM MUON COLLIDER CONSISTENT WITH THE TEVATRON TUNNEL

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Abstract

A recent effort is underway to design an efficient match of a Muon Collider to the Fermilab site, potentially using the Tevatron tunnel after decommissioning. This work represents a new design for such a collider with emphasis on shortened IR and systematic high-order correction and dynamics studies. With a 1 cm β^*, simultaneous control of geometric and chromatic aberrations is critical and can only be achieved through the deliberate addition of nonlinear fields in the Interaction Region itself. This work studies both the correction schemes and the unavoidable impact of high-order correctors – sextupoles, octupoles and even duodecapoles – located in the Interaction Region close to the low-beta quadrupoles or focusing elements. This study proposes and systematically addresses the aberrations for different systems of nonlinear correctors and optimizes performance of an advanced IR.

INTRODUCTION

Muon accelerators form a distinctive class of accelerating structures different from both proton and electron accelerators. The advantage that muons have over protons is that they are truly elementary in the sense of the Standard Model. Thus, when muons collide, they do not divide up the energy load. Muon–antimuon collisions are clean and the effective, collision energy is about 10 times higher than that of the proton beams with the same energy. Muons also have an advantage over electrons. Since muons are more massive than electrons, they produce less synchrotron radiation, when in a circular path. There are also drawbacks in using muons: they are unstable and decay rather quickly ($\tau = 2.2\ \mu\mathrm{sec}$). This imposes a restriction on the length of the structure and the intensity of the acceleration.

The idea of the study presented in this article is to design a lattice for the storage ring that fits or matches approximately the footprint of the Tevatron Main Ring tunnel. Taking into account the current status of the Tevatron project, the Muon Collider might be a logical next step in utilizing the existing tunnel with its infrastructure, thus saving a large amount of expenses connected to building a new accelerator complex for muons.

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750×750 GeV LATTICE

Currently a 50% dipole packing fraction is used for the 750×750 GeV lattice, which results in an arclength of 5.85 km (6.283−0.432 km of straights) in the dipole field of 5.3 T. At 750 GeV this field strength is reasonable, and in fact, the ultimate energy might be increased to 1×1 TeV.

The 50×50 GeV lattice [1] is used as a baseline, and its components are scaled to handle the muons the the energy of 750 GeV. The layouts of both 50×50 GeV and 750×750 GeV lattices are shown in Fig. 1. The 50×50 GeV lattice is a highly optimized one which, in turn, is based on the 2×2 TeV lattice [2], and therefore there is a strong reason to assume the 750×750 GeV design shares most of the advantages with these other lattices.

The 50×50 GeV ring has a roughly racetrack design with two circular arcs separated by an experimental insertion on one side, and a utility insertion for injection, extraction, and beam scraping on the other. The experimental insertion includes the interaction region (IR) followed by a local chromatic correction section and a matching section. The chromatic correction section is optimized to correct the ring's linear chromaticity, which is almost completely generated by the low beta quadrupoles in the IR.

The 750×750 GeV lattice design uses the same building blocks as the 50×50 GeV version, as it can be seen from Fig. 1: the final focusing section (FF), the chromaticity correction section (CCS), the matching module (MM), and the arc (ARC). The difference in the layouts is dictated by the fact that the 750×750 GeV lattice must match the Tevatron footprint. So the final focus sections are placed in two of the six straight sections of the Tevatron ring, while the chromaticity correction section and the matching section occupy parts of the Tevatron arc. The arcs of the original design are repeated in the arcs of the Tevatron as many times as necessary.

There are two IRs in the proposed lattice design to compensate for the luminosity loss due to the increased β^* as described in Section .

The main parameters of the 750×750 GeV lattice are summarized in Table 1 (second column). Similar parameters for the other lattices — 2×2 TeV (first column) and 50×50 GeV (third column) — are shown for comparison.

FINAL FOCUS SECTION

The low beta function values at the IP are mainly produced by three strong superconducting quadrupoles in the

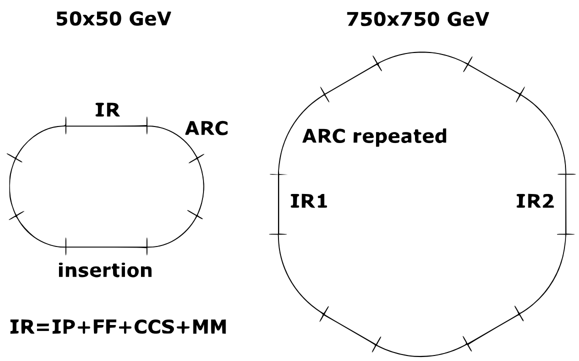

Figure 1: The baseline 50×50 GeV lattice scheme compared to the 750×750 GeV lattice scheme.

Table 1: Parameter comparison for various storage rings lattices

	4/1.5 TeV	1.5 TeV (this design)	100 GeV
β^* [mm]	3	10	40
l^* (IP to quad) [m]	4	5.5	4.5
peak β [km]	145	35	1.4
IR quad aperture [cm]	10	10	10
Poletip field [T]	12	9	8
$\epsilon_N(95\%)$ [mm mrad]	$841\pi/315\pi$	1306π	2176π
$\Delta p/p(95\%)[\%]$	.01-.08	$\geq$ .018-.144	$\geq$ .036-.288
$\xi_x(IR+CCS)$	-1500	-456	-53
$\xi_y(IR+CCS)$	-2000	-645	-73
α_{IR}	$3.6\cdot10^{-4}$	$1.0\cdot10^{-3}$	$3.0\cdot10^{-2}$
IR length [m]	1300	506	137
α_{arc}	$-2.1\cdot10^{-3}$	$-9.3\cdot10^{-3}$	$-9.5\cdot10^{-2}$
Arc length [m]	187	70	31

Final Focus Telescope with pole-tip fields of 9 T. The first quadrupole is located 5.5 m away from the interaction point and the beta functions reach a maximum value of 35 km in the final focus telescope. Because of the significant, large-angle backgrounds from the muon decay, a background sweep dipole is included in the final focus telescope and placed near the IP to protect the detector and the low-β quadrupoles [3]. Open midplane type magnets are used for background sweeping purposes. As the decay products are mainly distributed along the midplane, leaving the midplane open provides for an oportunity to protect the magnets and detectors from muon-decay electrons and γ rays. The bend starts at 35 meters, so the FF section fits the Tevatron straight section footprint. The layout of the preliminary Final Focus section design is shown in Fig. 2.

CHROMATIC CORRECTION SECTION

A local chromatic correction of the Muon Collider interaction region is required to achieve broad momentum acceptance. The Chromaticity Correction Section (CCS) contains two pairs of sextupoles, one pair for each transverse plane, all placed at the locations with high dispersion. The sextupoles of each pair are located at positions of equal, high beta values in the plane (horizontal or vertical) whose chromaticity is to be corrected, and very low beta waist in the other plane. Moreover, the two sextupoles of each pair are separated by a betatron phase advance of near π, and each sextupole has a phase separation of $(2n+1)\frac{\pi}{2}$ from the IP, where n is an integer. The result of this arrangement is that the geometric aberrations of each sextupole is cancelled by its companion while the chromaticity corrections add. The sextupoles of each pair are centered about a minimum in the opposite plane ($\beta_{min} < 1$), which provides a chromatic correction with a minimal cross correlation between the planes. A further advantage to locating the opposite planes minimum at the center of the sextupole, is that this point is $\frac{\pi}{2}$ away from, or "out of phase" with, the source of chromatic effects in the final focus quadrupoles; that is, the plane not being chromatically corrected is treated like the IP in terms of the phase to eliminate a second order chromatic aberration generated by an "opposite-plane" sextupole. The repetitive symmetry and the fact that the transfer map of the section is unity implies that the important aberration $(x|\delta\delta)$ vanishes as well. Such chromaticity correction module was implemented first in the 2×2 TeV Muon Collider storage ring [2].

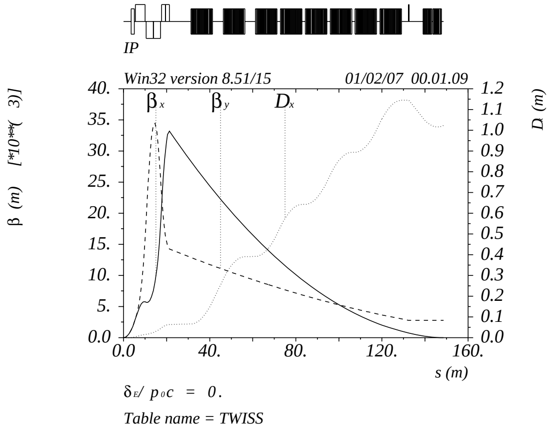

Figure 2: The final focus section beta functions and dispersion plots

ARC MODULE

The Flexible Momentum Compaction module provides negative momentum compaction values compensating for the positive momentum compaction generated by the Chromaticity Correction Section. Small beta functions are achieved through the use of a doublet focusing structure which produces a low beta simultaneously in both planes. At the dual minimum, a strong focusing quadrupole is placed to control the derivative of the dispersion with little impact on the beta functions. (The center defocusing quadrupole is used only to clip the point of the highest dispersion.) Ultimately a dispersion derivative can be generated which is negative enough to drive the dispersion negative through the doublet and the intervening waist.

ADVANTAGES AND DISADVANTAGES OF THE NEW DESIGN

The proposed design has a lot of advantages. As the lattice is isochronous, a bunch length change is prevented, which is very important for controlling the hour-glass effect. β^* is chosen to be 1 cm, which has the advantage of lower chromaticities and longer bunch lengths (due to the hour-glass effect), and also the apertures can be chosen smaller than the 3 mm lattice ones. Smaller chromaticities lead to weaker chromatic aberrations and larger momentum acceptance. All these facts contribute to a larger dynamic aperture.

As for the disadvantages, the choice of larger β^* leads to an undesirable decrease in luminosity. According to the formulas from [4, 5]:

$$L \propto \frac{1}{\beta^*},$$

where L is the luminosity. For $\beta^* = 3$ mm the hour-glass reduction factor is $\eta_A = 0.76$, while the disruption enhancement is $f_D = 1.5$. Overall, $H_D = \eta_A f_D = 1.14$. For $\beta^*_{new} = 1$ cm one has $\eta_A \to 1, f_D \to 1$, and hence

$$\left(\frac{L_{old}}{L_{new}}\right)_{eff} = 1.14\frac{\beta^*_{new}}{\beta^*_{old}} = 3.8.$$

Therefore, the luminosity for $\beta^* = 1$ cm is 3.8 times smaller than for $\beta^* = 3$ mm. However, the loss of luminosity can be compensated by the increased momentum aperture and by using the 2 IRs in the ring (see the scheme in Fig. 1).

One other problem arises due to the fact that one is trying to match the lattice to the existing geometry, which puts more constraints on the building blocks of the lattice.

The last and the most important for now is the one of shielding the IP and securing the temperature of the superconducting magnets from the undesired effect of electrons and γ rays produced by the muon decay. However, this problem is beyond the scope of this dissertation work and will be considered separately.

FUTURE PROSPECTIVES

The dynamic aperture studies similar to that in [6] are currently underway for the lattice design presented in this article. In general, the approaches to the dynamic aperture optimization described in [6] should stay perfectly valid and effieint for the 750×750 GeV storage ring.

Dynamic aperture represents the volume in phase space in which stable motion occurs. The dynamic aperture is one of the key parameters characterizing the performance of a circular machine. The DA can be larger than the beam physical aperture, and in general it is desired that the DA is as large as possible.

The main problem with the task of improving the dynamic aperture of the accelerator channel is a large number of nonlinearities to control, while the number of correctors is limited, and in general one wants to keep this number as small as possible. One very effective approach for achieving the goal is to use the dynamic aperture itself as a figure of merit and try to maximize it using optimization methods. In other words, the objective function to maximize for the study would be the sum of the maximum deviations of the particle, which stays stable for the required number of turns, in the sense that its coordinates are within the beam pipe for that number of turns. Other approaches, such as the minimization of the most important aberrations of higher orders or the minimization of the resonance strengths, show less pronounced results for the 50×50 GeV lattice, but the situation can be different for the 750×750 case. The normal form transformation [7] plays an important role in two of the three approaches' implementations, namely, the resonance strength minimization and the dynamic aperture maximization. This transformation allows for the calculation of the values of the objective functions and for representing the results of different approaches in a uniform way (in one common coordinate system).

REFERENCES

[1] C. Johnstone, W. Wan, and A. Garren. Lattice design for a 50-on-50 GeV Muon Collider. In *Proceedings of the 1999 Particle Accelerator Conference*, pages 3065–3067, New York, 1999.

[2] C. Johnstone and A. Garren. An IR and chromatic correction design for a 2 TeV Muon Collider. In *Proceedings of the Workshop on New Directions for High-Energy Physics*, page 222, 1996.

[3] C. J. Johnstone and N. V. Mokhov. Optimization of a Muon Collider interaction region with respect to detector backgrounds and the heat load to the cryogenic systems. Technical Report Fermilab-Conf-96/366, Fermilab, 1996.

[4] P. Chen. Disruption, beamstrahlung, and beamstrahlung pair creation. Technical Report SLAC-PUB-4822, SLAC, 1988. Contributed to the DPF Summer Study High Energy Physics in the 1990's, Snowmass, Colorado, June 27-July 15, 1988.

[5] P. Chen and K. Yokoya. Disruption effects from the interaction of round e+e- beams. *Phys Rev. D 38*, 38(3):987–1000, 1988.

[6] P. Snopok, D.A. Ovsyannrkov, A.D. Ovsyannikov, C. Johnstone, and M. Berz. Muon Collider interaction region simulation and optimization. In A. L. Fradkov and A. N. Churilov, editors, *Proc. of 2005 ICPC*, pages 278–281, August 2005.

[7] M. Berz. *Modern Map Methods in Particle Beam Physics*. Academic Press, San Diego, 1999.