Fast Ramping Acceleration for a Muon Collider

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17-20 March 2008 Fermilab
Neutrino Factory and Muon Collider Collaboration Meeting

30 to 400 GeV, 400 Hz Synchrotron

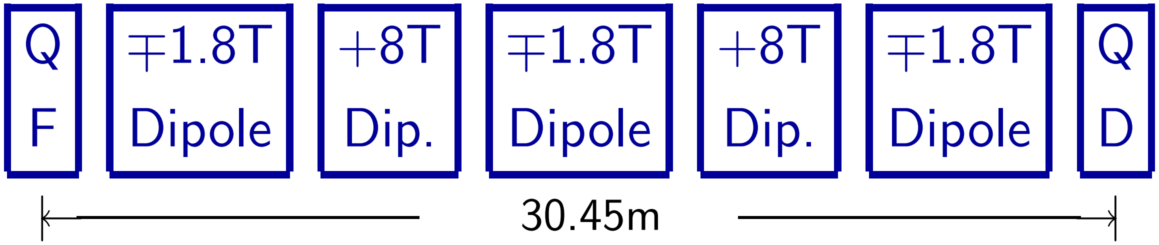
- 30 → 400 GeV in 28 orbits (0.59 ms)
  14 GV Superconducting RF (1.3 GHz, 31 MV/m)
  Muon Survival = 80%   Radius = 1000m

- Duplicate the Fermilab Main Ring FODO Lattice
- 1.7m, 30T/m Quadrupoles, $f =$ 400Hz
- 6.3m, 1.8T Dipoles (8/60.9m cell), $f =$ 400Hz
  Muon transverse emittance = 25 μm, γ(30 GeV) = 284
  h = 6σ = 6 $\sqrt{25\mu\mathrm{m}\ 99\mathrm{m}/(6\pi\beta\gamma)}$ = 6mm
  6×30mm bore, N=4; $I = B\,h/\mu_0 N$ = 2200A
  W = $\int\frac{B^2}{2\mu_0}d\tau = .5\,LI^2 = .5\,CV^2, f = 1/2\pi\sqrt{LC}$; V = 3400V
  .28mm grain oriented 3% Silicon steel laminations
  Core Loss (B@1.6T) = $4.38\times10^{-4}f^{1.67}B^{1.87}$ = 23 W/kg
  550 Tons @ 13Hz Duty Cycle → 540kW/ring

- β(30 → 400 GeV) = 0.99999380 → 0.99999996
  Adjust radius; 1000 → 1000.006 m

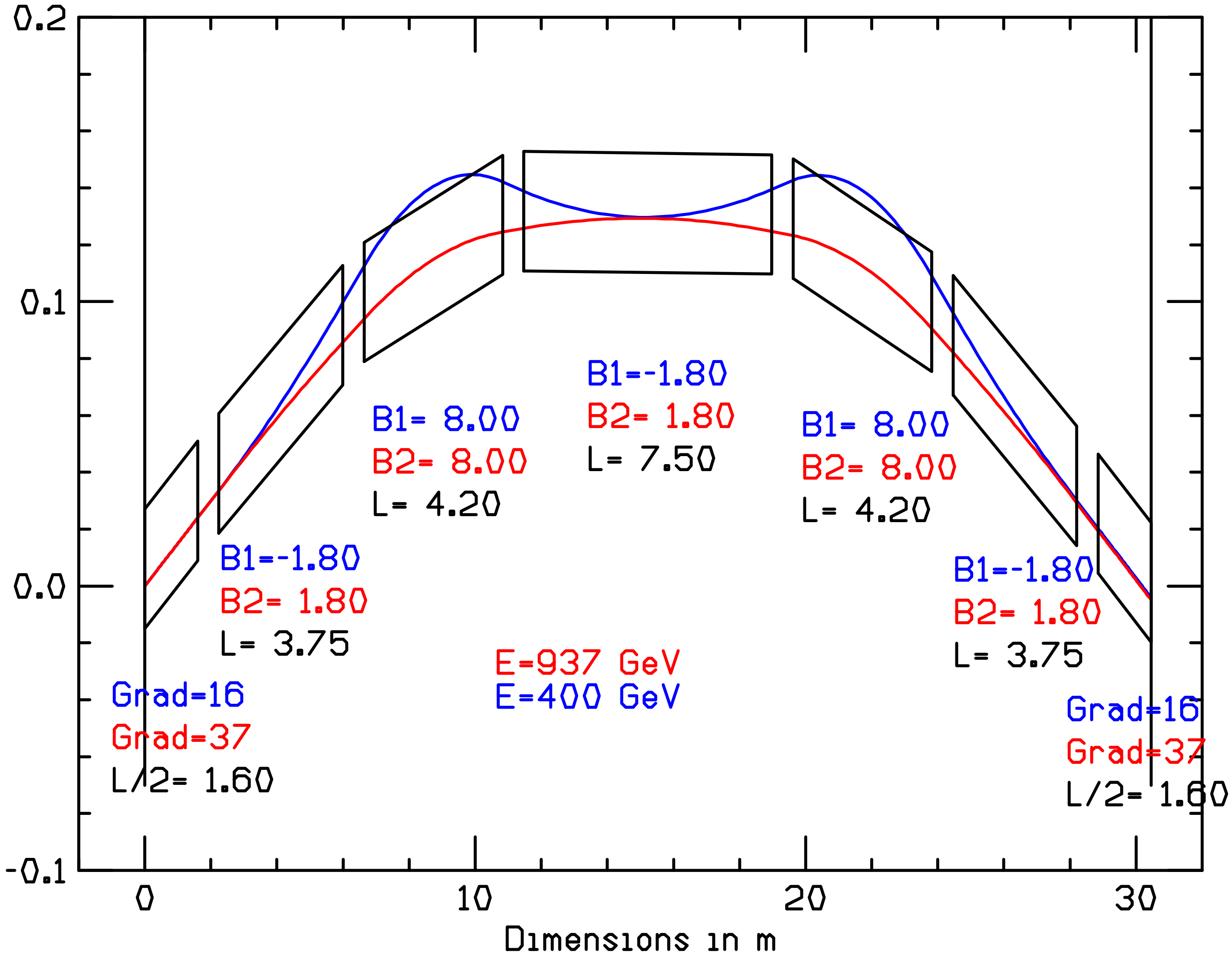
400 to 750 GeV, 550 Hz Hybrid Synchrotron

- 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, $f = 150$Hz
- 4.2m, 8T Fixed Superconducting Dipoles
- 3.75/7.5/3.75m, -1.8 → +1.8T Dipoles, $f = 550$Hz
  5mm×50mm×8.2m bore, N=2; $I = B\,h/\mu_0 N$ = 3600A
  W = $\int \frac{B^2}{2\mu_0} d\tau = .5\,LI^2 = .5\,CV^2$, $f = 1/2\pi\sqrt{LC}$; V = 4700V
  Core Loss (B@1.6T) = $4.38 \times 10^{-4} f^{1.67} B^{1.87}$ = 40 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

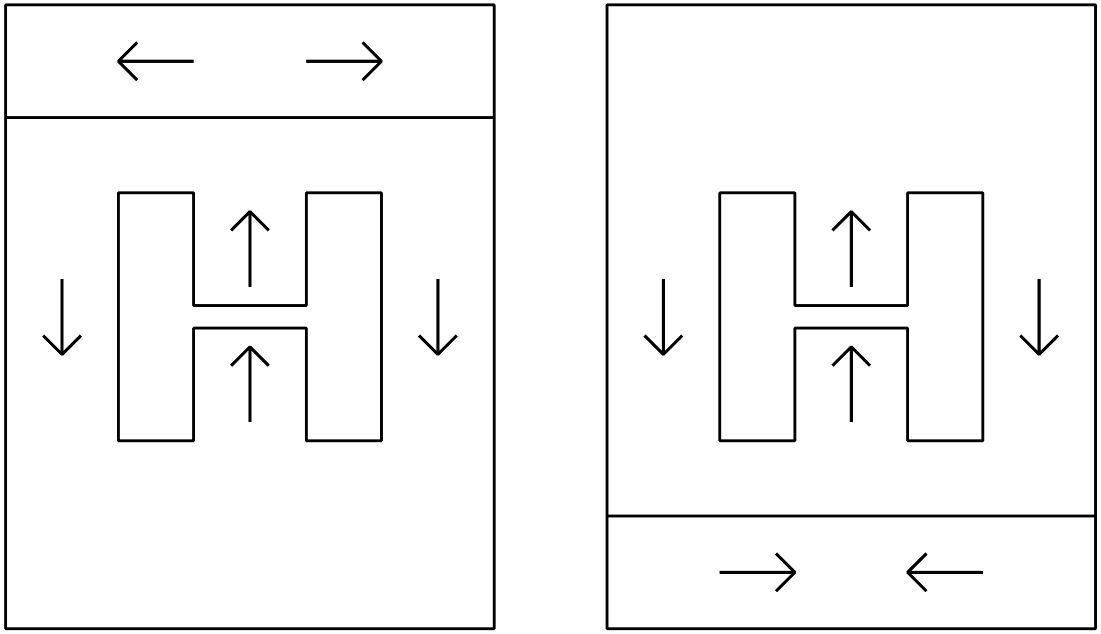
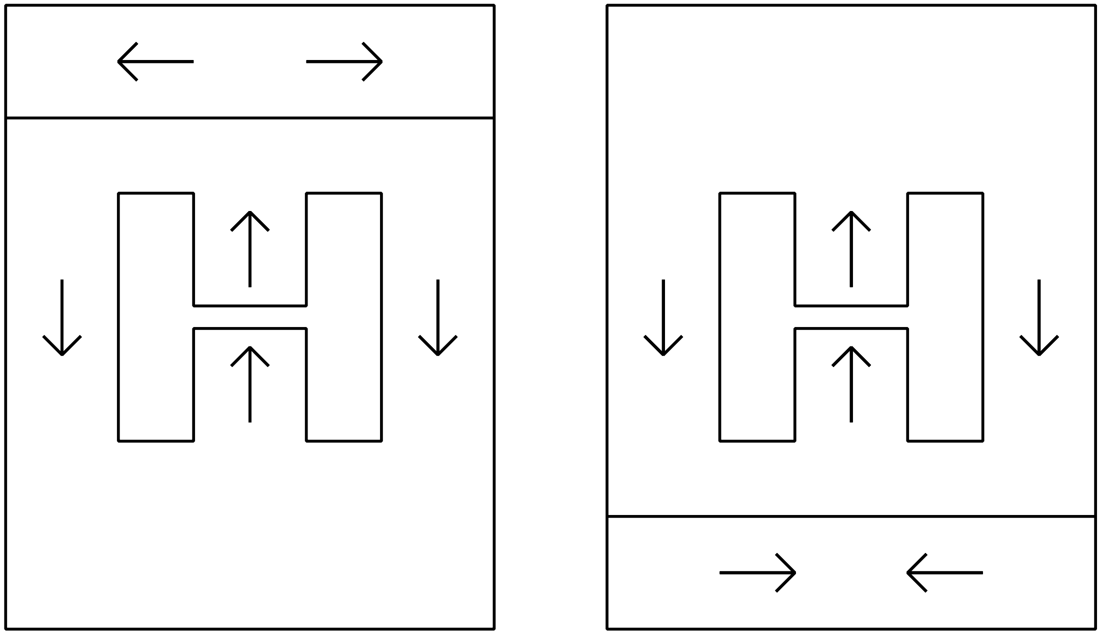


Table 1: Resistivity (ρ), coercivity (H$_c$), and permeability (μ) of steels. Higher resistivity lowers eddy current losses. Low coercivity minimizes hysteresis losses. Grain oriented 3% silicon steel has a far higher permeability parallel ($\|$) to than perpendicular ($\perp$) to its rolling direction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

Steel	ρ(nΩ-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 ($\|$) Si	470	8	$40000\mu_0$	$30000\mu_0$	$3000\mu_0$
Oriented ($\perp$) Si	470		$4000\mu_0$	$1000\mu_0$	

Sketch of a Short Prototype 1.8 T Fast Ramping Dipole



- 550 Hz Dipole Bore: 5 × 50 × 300 mm, W = 100 Joules
Sodick AQ325L Wire EDM .28 mm grain oriented 3% Si steel

- Eight 5 × 20 mm copper turns; 750 volts, 900 amps
Precision wind 2.5 mm magnet wire and epoxy impregnate

- LC Circuit: 350 μF polypropylene capacitor bank
35 1000V 10 μF capacitors @ $20 each from Mouser
Reset choke and diode, $1000 1000V 1000A IGBT switch
Fluke 415B 3kV @ 30ma HV power supply

1.3 GHz, 10 MW Klystrons

- **66 10MW Klystrons, 3 Cells/RF Coupler**
  72 orbits, $4\times10^{12}\mu$, 13 Hz
  3 cell superconducting cavities ∼kept full
  22 MW AC to modulators, 4 MW AC to cryogenic pumps
- **Head/Tail, Wakefield, and HOM issues for 1.3 GHz cavities:**
  2×10^{12} μ/bunch on crest → 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**
  $\mu(\|) = 3000\mu_0$ → lower magnet voltages
- **ν Radiation Safety: 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→750 GeV; Tevatron OK @ 220m

Synchrotron Oscillations per Orbit for 30 to 400 GeV Ring

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

$$\gamma_t = 18, \;\; \gamma(30\,\mathrm{GeV}) = 284$$

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

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

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

To Do List

- Fitting into 1.3 GHz RF, 5mm or 10mm bunch length?
- Longitudinal dynamics. 10mm $= 15^0$. $\cos(15^0) = .966$
- 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: 25μm SS  $\longrightarrow$ 115w/400Hz dipole
- Design 30/400 and 400/750 GeV/c lattices with OPTIM.
- Hexapole B fields from eddy currents. Find with OPERA-3d.
- Magnetic field quality with small aperture magnets.
- Forces on fast ramping magnet pole faces.

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
  38% Steel Eddy, 28% I^2R, 20% Hysteresis, 15% Cu Eddy
  Low duty cycle, 2mm copper, .28mm grain oriented Si Steel
- 66 10MW 1.3GHz Klystrons, $4 \times 10^{12}\mu$, 3 Cells/RF Coupler