A Lattice for the Muon Collider Demonstration Ring in the RHIC Tunnel *

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Abstract

The future $\mu^+\mu^-$ *Muon Collider* should have a luminosity of the order of 10^{35} cm^{-2}s^{-1}, an the energy of 2×2 TeV. We present here a demonstration machine at a lower energy to test the feasibility of all components involved, which could be placed inside the existing Relativistic Heavy Ion Collider (RHIC) tunnel. The maximum energy of the muons in the RHIC tunnel depends on the maximum attainable field in the dipoles. The maximum energy in the existing RHIC rings for protons is 250 GeV, where the strength of the magnetic field in the dipoles is 3.5 T. A design of the storage ring lattice for a 50 GeV muon demonstration machine is also presented.

1 INTRODUCTION

The *Muon Collider* advantage with respect to an electron collider at high energies is that it could be a circular machine, because of negligible synchrotron radiation (for energies less than 10 TeV). This makes the number of collisions per bunch much larger than 1 in linear electron colliders, and together with a larger mass makes,in principle, a luminosity advantage of a factor of 10^5 for the same size machine. Other components of the muon collider, its feasibility and physics opportunities are presented in reports [1],[2], [3], [4], [5], [6] etc. The muon collider storage ring will have 2 TeV energy μ^+ and μ^- bunches and will provide luminosity of $10^{35} cm^{-2} s^{-1}$. For this luminosity the rms bunch length has to be 3 mm, which defines the β^*=3 mm at IP. *Short* bunches require the collider to be isochronous [7]. In this report lattices for demonstration of the muon collider rings, with muon energies of 250 GeV and 50 GeV, are presented. Parameters for the *demo* machine (Section 1), like transverse and longitudinal emittances, distances of the first quadrupoles to the crossing point, etc. are defined first. Next, possible choices for values of the magnet apertures, lengths, and strength will be presented. The momentum spread of the μ^+ and μ^- beams sets up a limit for the dispersion function excursions. An existing ring and elements of the Relativistic Heavy Ion Collider (RHIC) were used to create a first example (Section 3) of an isochronous storage ring. The RHIC collision parameters and magnet elements were used for the new lattice. Next, a *demo* muon collider storage ring lattice, with 0.5 TeV center of mass energy, is set inside the RHIC tunnel (Section 4). Finally another *demo* machine with a 0.1 Tev center of mass energy is presented (Section 5).

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2 STORAGE RING PARAMETERS

Muons, μ^+ and μ^-, will be created from the decay of pions π^+ and π^+, made from higher energy protons on a high Z target. Muons, μ^+ and μ^-, will reach the collider storage ring after they have been accelerated and cooled in both longitudinal and transverse phase space.

Table 1

E (TeV)	Δp/p (%)	$\varepsilon(\pi\mathrm{m})$	β^* (mm)	*LD* (m)
4.0	0.12	50 10^{-6}	3	6.50
0.4	0.12	85 10^{-6}	10	4.00
0.2	0.12	108 10^{-6}	13	2.80
0.1	0.12	136 10^{-6}	16	2.00

A design of a *demonstration* muon collider storage ring would be at much lower muon energy than the proposed 4 TeV (center of mass energy) machine. The muon six-dimensional emittance, defined as:

$$\varepsilon_{6D} = \varepsilon_x^{Norm} \varepsilon_y^{Norm} \Delta p/p \;\; \sigma_z \; \gamma\beta, \tag{1}$$

of a lower energy *demo* ring should not be different from the estimated 4 TeV collider emittance (latest prediction $\varepsilon_{6D} = 170 \cdot 10^{-12} \pi \mathrm{m}$). A free space parameter *LD*, between the first high focusing quadrupole and the crossing collision point, is defined by the opening angle of the detector. The bunch length defines the β^* at the crossing point. The momentum compaction α ($\alpha = 1/\gamma_t^2$) also depends on the bunch length. Parameters of interest for a lattice design of lower energy storage rings, are presented in Table 1. The bunch lengths in the 200 GeV and 50 GeV *demo* muon colliders, as presented in Table 1, are equal to 10 cm and 16 cm, respectively. Short bunches require the momentum compaction to be adjusted. The maximum of the dispersion function in the lattice design is limited by the large beam momentum spread. Momentum offsets of the incoming muons are estimated to be large ($\Delta p/p = 0.12\%$). If the beam size, resulting from the momentum offset, σ_p, is of the order of the transverse beam size, defined by the betatron function, σ_β, than:

$$D_{max} \leq \sigma/(\Delta p/p). \tag{2}$$

The muons have a short life time. Products of the muon decay deposit energy in the magnets, requiring shielding of the superconducting magnets. The size of the aperture is reduced and has to be considered in the lattice design. The aperture of the magnets depends on the muon beam size.

Table 2

E TeV	Shield	Coil(cm)	P_l(W/m)	$L(s^{-1}cm^{-2})$
4.0	R=6.0cm	D=8.0	1292	732 10^{32}
0.4	R=4.0cm	D=6.0	431	8.4 10^{32}
0.2	R=3.5cm	D=5.5	431	2.6 10^{32}
0.1	R=3.0cm	D=5.0	431	0.8 10^{32}

Parameters like: the shield radius, quadrupole coil diameter, power per length dissipation, and luminosities at four different center of mass muon energies, are presented in Table 2:

3 ISOCHRONOUS RHIC LATTICE

The RHIC collider lattice is three fold symmetrical. It has standard FODO cells in the arcs and six "zero" dispersion anti-symmetric interaction regions (IR) with triplet quadrupoles. Dipoles reach a magnetic field of 3.5 T with 30% quench margin in the arcs. An isochronous lattice is designed by using *flexible momentum compaction* (FMC) modules, as previously presented [8], and magnets of the same size as in the present RHIC machine. Figure 1 shows the betatron functions inside one of the IRs together with one FMC module.

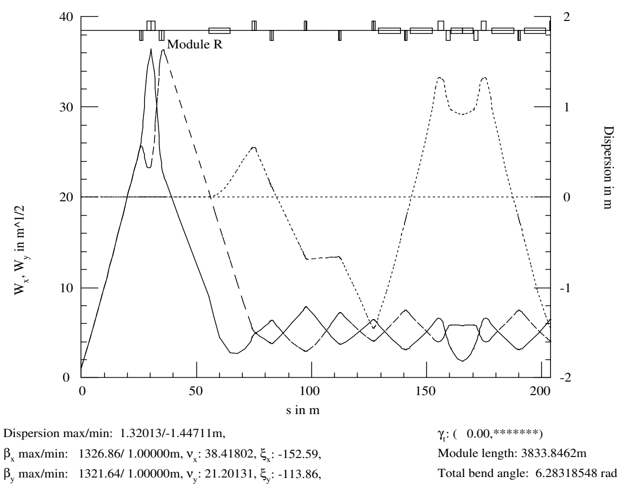

Figure 1: Isochronous RHIC lattice-IR with one FMC module.

4 250 GEV ISOCHRONOUS MUON *DEMO* COLLIDER LATTICE IN THE RHIC TUNNEL

Previous RHIC upgrade parameters at the crossing points, of $\beta^* = 1m$ and $\beta_{max} = 1326$m, are replaced by the 250 GeV *demo* muon collider storage ring of $\beta^* = 10$ mm and$\beta_{max} = 18525$m. The distance between the crossing point and the first quad is estimated to be *LD*$\sim$3 m. The RHIC triplet is replaced by quadrupole magnets optimized for the *demo* muon collider. Figure 2 shows the betatron functions inside one of the IRs together with one FMC module. The FMC module is the same as in the previous example. A dipole, located between the first and the second high focusing quadrupoles, reduces the background of the detector.

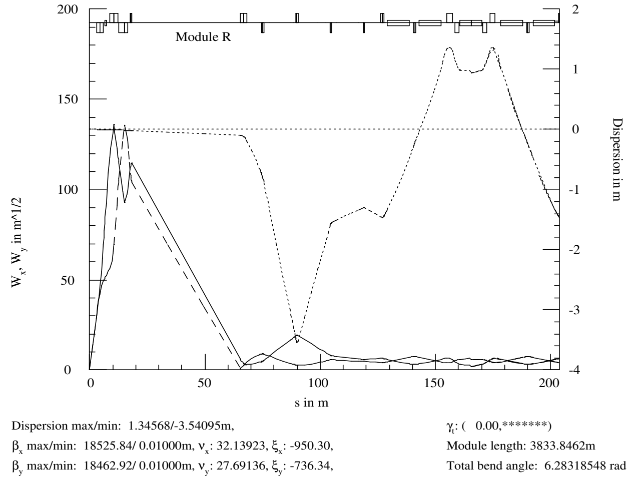

Figure 2: The IR and one FMC module of the 250 GeV isochronous *demo* muon collider lattice in the RHIC tunnel.

5 *DEMO* MUON COLLIDER 50 GEV STORAGE RING

The rms transverse emittance of a 50 GeV on 50 GeV muon storage ring is estimated to be $\varepsilon = 136 \cdot 10^{-6}\pi\mathrm{m}$ (see Table 1). The beam size is defined as:

$$\sigma = \sqrt{\sigma_\beta^2 + \sigma_p^2} \tag{3}$$

while from the rms transverse emittance:

$$\sigma_\beta = \sqrt{\frac{\varepsilon\beta_{Twiss}}{\gamma\beta}}. \tag{4}$$

The relativistic factor for a muon energy of 50 GeV is $\gamma\beta$=473.22. The rms muon beam momentum width reaching the 50 GeV *demo* collider is estimated to be $\Delta p/p = 0.12\%$. If the maximum value of the dispersion function is D_{max}=2m, the beam size $\sigma_p = D_{max}\Delta p/p =$ 2.4 mm. For $D_{max} = 1$m the rms of beam size from the momentum width is a factor of two smaller (σ_p=1.2 mm). If the maximum pole tip field at the quadrupoles is B_{max}=8 T, then estimated gradients are calculated by using the radii equal to 4 σ.

The *demo* muon collider storage ring consists of eight FMC modules, which make the arc part of the machine, and a single interaction region with one crossing point. The FMC module consists of four FODO cells with a π *low beta* section in the middle. Longitudinal dimensions of the magnets inside the FODO cells define the maximum values of the betatron functions. There has to be enough clearance between the wall of the beam pipe, which is reduced due to the shield and the circulating beam. Construction of the FMC module starts by defining a 90^o FODO cell which conforms to the σ_β beam size request. The maximum value of the dispersion function in this FODO cell is defined by the size of the bending angle. As reported earlier [9] the dispersion value in an FMC module is roughly half of the value within the 90^o FODO cell. The length of a dipole in the FMC module is L_d=3.7m. The maximum values of the betatron functions in the FMC module are β_x=17.1 m and β_y=17.5 m, and for the dispersion function $D_x = +1.38m$ and $D_x = -1.23$ m, as presented in Figure 3. A proce-

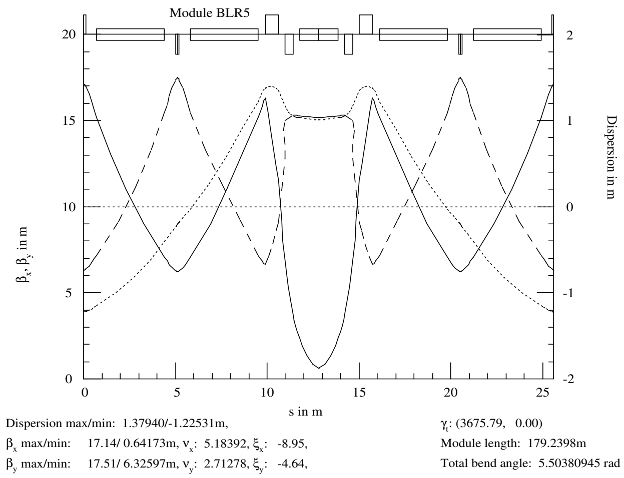

Figure 3: The *Flexible Momentum Compaction Module* of the 50 GeV *demonstration* storage ring

dure for the interaction region triplet design was previously reported [10]. Table 3 shows the quadrupole gradients and lengths:

Table 3

QUAD	G (1/m)	Length(m)	β_x (m)	β_y (m)
Q1	-115.0	0.686	597.0	331
Q2	58.34	2.293	2261.3	1140.0
Q3	-58.34	1.646	1083.15	2261.0
Q4	123.0	1.630	135.54	2.03

It is important to note that for experimental background reduction a dipole was installed between the first and the second quadrupoles inside the IR region, and that the quadrupoles on the opposite sides of the crossing point are antisymmetric to balance the chromaticities. The betatron functions of the interaction region together with FMC modules are presented in Figure 4. The circumference of the machine is 263.4 m with an average radius of 42 m. There are eight FMC modules each 25.6 m long, and one straight section-IR 58.5 m long. The chromaticity of the whole lattice is corrected by sextupoles within the FMC modules in the arcs. The second order tune shift induced by the sextupole is small (all $\alpha_{xx}, \alpha_{xy}, \alpha_{yy} \leq 10^4$ m^{-1}).

6 SUMMARY

A progress report on the muon collider *demonstration* machines was presented. First, two examples showed that an isochronous storage ring could be placed inside an existing tunnel (RHIC) with magnets already built. The center of mass energy for μ^+ and μ^- beams in these two rings is 0.5 TeV. If this energy is selected for a *demonstration* machine, the circumference of the new ring could be much smaller than in the examples presented. The two examples of 250

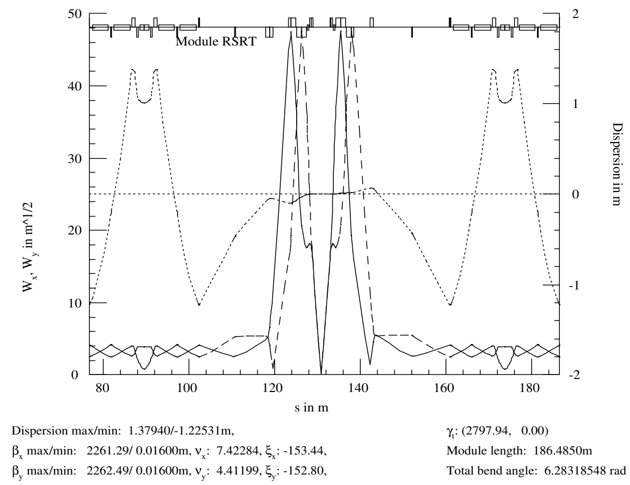

Figure 4: the IR with two FMC modules of the 50 GeV isochronous *demo* muon collider lattice.

GeV storage rings had a circumference 3833 m because this is the RHIC circumference. The size of the 0.1 TeV muon collider *demonstration* storage ring is very small (the circumference is only 263 m). More tracking and detector background studies will follow.

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