

Muon Acceleration to 750 GeV in the Tevatron Tunnel for a 1.5 TeV $\mu^+\mu^-$ Collider

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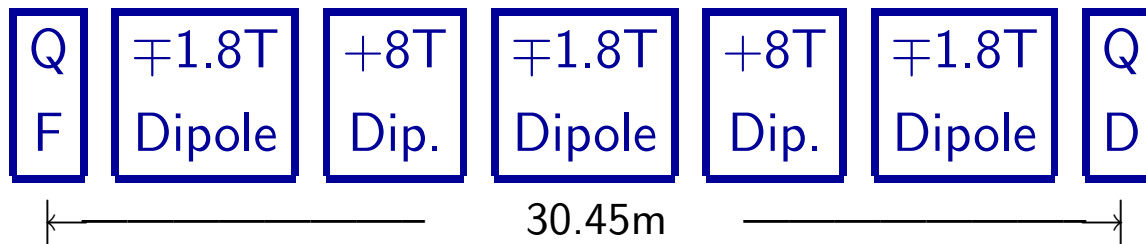


30 to 400 GeV, 400 Hz Synchrotron

- 30 → 400 GeV in 28 orbits (0.59 ms)
14 GV Superconducting RF (1.3 GHz, 31 MV/m)
Muon Survival = 80% Radius = 1000m
- Duplicate the Fermilab Main Ring FODO Lattice
- 1.7m, 30T/m Quadrupoles, $f = 400\text{Hz}$
- 6.3m, 1.8T Dipoles (8/60.9m cell), $f = 400\text{Hz}$
Muon transverse emittance = $25 \mu\text{m}$, $\gamma(30 \text{ GeV}) = 284$
 $h = 6\sigma = 6 \sqrt{25\mu\text{m} \cdot 99\text{m} / (6\pi\beta\gamma)} = 6\text{mm}$
 $6 \times 30\text{mm}$ bore, $N=4$; $I = B h / \mu_0 N = 2200\text{A}$
 $W = \int \frac{B^2}{2\mu_0} d\tau = .5 LI^2 = .5 CV^2$, $f = 1/2\pi\sqrt{LC}$; $V = 3400\text{V}$
.28mm grain oriented 3% Silicon steel laminations
Core Loss (B@1.6T) = $4.38 \times 10^{-4} f^{1.67} B^{1.87} = 23 \text{ W/kg}$
550 Tons @ 13Hz Duty Cycle → 540kW/ring
- $\beta(30 \rightarrow 400 \text{ GeV}) = 0.99999380 \rightarrow 0.99999996$
Adjust radius; 1000 → 1000.006 m

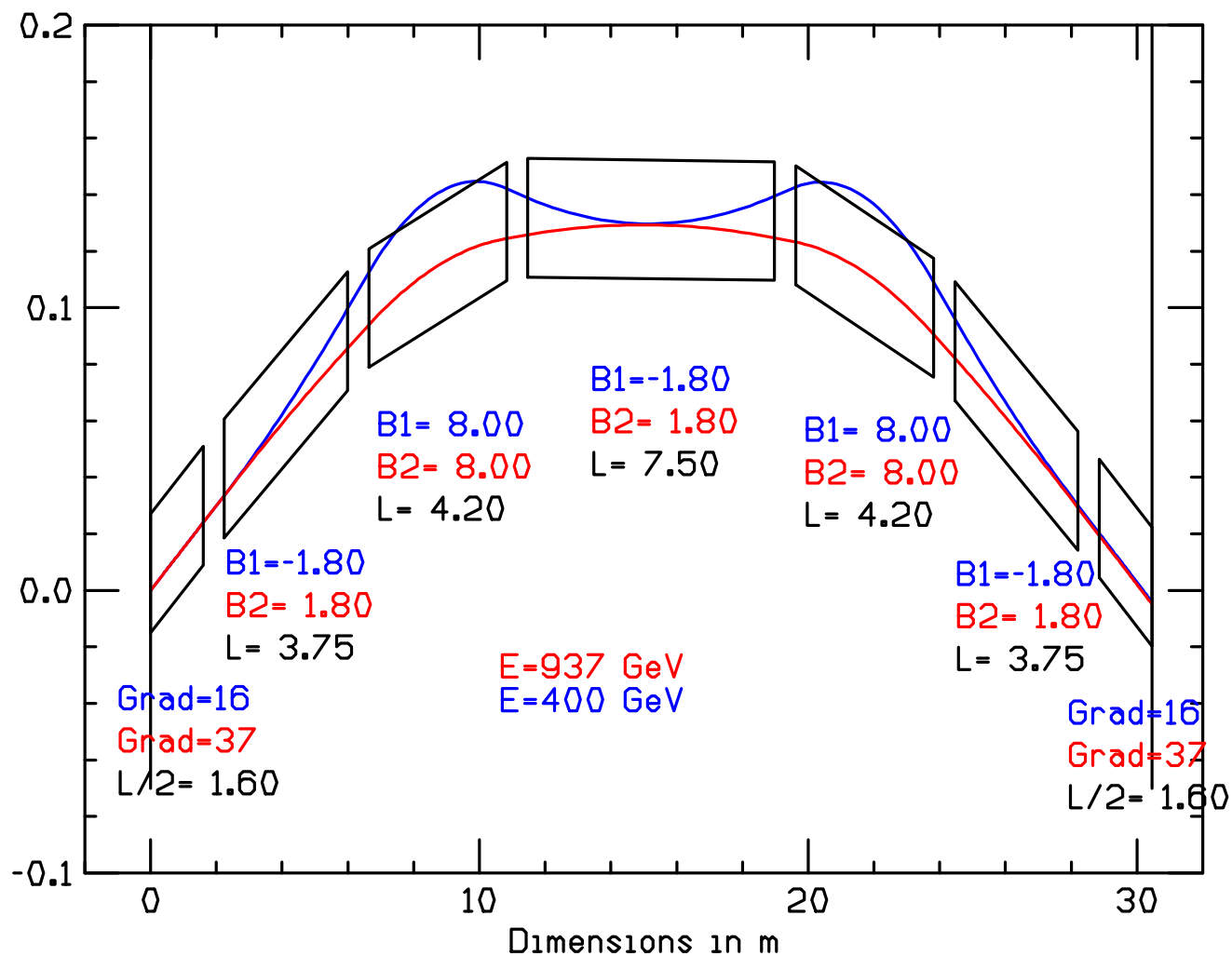
400 to 750 GeV, 550 Hz Hybrid Synchrotron

- 400 → 750 GeV in 44 orbits (0.92 ms) Radius = 1000m
8 GV, 1.3 GHz Superconducting RF; Muon Survival = 92%
- Approximate the Fermilab Main Ring FODO Lattice
- 3.2m, 30T/m Quadrupoles, $f = 150\text{Hz}$
- 4.2m, 8T Fixed Superconducting Dipoles
- 3.75/7.5/3.75m, -1.8 → +1.8T Dipoles, $f = 550\text{Hz}$
5mm×50mm×8.2m bore, N=2; $I = B h / \mu_0 N = 3600\text{A}$
 $W = \int \frac{B^2}{2\mu_0} d\tau = .5 LI^2 = .5 CV^2$, $f = 1/2\pi\sqrt{LC}$; $V = 4700\text{V}$
Core Loss (B@1.6T) = $4.38 \times 10^{-4} f^{1.67} B^{1.87} = 40 \text{ W/kg}$
780 Tons @ 13Hz Duty Cycle → 1200kW/ring



- Dipoles oppose, then act in unison
- 1/40000 Path Length Difference during an acceleration cycle
Adjust radius; 1000 → 1000.025 m

Particle Paths in a 400 to 750 GeV Hybrid Half Cell



- Dipoles oppose at injection, then act in unison at extraction.

Fast Ramping Dipole Parameters

Injection energy	GeV	30	400	400
Extraction energy	GeV	400	750	750
Dipoles / half cell		4	2	1
Dipole length, ℓ	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	μH	630	760	380
Capacitance, C	μF	250	110	220
Voltage, V	V	3400	4700	4700
Power Consumption	kW	0.6	1.4	2.8

Grain Oriented 3% Silicon Steel *EI* Transformer Laminations

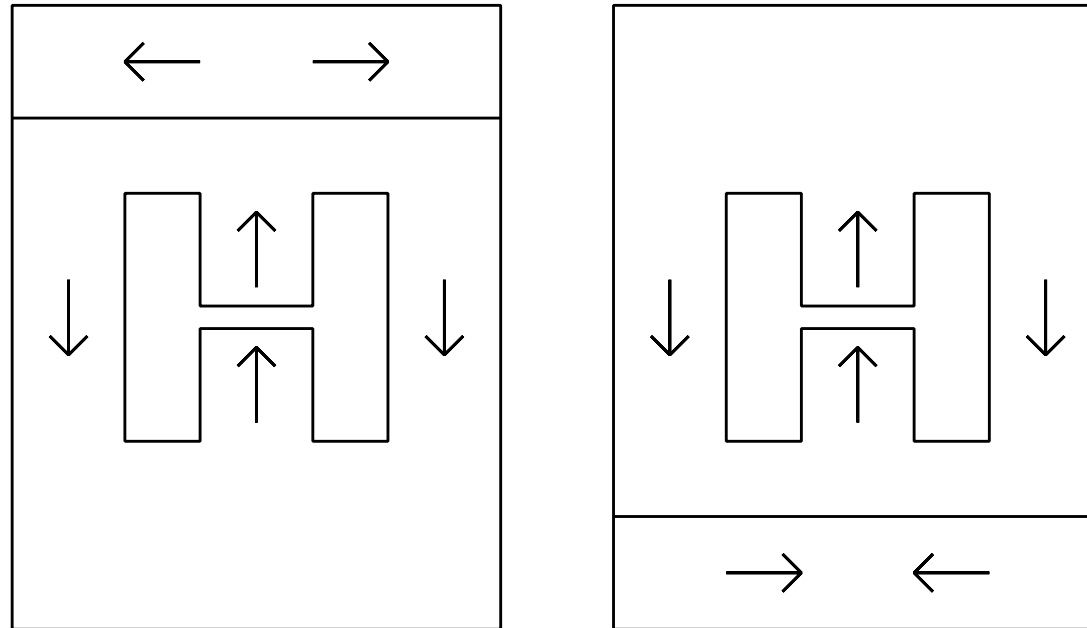


Table 1: Resistivity (ρ), coercivity (H_c), and permeability (μ) of steels. Higher resistivity lowers eddy current losses. Low coercivity minimizes hysteresis losses. Grain oriented 3% silicon steel has a far higher permeability parallel (\parallel) to than perpendicular (\perp) to its rolling direction and permits minimal energy ($B^2/2\mu$) storage, as compared to low carbon steel at 1.8 T.

Steel	ρ (n Ω -m)	H_c (A/m)	μ (1.0 T)	μ (1.5 T)	μ (1.8 T)
.0025% Carbon	100	80	$4400\mu_0$	$1700\mu_0$	$240\mu_0$
Oriented (\parallel) Si	470	8	$40000\mu_0$	$30000\mu_0$	$3000\mu_0$
Oriented (\perp) Si	470		$4000\mu_0$	$1000\mu_0$	

1.3 GHz, 10 MW Klystrons

- 66 10MW Klystrons, 3 Cells/RF Coupler
72 orbits, $4 \times 10^{12} \mu$, 13 Hz
3 cell superconducting cavities \sim kept full
22 MW AC to modulators, 4 MW AC to cryogenic pumps
- Head/Tail, Wakefield, and HOM issues for 1.3 GHz cavities:
 $2 \times 10^{12} \mu$ /bunch on crest \rightarrow 8% beam loading
- Eddy Currents controlled with 2mm copper wire and
0.28mm grain oriented 3% Silicon steel laminations.
Lamination losses dominate copper losses.
All losses equal 2 MW for ramping magnets in both rings.
- Minimal $W = \int \frac{B^2}{2\mu} d\tau$ in 3% Silicon steel at 1.8T
 $\mu(\parallel) = 3000\mu_0 \rightarrow$ lower magnet voltages
- ν Radiation Safety: $\text{km} \left(\frac{2 \text{ bananas}}{\text{week}} = \frac{\text{mrem}}{\text{year}} \right) \propto \sqrt{\mu/\text{yr}} E^{1.5}$
Elevations: Fermilab 227m, Batavia 218m
Distance: 2.7km for 30 \rightarrow 750 GeV; Tevatron OK @ 220m

Synchrotron Oscillations per Orbit for 30 to 400 GeV Ring

$$d\tau/\tau = (1/\gamma_t^2 - 1/\gamma^2)(dp/p) = \eta(dp/p)$$


$$\gamma_t = 18, \quad \gamma(30 \text{ GeV}) = 284$$

$$h = 2\pi \times 1000\text{m} \times 1.3 \text{ GHz}/c = 27200$$

$$\nu_s = \sqrt{-\frac{h\eta}{2\pi\beta^2 E_s} \text{ eV} \cos \phi_s}$$

$$\nu_s = \sqrt{-\frac{27200 \times 1/18^2}{2\pi(1^2)(30 \times 10^9)} (14 \text{ GV})(-0.1)} = 0.8$$

To Do List

- Fitting into 1.3 GHz RF, 5mm or 10mm bunch length?
- Longitudinal dynamics. $10\text{mm} = 15^\circ$. $\cos(15^\circ) = .966$
- Wakefields and longitudinal dynamics with 8% beam loading.
- Want 2.5% Δp at 30 GeV/c. MI does 1.4% at 8.9 GeV/c.
- Beam stability, small aperture, and wall impedance.
- Beam vacuum pipe: $25\mu\text{m}$ SS  \rightarrow 115w/400Hz dipole
- Design 30 to 400 GeV/c and 400 to 750 GeV/c lattices.
- Hexapole B fields from eddy currents. Find with OPERA-3d.
- Magnetic field quality with small aperture magnets.
- Forces on fast ramping magnet pole faces.
- Design a short prototype fast ramping dipole.

Synchrotron Summary

- 30 → 400 GeV Synchrotron: 28 orbits in 0.59 ms
14 GV Superconducting 1.3 GHz RF, 80% Muon Survival
FNAL main ring FODO lattice with 3400V, 1.8T dipoles
Cool muons at high γ → small aperture magnets
- 400 → 750 GeV Synchrotron: 44 orbits in 0.92 ms
8 GV Superconducting 1.3 GHz RF, 92% Muon Survival
Interleaved dipoles oppose (-1.8T), then act in unison (1.8T)
- 2 MW consumed for ramping magnets in both rings @ 13Hz
Low duty cycle, 2mm copper, .28mm grain oriented Si Steel
- 66 10MW 1.3GHz Klystrons, $4 \times 10^{12} \mu$, 3 Cells/RF Coupler

