MUON ACCELERATION TO 750 GeV IN THE TEVATRON TUNNEL FOR A 1.5 TeV $\mu^+\mu^-$ COLLIDER

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Abstract

Muon acceleration from 30 to 750 GeV in 72 orbits using two rings in the 1000 m radius Tevatron tunnel is explored. The first ring ramps at 400 Hz and accelerates muons from 30 to 400 GeV in 28 orbits using 14 GV of 1.3 GHz superconducting RF. The ring duplicates the Fermilab 400 GeV main ring FODO lattice, which had a 61 m cell length. Muon survival is 80%. The second ring accelerates muons from 400 to 750 GeV in 44 orbits using 8 GV of 1.3 GHz superconducting RF. The 30 T/m main ring quadrupoles are lengthened 87% to 3.3 m. The four main ring dipoles in each half cell are replaced by three dipoles which ramp at 550 Hz from -1.8 T to +1.8 T interleaved with two 8 T fixed superconducting dipoles. The ramping and superconducting dipoles oppose each other at 400 GeV and act in unison at 750 GeV. Muon survival is 92%. Two mm copper wire, 0.28 mm grain oriented silicon steel laminations, and a low duty cycle mitigate eddy current losses. Low emittance muon bunches allow small apertures and permit magnets to ramp with a few thousand volts. Little civil construction is required. The tunnel exists.

MUON COLLIDER INTRODUCTION

A muon collider[1] can do s-channel scans to try to split the $H^0/A^0$ Higgs doublet[2]. At a 1.5 TeV frontier energy, there may be a large array of supersymmetric particles and, if large extra dimensions exist, mini black holes[3]. Like SPEAR, the resolution of a muon collider is unaffected by beamstrahlung. Muon ionization cooling is the key to this machine and a vigorous R&D program is underway[4, 5]. Given a large initial emittance, focusing magnets and RF cavities must be in close proximity. Magnetic fields perpendicular to RF cavity surfaces enhance breakdown[6]. Possible cures include lattices with magnetic fields parallel to RF cavity surfaces to bend electrons back into the cavity surface before they can accelerate, high pressure hydrogen gas in RF cavities to slow electrons[7], grooved RF cavity walls to trap electrons[8], or high melting point, low density materials such as beryllium to allow sparks to spread their energy without melting RF cavity walls. 6D cooling guggenheims[9] and rings[10] show promise. Final muon cooling requires short focal length lattices. High Tc superconductors at 4K can carry large currents in the 35 to 50 T range[11]. Parametric resonances[12] and inverse

Eq. 6[18] gives a value of 23 W/kg for the steel. An average magnetic field of 1.6 T is used. Both eddy currents and hysteresis losses, $\int H\cdot dB$, which scale with the coercive force, $H_c$, given in Table 2, are included. Eddy currents alone[19] give 15 W/kg in eq. 7. The total core loss for a one ton dipole is 23 kW. $I^2R$ losses for four turns of
1 cm copper (4500 $\mu\Omega$) carrying 2200 A of sinusoidal current are 11 kW. Using eq. 7 with an 0.1 T field and coils made of 2 mm transposed strands, the eddy current losses in the copper are 13 kW. So multiplying 118 kW per dipole times 200 7.5 m and 400 3.75 m dipoles and adding 6% for quadrupoles, one gets 50000 kW. But the magnets are only on for a 550 Hz cycle, 13 times per second, for a duty cycle of 2.4% and a total power consumption of 1200 kW.

Now we estimate the power consumption of the magnets. Using an average magnetic field of 1.6 T and a frequency of 550 Hz, Eq. 6 [18] gives a value of 40 W/kg for the 0.28 mm grain oriented 3% silicon steel. The total core loss for a 2400 kg, 7.5 m long dipole is 96 kW. $I^2R$ losses for two turns of $2 \times 2$ cm copper (1350 $\mu\Omega$) carrying 3600 A of sinusoidal current is 9 kW for the 7.5 m long dipole. Using eq. 7 with an 0.1 T field and coils made of 2 mm transposed strands, the eddy current losses in the copper are 13 kW. So multiplying 118 kW per dipole half cell are replaced by five dipoles, two fixed 8 T superconducting dipoles in between three dipoles ramping from -1.8 T to 1.8 T at 550 Hz, as shown in Fig. 2. The ramping dipoles oppose the superconducting dipoles at injection and work in unison at extraction. Ramping dipole parameters are given in the last two columns of Table 1.

### Table 1: Fast ramping dipole parameters.

| Injection energy | GeV | 30 | 400 | 400 |
|------------------|-----|----|-----|-----|
| Extraction energy| GeV | 400| 750 | 750 |
| Dipoles/half cell|     | 4  | 2   | 1   |
| Dipole length, $\ell$ | m  | 6.3| 3.75| 7.5 |
| Bore height, $h$  | mm | 6  | 5   | 5   |
| Bore width, $w$   | mm | 30 | 50  | 50  |
| Initial magnetic field, $B$ | T  | 0.14| -1.8| -1.8|
| Final magnetic field, $B$ | T  | 1.8 | 1.8 | 1.8 |
| Orbits            |     | 28 | 44  | 44  |
| Acceleration period | ms | 0.59| 0.92| 0.92|
| Frequency, $f$    | Hz  | 400| 550 | 550 |
| Coil turns, $N$   |     | 4  | 4   | 2   |
| Coil resistance, $R$ | $\mu\Omega$ | 4500| 2700| 1350|
| Current, $I$      | A   | 2200| 1800| 3600|
| Magnet energy, $W$| J   | 1500| 1200| 2400|
| Magnet inductance, $L$ | $\mu$H | 630| 760 | 380 |
| Capacitance, $C$  | $\mu$F | 250 | 110 | 220 |
| Voltage, $V$      | V   | 3400| 4700| 4700|
| Power Consumption | kW | 0.6 | 1.4 | 2.8 |

### 400 TO 750 GeV, 550 Hz HYBRID RING

The 400 GeV Fermilab main ring FODO lattice is slightly modified to reach 750 GeV. The 30 T/m quadrupoles are lengthened from 1.7 m to 3.2 m and run at 150 Hz. The four ramping dipoles per half cell are replaced by five dipoles, two fixed 8 T superconducting dipoles in between three dipoles ramping from -1.8 T to 1.8 T at 550 Hz, as shown in Fig. 2. The ramping dipoles oppose the superconducting dipoles at injection and work in unison at extraction. Ramping dipole parameters are given in the last two columns of Table 1.

Now we estimate the power consumption of the magnets. Using an average magnetic field of 1.6 T and a frequency of 550 Hz, Eq. 6 [18] gives a value of 40 W/kg for the 0.28 mm grain oriented 3% silicon steel. The total core loss for a 2400 kg, 7.5 m long dipole is 96 kW. $I^2R$ losses for two turns of $2 \times 2$ cm copper (1350 $\mu\Omega$) carrying 3600 A of sinusoidal current is 9 kW for the 7.5 m long dipole. Using eq. 7 with an 0.1 T field and coils made of 2 mm transposed strands, the eddy current losses in the copper are 13 kW. So multiplying 118 kW per dipole times 200 7.5 m and 400 3.75 m dipoles and adding 6% for quadrupoles, one gets 50000 kW. But the magnets are only on for a 550 Hz cycle, 13 times per second, for a duty cycle of 2.4% and a total power consumption of 1200 kW.

![Figure 2: The 30.45 m long FODO lattice half cell consists of half of two 3.2 m ramping quadrupoles, two fixed, 4.2 m 8 T superconducting dipoles, and two 3.75 m plus one 7.5 m ramping dipoles. The ramping dipoles, which go from -1.8 T to 1.8 T at 550 Hz, oppose the superconducting dipoles at 400 GeV and act in unison at 750 GeV or perhaps a bit higher.](image-url)
1.3 GHz, 10 MW KLYSTRONS

Acceleration from 30 to 400 GeV uses 14 GV of 1.3 GHz superconducting RF in 42 locations evenly spaced around the ring. The acceleration occupies 0.59 ms and 28 orbits. Muon survival is 80%. Forty-two 10 MW klystrons allow the energy extracted by a pair of $2 \times 10^{12}$ muon bunches to be replaced. One RF coupler for every three cells is required.

Accelerated from 400 to 750 GeV uses 8 GV of 1.3 GHz superconducting RF in 12 locations evenly spaced around the ring. The acceleration occupies 0.92 ms and 44 orbits. Muon survival is 92%. Twenty-four 10 MW klystrons allow the energy taken by a pair of $2 \times 10^{12}$ muon bunches to be replaced. One RF coupler for every three cells is required.

Running at 13 Hz, the cryogenics and klystron modulators require 4 and 22 MW of AC wall power, respectively. A bunch with $2 \times 10^{12}$ muons extracts 8% of the energy from an RF cavity leading to head/tail, wakefield [22], and HOM [23] issues. One cell stores 13 joules at 31.5 MV/m. However, as shown in eqs. 8 and 9, there are synchrotron oscillations [22] to aid longitudinal dynamics. $h$ is the harmonic number (number of 0.23 m RF wavelengths around the ring). The transition $\gamma$ is 18 for the main ring, which gives a momentum compaction, $\eta$, of $\frac{1}{187}$. $\nu_s = \sqrt{\frac{h \eta(GV) \cos \phi_e}{2 \pi \beta^2 E_s}} = \sqrt{\frac{27200(18)}{2 \pi (12)(30)}} = .8$.

Muon bunches must stay in phase with the RF. The muon speed increase from $\beta = 0.999999380$ to $\beta = 0.999999996$ in the first ring can be corrected by increasing the orbital radius by 6 mm during acceleration. The one in 4000 path length decrease in the second ring can be corrected by increasing the orbital radius by 25 mm during acceleration.

A longitudinal emittance of 0.072 $\pi$ m-rad [5] leads to an 0.01 m long muon bunch injected at 30 GeV/c with a 2.5% momentum spread, i.e. 0.072 = $0.025(30)/m_{u\mu}$ (0.01), where $m_{u\mu} = 0.106$ GeV/c$^2$. Better might be 0.005 m and 2% [22]. The RF wavelength is 0.23 m. A muon on crest gets 4% more acceleration than one 0.01 m (15$^0$) off crest. Using eq. 10, and integrating over the acceleration cycle from 30 to 750 GeV with $4 \times 10^{12}$ muons at 13 Hz, and neglecting downtime and straight sections in the ring, a person would receive a dose of a millirem at 2700 m from decays into neutrinos, if they stood in the beam constantly. Note that the Fox River is 5000 m away from and 4 m below the Tevatron, so neutrinos at 2700 m are still underground.

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\text{distance(meters)} = 5 \times 10^{-7} \sqrt{\mu} / \text{year E(TeV)}^{1.5} \quad (10)
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