Muon Acceleration to 750 GeV in the Fermilab Tevatron Tunnel

D. J. Summers

Univ. of Mississippi - Oxford

Neutrino Factory and Muon Collider Collaboration Friday Meeting

Fermilab

Batavia, Illinois

23 March 2007

Modify the 400 GeV Main Ring

- **70 $\rightarrow$ 750 GeV in 68 orbits (1.4 ms).**
  10 GV of 1.3 GHz, 30 MV/m SRF.
  Muon Survival = 79%. C = 6283 m.
- **FODO Lattice 30.45 m Long Half Cell.**
  3.3 m, 160 Hz, 30 T/m Quadrupoles.
  3.2 m, 8 Tesla Superconducting Dipoles.
  5.7 m, 360 Hz, $\mp$1.8 Tesla Dipoles.
  Dipoles oppose, then act in unison.

Q F	$\mp$1.8T Dipole	+8T Dip.	$\mp$1.8T Dipole	+8T Dip.	$\mp$1.8T Dipole	Q D

- **Eddy Currents: Thin copper wire and .28mm grain oriented Si steel laminations.**
- **1.5 TeV $\mu^+ \leftrightarrow \mu^-$ in C = 3319 m MI Tunnel.**
  Little civil construction. Existing tunnels.

Horizontal Magnet Apertures and Longitudinal Dynamics

- **Horizontal Dipole Aperture Required.**
  200 half cells/ring.
  1.8° per half cell.
  5.7m, 1.8T dipole bends 0.4° at 400 GeV.
  5.7m, -1.8T dipole bends 2.3° at 70 GeV.
  Use the single bend point approximation.
  5.7/2 sin(2.3°) = 12 cm bore width.
- **Longitudinal Dynamics.**
  Path length difference during acceleration.
  Use Pythagorus.
  $[\sqrt{2.85^2 + 0.12^2} - 2.85]/2.85 = 1/400$
  4 dipoles/half cell ⇒ 58% real estate
  So a 1/700 SRF frequency shift is needed.
  ILC 3 μm/m stretcher ⇒ 1/10^6; need 5mm.

Two Ring Option to Reduce Path Length Difference

- **20 → 400 GeV in 38 orbits (0.8 ms).**
  No superconducting magnets, just Si-iron.
  10 GeV of 1.3 GHz, 30 MV/m SRF.
  Muon Survival = 74%. r = 1000 m.
  No Path Length Difference, only Speed.
  β **= .999988 → .99999994**
  Adjust radius; 1000 → 1000.012 m.

- **400 → 900 GeV in 50 orbits (1.1 ms).**
  Hybrid magnet system with larger superconducting magnet fraction.
  10 GeV of 1.3 GHz, 30 MV/m SRF.
  Muon Survival = 92%. r = 1000 m.
  1/25000 Path Length Difference.
  Adjust radius; 1000 → 1000.04 m.

Enabling Technology: Grain Oriented Silicon Steel

- **Much less $E = B^2/2\mu$ in Si-steel at 1.8T.**

Material (μ/μ_0)	1.0T	1.5T	1.8T
1008 Steel	3000	2000	200
Grain Oriented ($\|$)	40000	30000	3000
Grain Oriented ($\perp$)	4000	1000	

Transverse Beam Size with Cold Muons

- $\epsilon =$ **25 mm-mrad.**
  $\beta =$ **99 meters (as in the main ring design).**
  $\mathbf{6}\sigma = 6\sqrt{\epsilon\beta/[6\pi(v/c)\gamma]}$
- **20 GeV/c,** γ **= 190** $\rightarrow$ **6**$\sigma =$ **9.0mm**
- **70 GeV/c,** γ **= 660** $\rightarrow$ **6**$\sigma =$ **4.7mm**
- **Apertures and magnets are small.**

Dipole LC Circuit Voltage

- **Dipole Bore: 5.7m $\times$ 0.15m $\times$ 0.005m**
  Dipole B Field: 1.8 T, f = 360 Hz
  W = [Volume] $\mathbf{B}^2/2\mu_0$ = 5500 Joules
  $\mu_0 = 4\pi \times 10^{-7}$, **h = 0.005m, N = 1 turn**
  $B = \mu_0 NI/h \rightarrow I = Bh/\mu_0 N =$ **7000 Amps**
  $W = .5LI^2 \rightarrow L = 2W/I^2 =$ **225 μH**
  $f = (1/2\pi)\sqrt{1/LC} \rightarrow C = 1/L(2\pi f)^2 =$ **870 μF**
  $W = .5CV^2 \rightarrow V = \sqrt{2W/C} =$ **3500 Volts**

- **Under the Ken Bourkland 5000 Volt Limit**

Ramping Dipole Power Loss

- **Copper Volume: 1200cm $\times$ 3cm $\times$ 6cm**
  R = 1200 1.8$\mu\Omega$-cm/(3) (6) = 120$\mu\Omega$
  I = 7000 A, P = .5 I^2 R = 3000 watts
  Eddy Currents: wire w = 1mm, B = 0.1T
  P = [Vol] $(2\pi f B w)^2/24\rho$ = 2500 watts
  316L Stainless Steel cooling tube,
  OD=12mm, ID=10mm, L=24m
  P = [Vol] $(2\pi f B)^2(OD^2 - ID^2)/32\rho$ = 400 w

- **Grain Oriented Silicon Steel Core Losses**
  .28mm laminations, f = 360 Hz, B = 1.6T
  P = $4.38 \times 10^{-4} f^{1.67} B^{1.87}$ = 20 w/kg
  Vol = 5.7 $\times$ 0.4 $\times$ 0.26m $\rightarrow$ 95 kW/magnet

- **100 kW/magnet $\times$ 600 magnets = 60 MW**
  Duty Cycle: 60 MW / 120 = 500 kW/ring

1.3 GHz Superconducting RF

- **Costs from the TESLA TDR.**
  0.9 M Euro / 12m acceleration module
  1.8 M Euro / 10 MW RF station
- **Stored Energy with 30 MV/m and**
  Thirty 12m acceleration modules.
  41 000 Joules (Note 8% beam loading!)
- **Energy of 4×10^{12} 750 GeV Muons.**
  480 000 Joules
- **Energy of Ten 10MW Klystrons in 1.4ms.**
  140 000 Joules.
- **Options to get enough energy.**
  Twenty Klystrons, Two couplers per cavity.
  Let MV sag, high γ muons decay slowly.
  Longer pulse, more caps in the modulator.
  15 GeV of SRF rather than 10 GeV.

RF Options and Muon Survival

RF	20 → 400 GeV	70 → 750 GeV	400 → 900 GeV
10 GV	108 orbits	198 orbits	144 orbits
100 MW	49%	53%	79%
10 GV	56 orbits	101 orbits	74 orbits
200 MW	67%	71%	89%
10 GV	38 orbits	68 orbits	50 orbits
300 MW	74%	79%	92%
15 GV	70 orbits	130 orbits	94 orbits
150 MW	64%	66%	86%
15 GV	37 orbits	67 orbits	49 orbits
300 MW	77%	80%	92%

To Do List

- **Shifting RF Frequency**
- **International Date Line Magnetic Insert**
  RF wavelength = 23 cm
  Path length decreases with acceleration
  Insert increases path length up to 23 cm
  Insert then goes back to zero and repeats
- **High Power RF Couplers**
- **Lattice Simulation**
- **Calculate Synchrotron Oscillations**
  Need momentum compaction & dispersion
- **Beam Loading and Wakefields**
- **Forces on Ramping Magnets**
- **Ramping Magnet Eddy Current Multipoles**
- **Build a Prototype Ramping Magnet**