Rapid Cycling Acceleration

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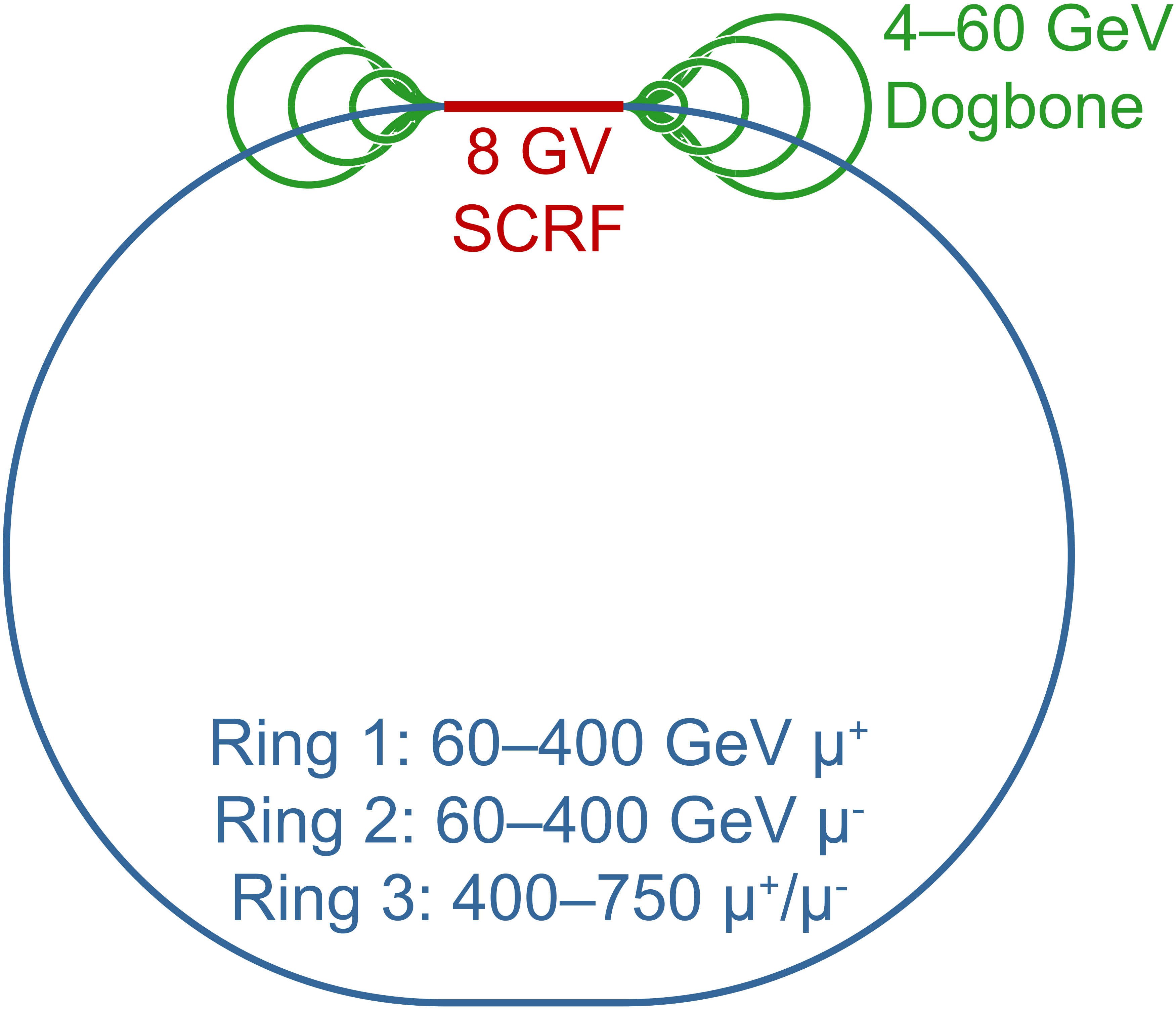
Muon Technical Advisory Committee (MuTAC) Review

Accelerate muons to 750 GeV with one 8 GV Linac

- **Components:**
  Low energy cool muon source.
  One 8 GV Linac. RF is not dispersed around the rings.
  One Dogbone with 8 passes.
  Two 1000 m radius synchrotrons with rapid cycling magnets.
  One 1000 m radius synchrotron with interleaved dipoles
  (Fixed superconducting dipoles and rapid cycling dipoles).

- **For a sketch of acceleration with RF dispersed around rings see: D. J. Summers** *et al.*, **PAC07, axXiv:0707.0302**


4–60 GeV
Dogbone
8 GV
SCRF
Ring 1: 60–400 GeV μ+
Ring 2: 60–400 GeV μ-
Ring 3: 400–750 μ+/μ-

Superconducting RF Frequency: 805 MHz or 1300 MHz?

- **Red Flag:** $2 \times 10^{12}\,\mu$ extract 8% energy w/1300 MHz cavity.
  Estimate longitudinal wakefields. Ref: V. Yakolev et al.
  $k(||) = [N(\Gamma(1/4)Z_0 c)/(\pi^{5/2}a)]\sqrt{g/\sigma}$ = loss factor
  N = 9 cells/cavity, a = 35 mm, g = 115 mm
  $\Gamma(1/4) = 3.63$, $Z_0 = 377\Omega$, σ = bunch length = 10 mm
  $k(||)$ = 5.1 V/pC/cavity, $2 \times 10^{12}\mu$ = 320 nC
  $k(||)$ = 1.6 MV/cavity and a cavity is a meter long...
  This can make the bunch length increase.
- What klystrons are available at 805 MHz? Ask S. Henderson.
  SNS uses 750 kW, 8% duty cycle costing \$170k each
  13% more per MW than 10 MW, 1300 MHz ILC klystrons.
  But SNS allows 8% duty factor and ILC only has 2%!
- Work out power needed to run an 8 GV Linac.
  Consider $2 \times 10^{12}\mu^+$ and $2 \times 10^{12}\mu^-$ in a 1000 m radius ring.
  320 750 kW klystrons will keep up. Cost: \$54M for klystrons.
- Do 8 dogbone passes in the 805 MHz, 8GV Linac.
  Get up to 60 GeV with very high muon survival.
  Count on stored cavity energy for these 8 passes.

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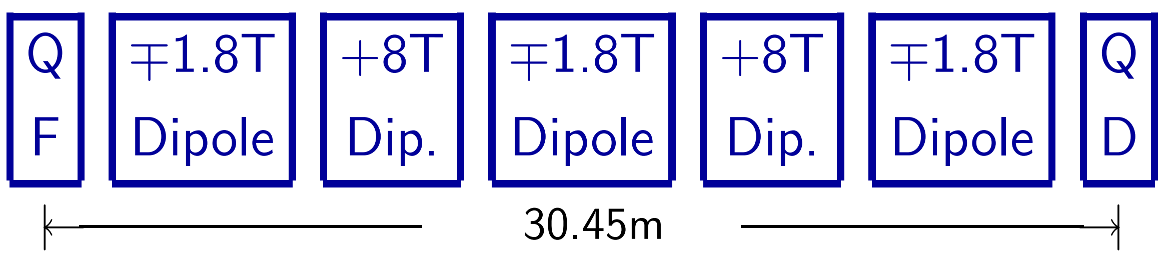
60 to 400 GeV, 260 Hz Synchrotron

- 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.
  6×30mm 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

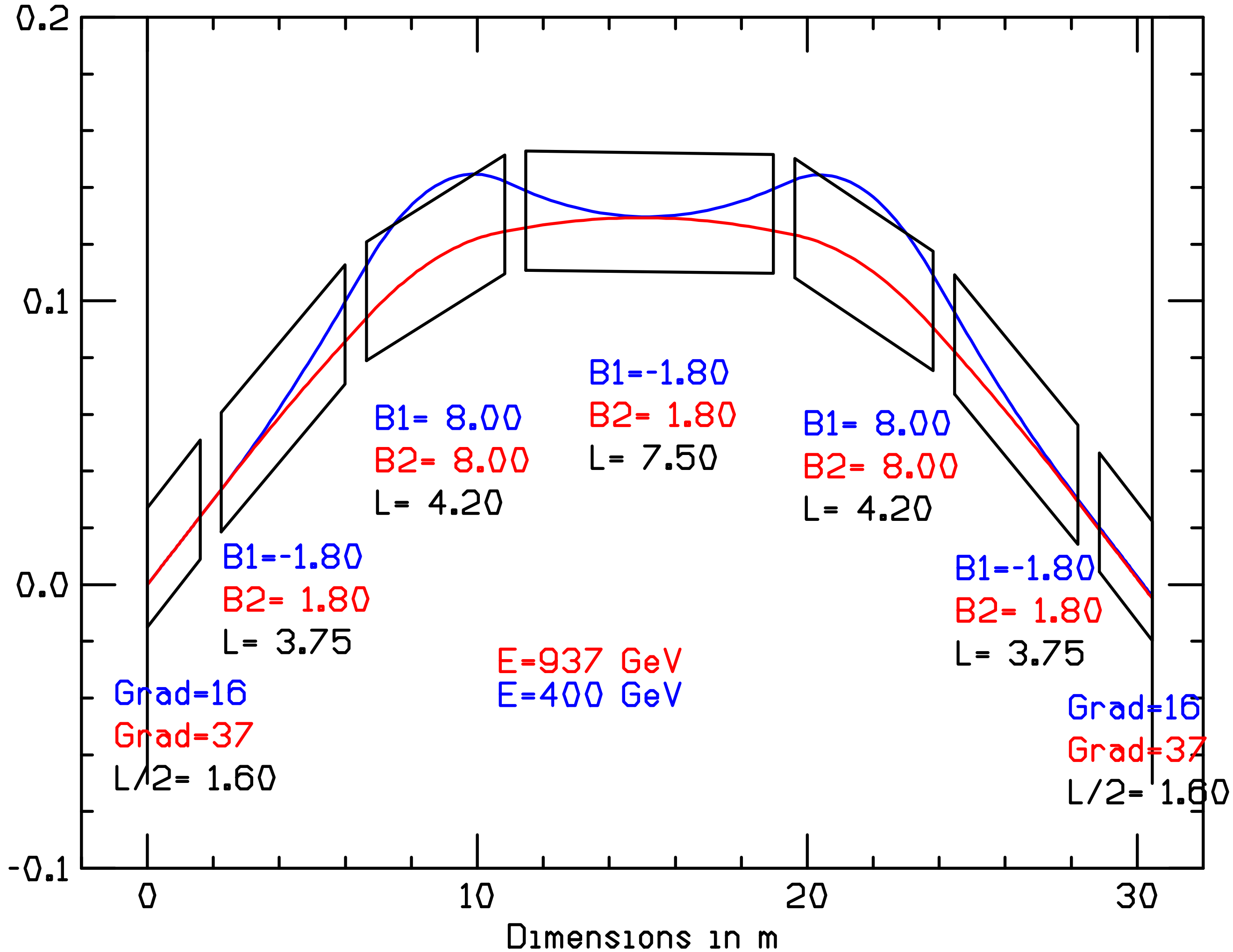
400 to 750 GeV, 550 Hz Hybrid Synchrotron

- 400 → 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 → +1.8T Dipoles, f = 550Hz
  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. Edge focusing changes during the cycle. Can quads correct? Try to simulate focusing with OPTIM.**

Grain Oriented 3% Silicon Steel EI Transformer Laminations

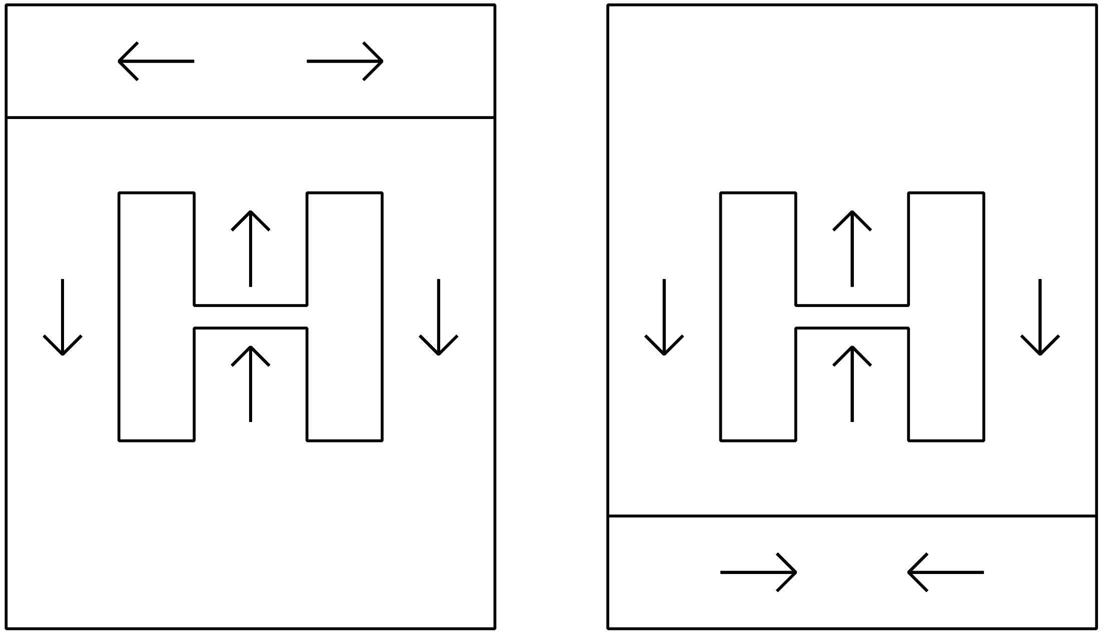


Table 1: Resistivity (ρ), coercivity (H_c), and permeability (μ) of steels. Higher resistivity lowers eddy current losses. Low coercivity minimizes hysteresis losses. Grain oriented 3% silicon steel has a far higher permeability parallel ($\|$) to than perpendicular ($\perp$) to its rolling direction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

Synchrotron Oscillations per Orbit for 60 to 400 GeV Ring

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

$\gamma_t = 18$, **like the main ring.** $\gamma(60\,\mathrm{GeV}) = 570$

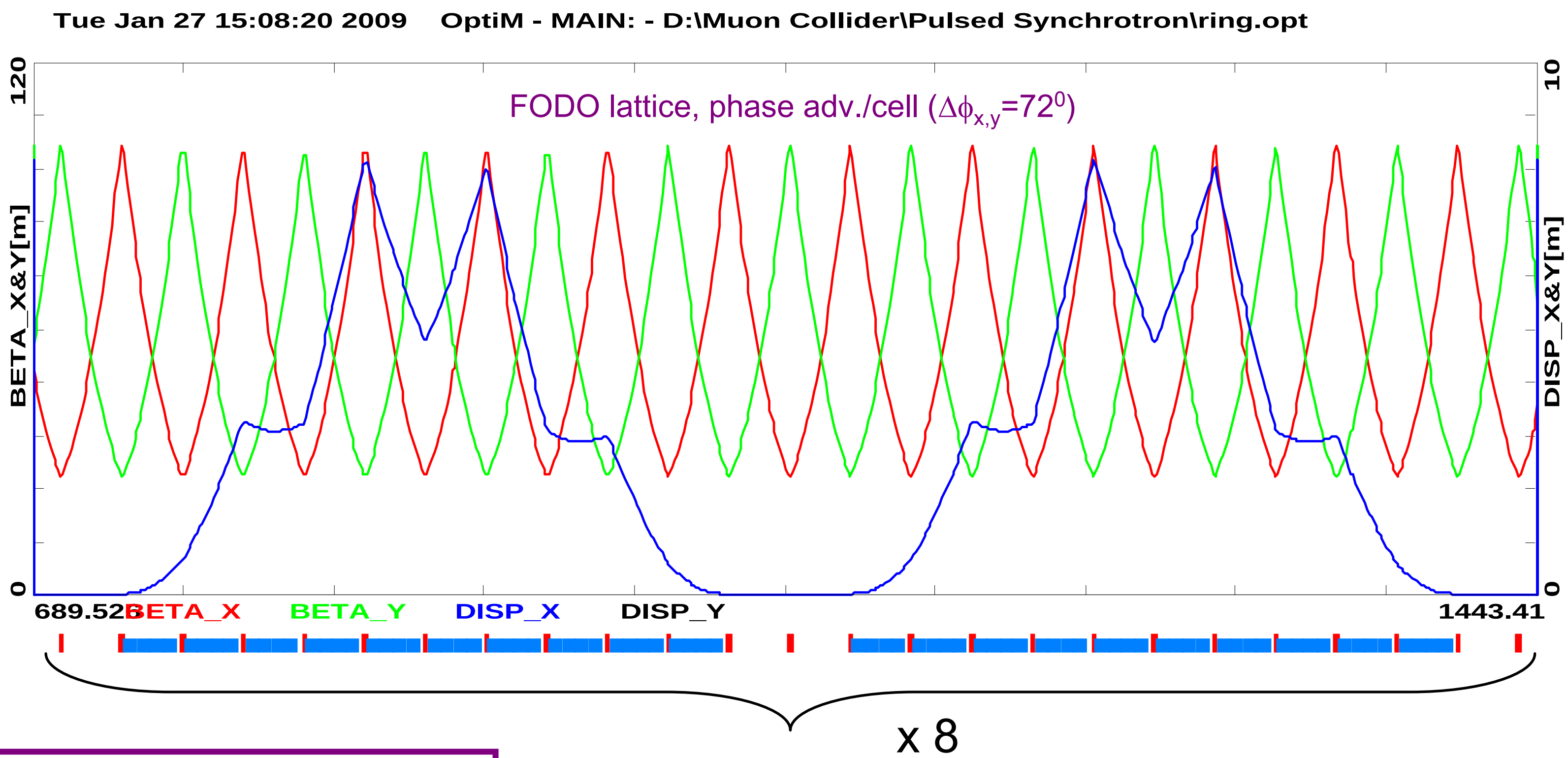
$$h = 2\pi \times 1000\mathrm{m} \times 805\,\mathrm{MHz}/c = 16800$$

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

$$\nu_s = \sqrt{-\frac{16800\times 1/18^2}{2\pi(1^2)(60\times 10^9)}\,(8\,\mathrm{GV})(-0.1)} = 0.3$$

- **Need 0.15 not 0.3 for longitudinal stability.**
  Consider doubling the transition gamma to 36.

Main Ring Lattice at 30 GeV



magnet	L[cm]	B[kG]
Dipole	627	1.57

magnet	L[cm]	G[kG/cm]
F quad	169	0.2337
D quad	169	-0.2337

momentum compaction

$$M_{56} = -\int \frac{D_x}{\rho}\, ds = -D_x^{dip} \int d\left(\frac{s}{\rho}\right) = -D_x^{dip} \int d\theta_{rad} = -D_x^{dip} \times \theta_{rad}^{tot} = -3.3m \times 2\pi = 21m$$

$$\alpha = -{M_{56}}/{L} = \frac{2\pi \times 3.3\ m}{5847\ m} = 3.6 \times 10^{-3}$$

Prototype 550 Hz, 1.8T, 30 cm Long Dipole Magnet

- 3% grain oriented steel laminations
  Vendor: T C Metal Slitting & Shearing, Los Angeles, CA
  Cut laminations with Sodick AQ325L Wire EDM

- Stainless steel cooling tubes for water and thin copper wire.
  Epoxy impregnate the coils.
  Conductor in use at ISIS. Made by Trench Ltd.

- LC circuit. Polypropylene capacitor bank. IGBT switch.
  Fluke 415B High Voltage Supply for topping off capacitors.
  5mm×50mm×0.3m bore, N=10; $I = B\,h/\mu_0 N$ = 720A
  W = $\int \frac{B^2}{2\mu_0} d\tau = .5\,LI^2 = .5\,CV^2$, $f = 1/2\pi\sqrt{LC}$; V = 860V

- F. W. Bell 4048 Hall Probe to measure 1.8T.
  Good to 2% at up to 3000 Hz.

- Have applied for QuarkNet funds to build in July 2009.

Summary

- 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.
  For loss calculations see: D. J. Summers, physics/0108001
  Conductor in use for new ISIS choke. Made by Trench Ltd.

- 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 cycling synchrotron.

- Goal: 1.5 TeV collider with one 8GV, 805 MHz Linac.

Fast Cycling Acceleration: R&D Plan

- Study ring lattices and apertures
  - Smaller apertures: lower ramping voltages
- Build short prototype fast ramping dipole and power supply
- Build full length prototype fast ramping dipole and power supply