Fast Ramping Muon Synchrotron Acceleration

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1-3 December 2009 Brookhaven
Muon Collider Design Workshop

Guiding Principles

- High injection γ due to low muon mass plus cool muons
  $\longrightarrow$ small magnets ramping with a few thousand volts.
  Power supplies are similar to those for neutrino horns.
  Capacitors: $5/joule. Choke: $3/joule. Switch: $1000/MW
  Many thanks to Dan Wolff and Ken Bourkland for advice.
- Ameliorate eddy current and hysteresis losses in magnets.
  Thin grain oriented silicon steel laminations.
  Stainless steel cooling tubes for water and thin copper wire.
  Conductor in use for new ISIS choke. Made by Trench Ltd.
  For loss calculations see: D. J. Summers, physics/0108001
- Exploit the 4% duty cycle.
  25x lower losses than continuous operation.
  96% of the time energy just sits in the capacitor banks.
- Muon survival is reasonable in a fast ramping synchrotron.
- Power can be go into cavities fast enough (need 3x ILC).
- Goal: 1.5 TeV collider with moderate acceleration cost.

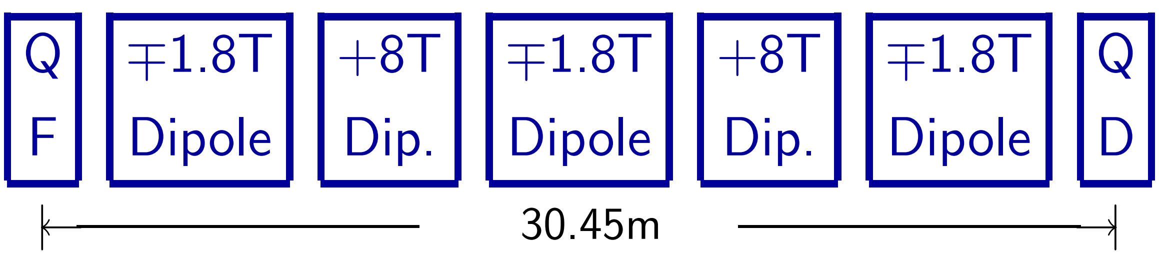
Example: 60 to 400 GeV, 260 Hz Synchrotron

- 60 $\rightarrow$ 400 GeV in 43 orbits (0.9 ms)
  8 GV Superconducting RF (805 MHz)
  Muon Survival = 79%   Radius = 1000m

- Duplicate the Fermilab Main Ring FODO Lattice
- 1.7m, 30T/m Quadrupoles, f = 260Hz
- 6.3m, 1.8T Dipoles (8/60.9m cell), f = 260Hz
  Muon transverse emittance = 25 μm, γ(60 GeV) = 570
  h = 6σ = 6 $\sqrt{25\mu\text{m}\ 99\text{m}/(6\pi\beta\gamma)}$ = 4mm
  Beam is small, but need OPTIM to get real magnet gaps.
  6$\times$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 = 2200V
  .28mm grain oriented 3% Silicon steel laminations
  Core Loss (B@1.6T) = $4.38 \times 10^{-4} f^{1.67} B^{1.87}$ = 11 W/kg
  550 Tons @ 13Hz Duty Cycle $\rightarrow$ 260kW/ring

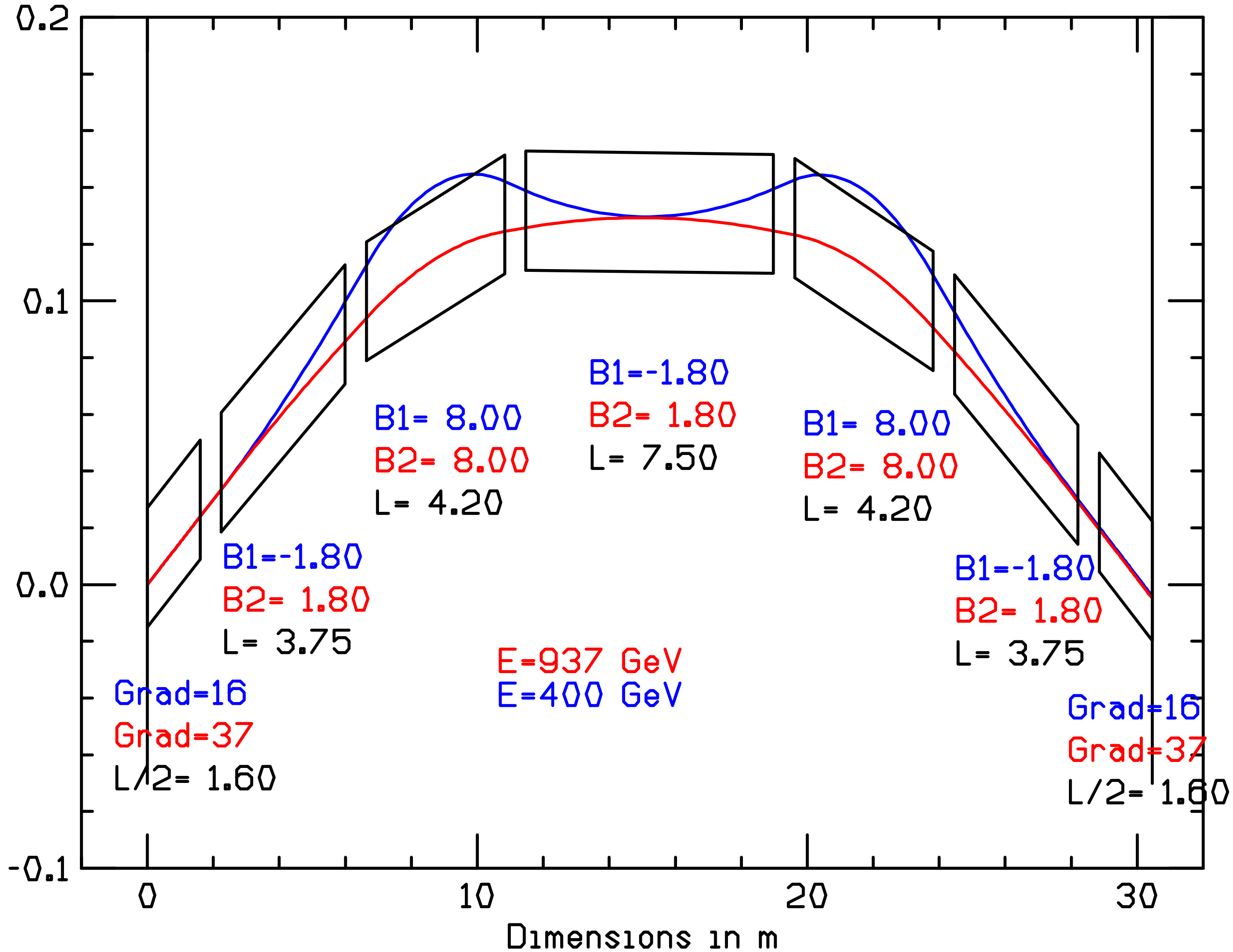
Example: 400 to 750 GeV, 550 Hz Hybrid Synchrotron

- 400 $\longrightarrow$ 750 GeV in 44 orbits (0.92 ms)   Radius = 1000m
  8 GV, 805 MHz Superconducting RF; Muon Survival = 92%
- Approximate the Fermilab Main Ring FODO Lattice
- 3.2m, 30T/m Quadrupoles, f = 150Hz
- 4.2m, 8T Fixed Superconducting Dipoles
- 3.75/7.5/3.75m, -1.8 $\longrightarrow$ +1.8T Dipoles, f = 550Hz
  5mm$\times$50mm$\times$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 $\longrightarrow$ 1200kW/ring



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

Particle Paths in a 400 to 750 GeV Hybrid Half Cell



- Dipoles oppose at injection, then act in unison at extraction. Edge focusing changes during the cycle. Can quads correct? Try to simulate focusing with OPTIM.

Grain Oriented 3% Silicon Steel EI Transformer Laminations

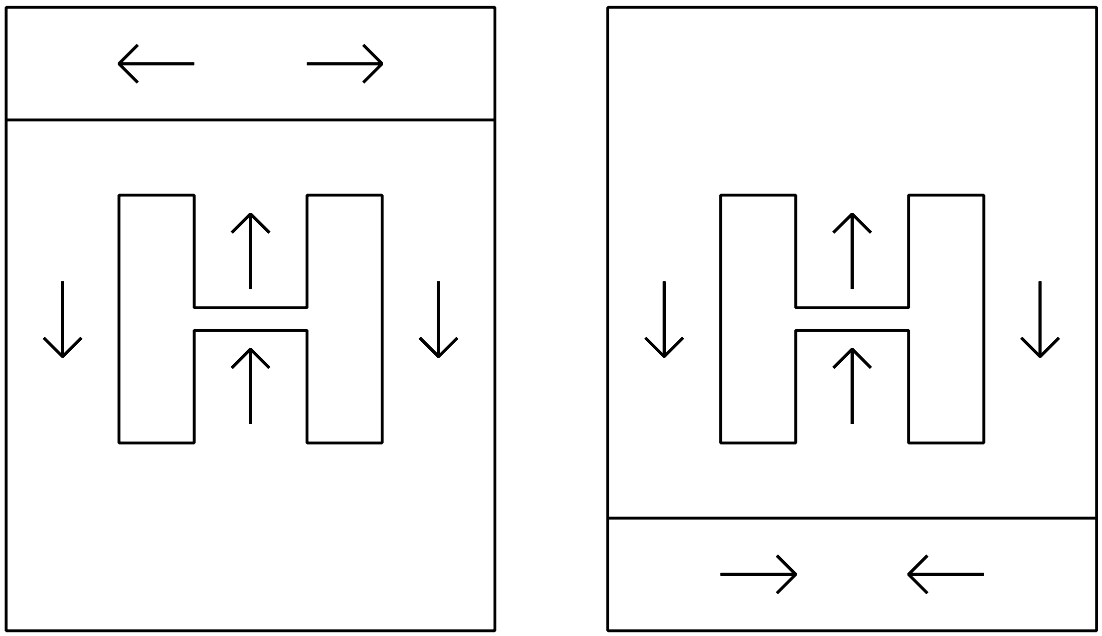


Table 1: Resistivity (ρ), coercivity (H_c), and permeability (μ) of steels. Higher resistivity lowers eddy current losses. Low coercivity minimizes hysteresis losses. Grain oriented 3% silicon steel has a far higher permeability parallel ($\|$) to than perpendicular ($\perp$) to its rolling direction 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		$4000\mu_0$	$1000\mu_0$	

Prototype 400 Hz, 1.8T, 100 mm Long Dipole Magnet

- Practice Dipole. We put a slot in a $20 "EI" transformer.
  And reached 1.6 Tesla in the slot with DC current.
  F. W. Bell 4048 Hall Probe good to 2% at up to 3000 Hz.

- Now assembling dipole with 100 x 46 x 1.5 mm gap
  Thomas-Skinner 3-phase transformer 11-mil "EI" laminations
  SuPer-Orthosil grain oriented 3% Si steel. $\mu = 3000\mu_0$ @ 1.8T
  We have now "slotted" all laminations with our wire EDM.
  Winding coils with 12 gauge copper magnet wire. D = 2 mm.
  Exploring stainless steel water cooling tubing as used at RAL

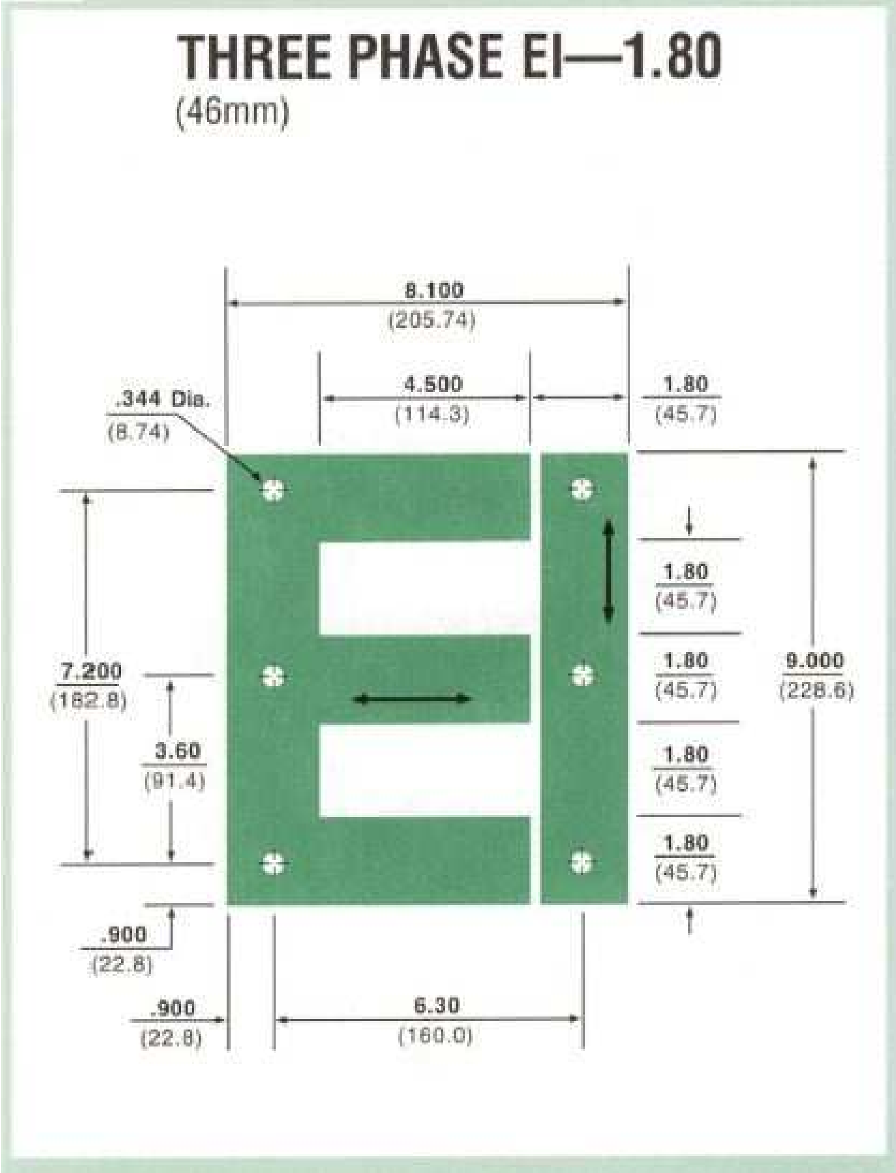
- LC circuit with polypropylene capacitor and IGBT switch.
  1.5×46×100 mm bore, N=40; $I = B\,h/\mu_0 N$ = 54A
  W $= \int \frac{B^2}{2\mu_0} d\tau = .5\,LI^2 = .5\,CV^2, f = 1/2\pi\sqrt{LC}$; V = 750V
  Polypropylene Capacitor: Cornell Dubilier 33μF, 1400V, 64A
  Fluke 415B High Voltage Supply for topping off capacitor.
  IGBT switch: Powerex CM600HX-24A, 1200V, 600A
  IGBT Gate Drive: Powerex VLA500-01 (5V pulse control)

Power Supply Parts and Costs

Part Description	Manufacturer	Cost
Polypropylene Capacitor: 33μF, 1400V, 64A	Cornell Dubilier	$51
1200V, 600A IGBT Switch	Powerex	$166
IGBT Gate Driver	Powerex	$43

- Vendor: Digi-Key.

"EI" Silicon Steel Lamination Set, $11/kilogram



- **A slot in the center leg to turns a transformer into a dipole.**

Summary

- A small prototype 400 Hz 1.8T dipole is in progress.
- Cool muons plus high injection γ due to low muon mass $\longrightarrow$ small magnets ramping with a few thousand volts. Capacitors: \$5/joule. Choke: \$3/joule. Switch: \$1000/MW
- Ameliorate eddy current and hysteresis losses in magnets. Thin grain oriented silicon steel laminations. Get to 1.8T! Stainless steel cooling tubes for water and thin copper wire.
- Exploit the 4% duty cycle. 25x lower losses than continuous operation. 96% of the time energy just sits in the capacitor banks.
- Muon survival is reasonable in a fast ramping synchrotron.
- Power can be go into SRF cavities fast enough (need 3x ILC)
- Goal: 1.5 TeV collider with moderate acceleration cost.
- Partial list of things to do
  Build on Alex Bogacz's OPTIM lattice simulation
  6mm diameter beam pipe impedance calculation ($Z_{||}$ and $Z_{\perp}$)
  1 not 2 rings if SRF frequency can shift 0.1% in a millisecond