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A Lattice for a Hybrid Fast-Ramping Muon Accelerator to 750 GeV

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We describe a lattice for accelerating muons from 375 GeV to 750 GeV. The lattice is a fast-ramping synchrotron with a mixture of fixed-field superconducting dipoles and warm dipoles, so as to have a high average bending field while still being able to rapidly change the average bending field as the beam momentum increases.

For a 1.5 TeV center of mass muon collider, muons must be rapidly accelerated to 750 GeV. To accomplish this efficiently, we wish to make as many passes through the RF cavities as possible, while keeping the average RF gradients sufficiently high to avoid excess muon decays.

A synchrotron where the magnets are very rapidly ramped has been envisioned as one option to accomplish this. The entire acceleration cycle takes place in less than 1 ms, presenting a technological challenge for the magnets. Clearly superconducting magnets cannot be ramped on this time scale, so instead room-temperature magnets will be ramped. To keep losses low, dipoles can use grain-oriented silicon steel, but quadrupoles will probably need to use more conventional steel, giving a lower maximum field for these high ramping rates.

If we want to have a large average RF gradient and simultaneously make a large number of passes through the RF cavities, the average bending field must be high. To achieve such a large bending field while rapidly ramping magnets, it has been proposed to use a hybrid lattice consisting of interleaved superconducting dipoles and bipolar ramped dipoles [1-5].

Due to the large single-bunch current and the relatively small apertures we desire (both

Table 1: Constraints of the lattice design

Minimum momentum	375 GeV/c
Maximum momentum	750 GeV/c
Fixed dipole field	8 T
Minimum ramped dipole field	−1.8 T
Maximum ramped dipole field	+1.8 T
Max. quadrupole pole tip field	1.3 T
Superperiods	8
Straight cells per superperiod	3

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Table 2: Cell layout for the first arc half-cell; the second half is a reflection of the first. The fields given are for the central momentum of 562.5 GeV/*c*.

Type	Length (m)	Field
Drift	0.29002	
Quadrupole (F)	1.60	+26.4219 T/m
Drift	0.35	
Dipole (Cold)	2.6568	8.00001 T
Drift	0.35	
Dipole (Warm)	3.97319	0 T
Dipole (Warm)	3.97319	0 T
Drift	0.35	
Dipole (Cold)	2.6568	8.00001 T
Drift	0.35	
Dipole (Cold)	2.6568	8.00001 T
Drift	0.35	
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Dipole (Warm)	3.97319	0 T
Drift	0.35	
Dipole (Cold)	2.6568	8.00001 T
Drift	0.35	
Quadrupole (D)	1.60	−26.3243 T/m
Drift	0.29002	

because we would like to use high-frequency RF, and because power requirements and heating will be more reasonable for smaller aperture ramped magnets), collective effects are expected to be very significant. To reduce

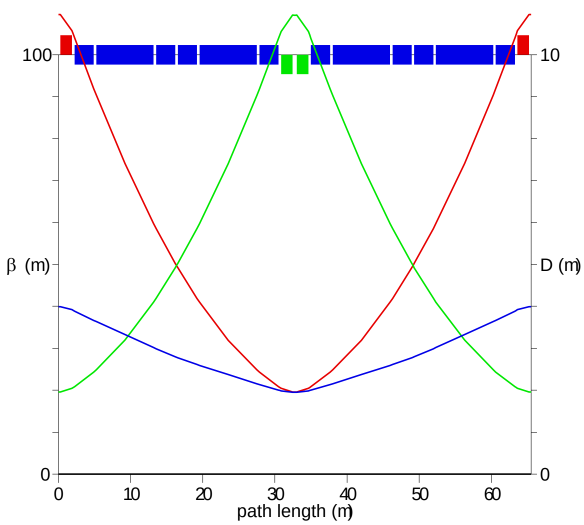

Figure 1: Lattice functions for an arc cell.

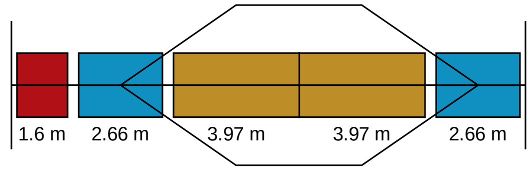

Figure 2: Structure of a quarter cell, showing the expected deviation of high and low energy closed orbits. From left to right, magnets are a quadrupole, cold dipole, two warm dipoles, and a cold dipole.

Table 3: Fields of the ramped magnets at the momentum extremes.

Type	375 GeV/*c*	750 GeV/*c*
Dipole (Warm) (T)	−1.78315	+1.78315
Quadrupole (F) (T/m)	+17.6143	+35.2292
Quadrupole (D) (T/m)	−17.5495	−35.0991

their effects, we propose to have strong synchrotron oscillations (a synchrotron tune of over 1). To have such a high synchrotron tune, a large number of superperiods are needed.

Putting together all of these requirements, a set of requirements for a final acceleration stage for a muon collider has been proposed in Table 1. These basic requirements and some basics of the lattice structure for such a machine were decided upon at a workshop in April 2011 at the University of Mississippi, Oxford [6].

Each superperiod consists of 6 arc cells, two sets of 2-cell dispersion suppressors, and three straight cells, for a total of 13 cells. Every cell has a FODO lattice structure. Each cell has a phase advance of $\pi/2$ in both the horizontal and vertical planes. The magnets will have their fields ramped with time so as to keep the cell tunes constant. All dipole magnets are rectangular. The quadrupoles are split into two pieces to allow the eventual insertion of sextupoles for chromaticity correction.

Table 4: Cell layout for a dispersion suppressor cell. The fields given are for the central momentum of 562.5 GeV/*c*. The full cell is obtained by reflecting this sequence about its end.

Type	Length (m)	Field
Drift	0.38665	
Quadrupole (F)	2.13333	+27.4245 T/m
Drift	0.26322	
Dipole (Cold)	1.77120	8.00001 T
Drift	0.26322	
Dipole (Warm)	2.64880	0 T
Dipole (Warm)	2.64880	0 T
Drift	0.26322	
Dipole (Cold)	1.77120	8.00001 T
Drift	0.26322	
Dipole (Cold)	1.77120	8.00001 T
Drift	0.26322	
Dipole (Warm)	2.64880	0 T
Dipole (Warm)	2.64880	0 T
Drift	0.26322	
Dipole (Cold)	1.77120	8.00001 T
Drift	0.26322	
Quadrupole (D)	2.13333	−27.3753 T/m
Drift	0.38665	

The arc cell is described in Table 2, and its lattice functions are plotted in Figure 1. In the arc cells, the fields will be set to keep the on-energy closed orbit centered in the quadrupoles and in the drift at the center of each half cell. The behavior of the off-energy orbits is shown in Figure 2. At the energy extremes, the ramped fields take on the values given in Table 3.

The dispersion suppressors consist of two 90° cells with similar structure to that of the normal cells with the following differences: they have 3/4 the cell length, 2/3 the dipole length, and 4/3 the quadruple length of the normal cell's values, with the same fields in the dipoles and slightly different quadrupole gradients. The reason that this design works is that the equilibrium dispersion of a cell is proportional to its length times its bending angle; the above

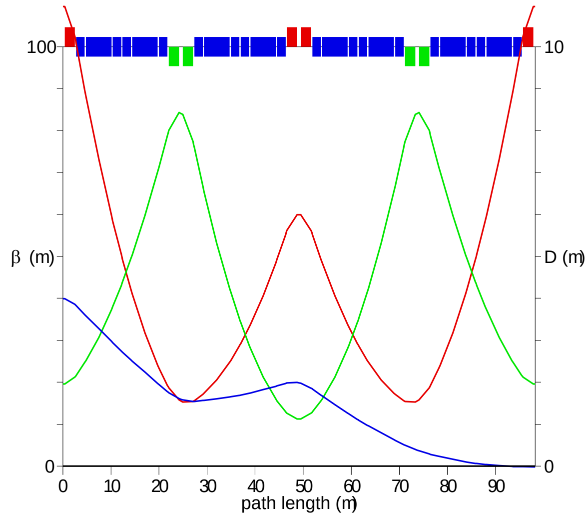

Figure 3: Lattice functions in the dispersion suppression section.

prescription gives a dispersion that is $3/4 \times 2/3 = 1/2$ that of the normal cell. The dispersion ray enters the suppressor with dispersion D_0, that of the suppressor cells is $D_0/2$, so the ray makes a 180 deg cosine-like oscillation about that value, from $D_0 = D_0/2 + D_0/2$ to $D_0/2 - D_0/2 = 0$. This design has a high dipole packing fraction and was incorporated in the SSC lattice. The lattice is described in Table 4, and its lattice functions are plotted in Figure 3. As for the arc, the on-energy closed orbit will be kept at the centers of the quadrupoles and the drift at the center of each cell. The dispersion and its derivative will be zeroed at the end of the dispersion suppressor. At the energy extremes, the ramped fields take on the values given in Table 5.

The straight section is identical to an arc cell, except the bends are removed. Its cell structure is described in Table 6. The tunes are kept constant during the ramping, and thus the quadrupole fields should be close to those given in Tables 2 and 3. The beta functions are nearly identical to those in Figure 1, but the dispersion will be zero.

Table 5: Ramped magnet fields for the dispersion suppression section at the extremes in momentum.

Type	375 GeV/*c*	750 GeV/*c*
Dipole (Warm) (T)	−1.78315	+1.78315
Quadrupole (F) (T/m)	+18.2830	+36.5960
Quadrupole (D) (T/m)	−18.2502	−36.5004

Table 6: Cell structure of the straight cells.

Type	Length (m)	Field
Drift	0.29002	
Quadrupole (F)	1.60	+26.4219 T/m
Drift	28.96996	
Quadrupole (D)	1.60	−26.3243 T/m
Drift	0.29002	

There are still a number of items to work on for this lattice design. The first is to address the time of flight variation with energy. Acceleration will be too fast to adjust the RF phase to match the variation in the time of flight during the acceleration cycle. Thus, the time of flight of the reference particle must be made constant as a function of the reference particle momentum. Alternatively, we must demonstrate that the time of flight variation is sufficiently small that it will have no significant impact on the longitudinal dynamics. To make the time of flight constant, we will either need to modify the existing lattice design in some way, or add chicanes to the straight sections.

Chromaticity correction must be added to the lattice, most importantly to prevent growth of collective instabilities. One would like to cancel the nonlinearities generated by the chromatic correction sextupoles.

Currently the ring tune is an integer. We will therefore need to change this slightly, presumably by adjusting the phase advance in the straight section.

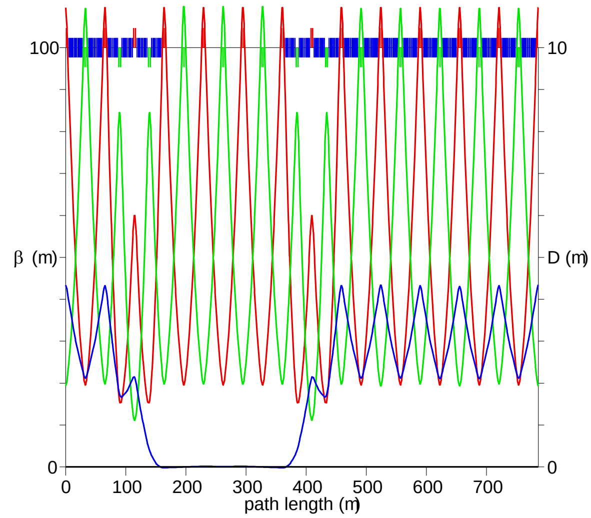

Figure 4: Lattice functions for the full superperiod.

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