

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

D. J. Summers<sup>†</sup>, L. M. Cremaldi, R. Godang<sup>‡</sup>, B. R. Kipapa, H. E. Rice, Univ. of Mississippi-Oxford, University, MS 38677, USA; R. B. Palmer, Brookhaven National Lab, Upton, NY 11973, USA

## 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  $T_c$  superconductors at 4K can carry large currents in the 35 to 50 T range [11]. Parametric resonances [12] and inverse

cyclotrons [13] are also being explored for cooling.

## 30 TO 400 GeV, 400 Hz RING

Historically synchrotrons have provided economical acceleration. Here we outline a relatively fast 400 Hz synchrotron [14] for muons, which live for 2.2  $\mu$ S. A 200  $\mu$ S (1250 Hz) pulsed wiggler has been built with vanadium permendur which is similar to the magnets required here. It achieved 2.1 T in a 4 mm gap with a 10 cm wavelength [15]. In eq. 1, the dipole vertical aperture,  $h$ , is calculated using an emittance of  $\epsilon_y = 25 \pi$  mm-mrad [5] and the Fermilab main ring FODO lattice parameter,  $\beta_y = 99$  m. Acceleration to 30 GeV might use dogbone recirculating LINACs and Fixed Field, Alternating Gradient (FFAG) rings [16].

$$h = 6\sigma = 6\sqrt{\frac{\epsilon_y \beta_y}{6\pi\beta\gamma}} = 6\sqrt{\frac{25\mu\text{m} \ 99\text{m}}{6\pi(1)(284)}} = 6\text{mm} \quad (1)$$

Eqs. 2 and 3 are now used to calculate the dipole voltages and amperages in Table 1.  $N$  is the number of turns in a coil. A simple LC circuit with an IGBT or SCR switch is used. The voltages are reasonable because the magnetic field volume is small and little energy is stored in the grain oriented 3% silicon steel (Table 2). Achieving good field quality in small aperture magnets needs to be explored.

$$W = \int \frac{B^2}{2\mu_0} dh dw dl = \frac{LI^2}{2} = \frac{CV^2}{2}, \quad f = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

$$I = B h / \mu_0 N, \quad V = 2\pi B f N w l \quad (3)$$

Using eq. 4, the skin depth,  $\delta$ , of steel with  $\mu = 3000\mu_0$  at 400 Hz is 0.3 mm. From eq. 5, only 2% of  $t = 0.28$  mm thick steel is lost due to shielding by eddy currents [17]. The skin depth for 18 n $\Omega$ -m copper at 400 Hz is 3.4 mm.

$$\delta = \sqrt{\rho / (\pi f \mu)} = \sqrt{470 \times 10^{-9} / (\pi 400 (3000 \mu_0))} \quad (4)$$

$$L/L_0 = \frac{(\delta/t) (\sinh(t/\delta) + \sin(t/\delta))}{\cosh(t/\delta) + \cos(t/\delta)} = 0.98 \quad (5)$$

Now we estimate the power consumption of the magnets. Laminations are laid out to minimize core losses (Fig. 1). 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,  $\int \mathbf{H} \cdot d\mathbf{B}$ , 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.  $I^2 R$  losses for four turns of

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<sup>†</sup> summers@phy.olemiss.edu

<sup>‡</sup> Also with University of South Alabama, Mobile, AL 36688, USA

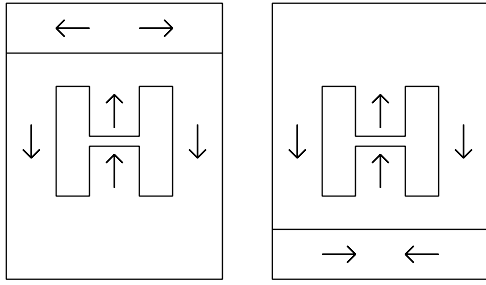


Figure 1: Alternating dipole laminations of grain oriented silicon steel. The arrows show the  $\mathbf{B}$  field direction and the grain direction. The layout resembles an “EF” transformer.

$1 \times 2$  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 6 kW. So multiplying 40 kW per dipole times 800 dipoles and adding 6% for quadrupoles, one gets 34000 kW. But the magnets are only on for half of a 400 Hz cycle, 13 times per second, for a duty cycle of 1.6% and a total power consumption of 540 kW. A choke and diode are used to do a leisurely reset of the polypropylene capacitor bank polarity for each new cycle.

$$\text{Core Loss} = 4.38 \times 10^{-4} f^{1.67} B^{1.87} = 23 \text{ W/kg} \quad (6)$$

$$P = [\text{Volume}] \frac{(2\pi f B w)^2}{24\rho} = 15 \text{ W/kg} \quad (7)$$

## 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

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, $L$	$\mu\text{H}$	630	760	380
Capacitance, $C$	$\mu\text{F}$	250	110	220
Voltage, $V$	V	3400	4700	4700
Power Consumption	kW	0.6	1.4	2.8

Table 2: Resistivity ( $\rho$ ), coercivity ( $H_c$ ), and permeability ( $\mu/\mu_0$ ) 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 [20] and permits minimal energy ( $B^2/2\mu$ ) storage in the yoke, as compared to low carbon steel [21] at 1.8 T.

Steel	$\rho(\text{n}\Omega\text{-m})$	$H_c(\text{A/m})$	1.0 T	1.5 T	1.8 T
.0025% Carbon	100	80	4400	1700	240
Oriented ( $\parallel$ ) Si	470	8	40000	30000	3000
Oriented ( $\perp$ ) Si	470		4000	1000	

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 7.5 m 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.

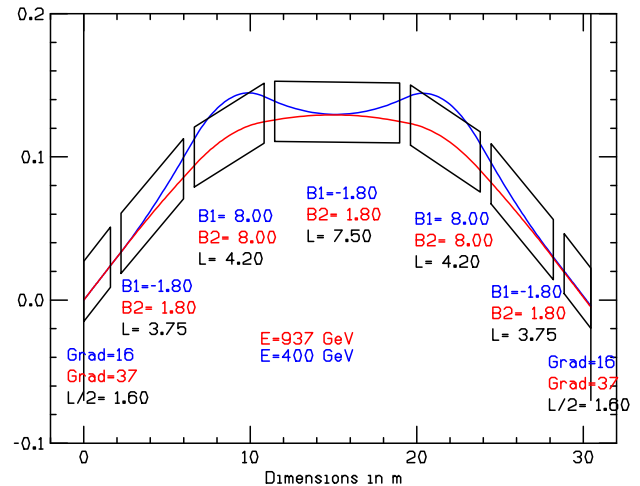


Figure 2: The 30.45 m long FODO lattice half cell consists of half of two 3.2 m ramping quadrupoles, two fixed, 4.2 m 8 T superconducting dipoles, and two 3.75 m plus one 7.5 m ramping dipoles. The ramping dipoles, which go from -1.8 T to 1.8 T at 550 Hz, oppose the superconducting dipoles at 400 GeV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

## 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.

Acceleration 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 [24] 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  $\frac{1}{18^2}$ .

$$d\tau/\tau = (1/\gamma_t^2 - 1/\gamma^2)(dp/p) = \eta(dp/p) \quad (8)$$

$$\nu_s = \sqrt{\frac{h\eta(\text{GV}) \cos \phi_s}{-2\pi\beta^2 E_s}} = \sqrt{\frac{27200(\frac{1}{18^2})14(.1)}{2\pi(1^2)(30)}} = .8 \quad (9)$$

Muon bunches must stay in phase with the RF. The muon speed increase from  $\beta = 0.99999380$  to  $\beta = 0.99999996$  in the first ring can be corrected by increasing the orbital radius by 6 mm during acceleration. The one in 40000 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.  $0.072 = (0.025(30)/m_{\mu^\pm})(0.01)$ , where  $m_{\mu^\pm} = 0.106 \text{ GeV}/c^2$ . 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. This is 1% of the federal limit, 10% of the Fermilab offsite limit, and equivalent to eating two bananas a week. Note that the Fox River is 5000 m away from and 4 m below the Tevatron, so neutrinos at 2700 m are still underground.

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

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D. J. Summers, L. M. Cremaldi, R. Godang,  
B. R. Kipapa, H. E. Rice

University of Mississippi-Oxford

R. B. Palmer

Brookhaven National Laboratory

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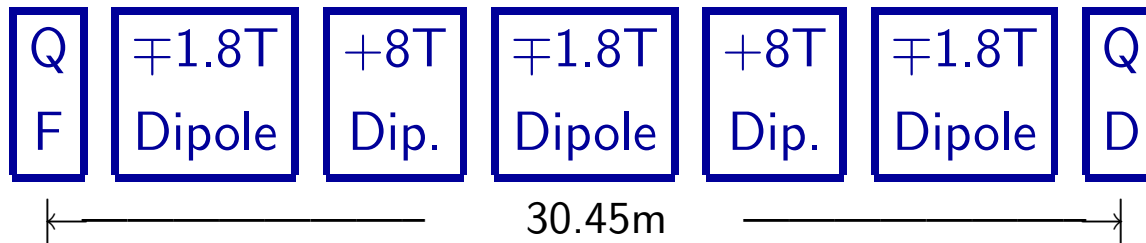


## 30 to 400 GeV, 400 Hz Synchrotron

- 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

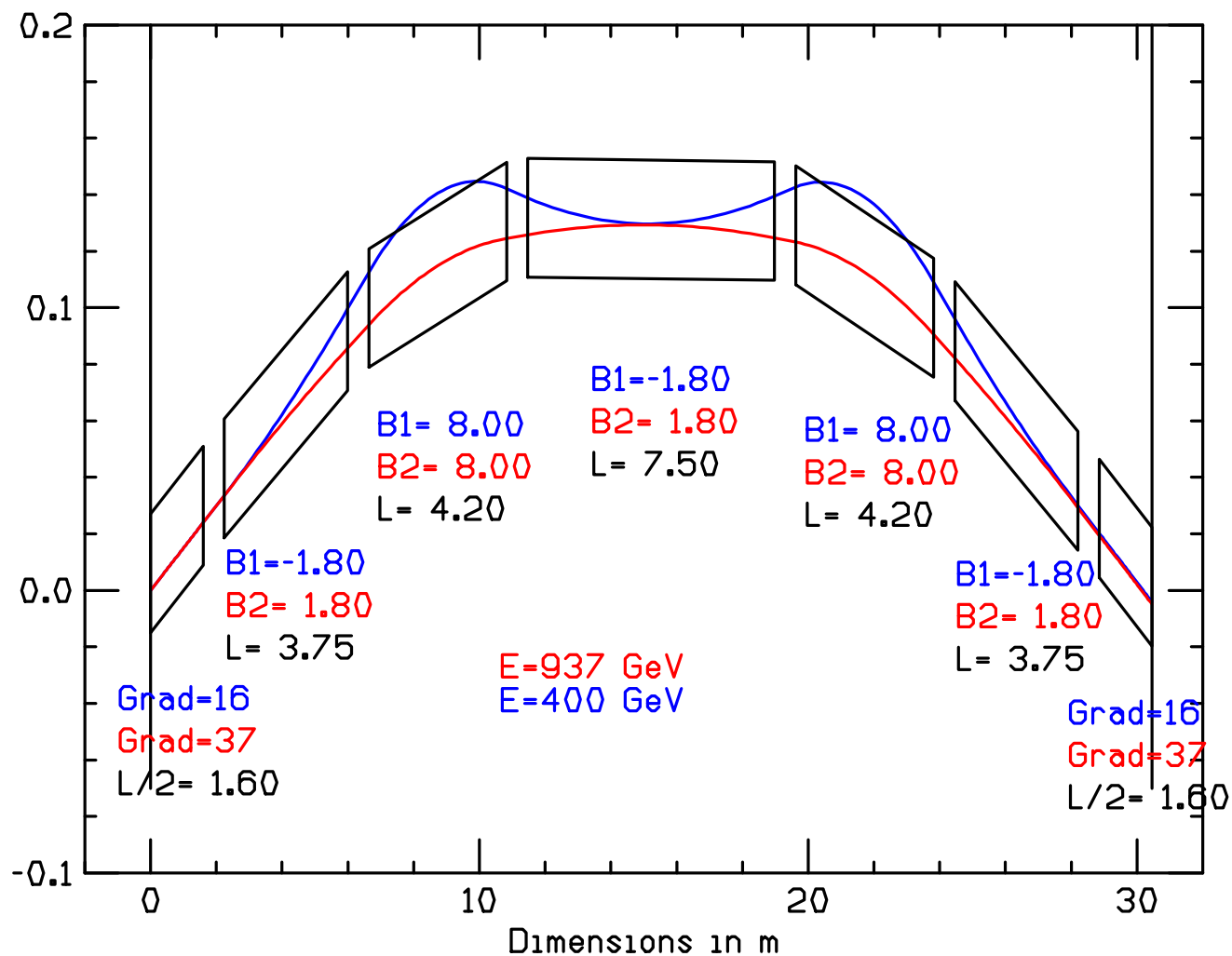
## 400 to 750 GeV, 550 Hz Hybrid Synchrotron

- 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, $\ell$	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, $L$	$\mu\text{H}$	630	760	380
Capacitance, $C$	$\mu\text{F}$	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

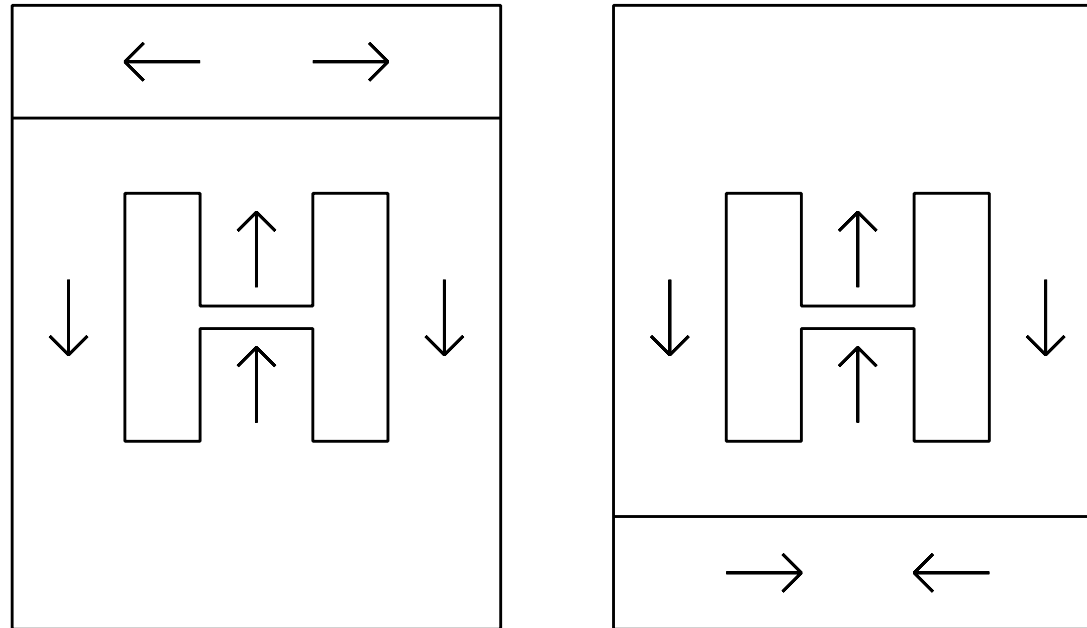


Table 1: Resistivity ( $\rho$ ), coercivity ( $H_c$ ), and permeability ( $\mu$ ) of steels. Higher resistivity lowers eddy current losses. Low coercivity minimizes hysteresis losses. Grain oriented 3% silicon steel has a far higher permeability parallel ( $\parallel$ ) to than perpendicular ( $\perp$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

Steel	$\rho$ (n $\Omega$ -m)	$H_c$ (A/m)	$\mu$ (1.0 T)	$\mu$ (1.5 T)	$\mu$ (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
- $\nu$  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, head/tail...
- Wakefields with 8% beam loading.
- Momentum compaction of the 400 to 750 GeV hybrid ring.
- Momentum acceptance and magnet apertures.
- Design complete lattices.
- Multipole B fields from eddy currents in the pole faces.
- Magnetic field quality with small aperture magnets.
- Forces on fast ramping magnet pole faces.
- Build 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  $\gamma$  lead to 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

