A Pulsed Muon Synchrotron for Acceleration at a Neutrino Factory

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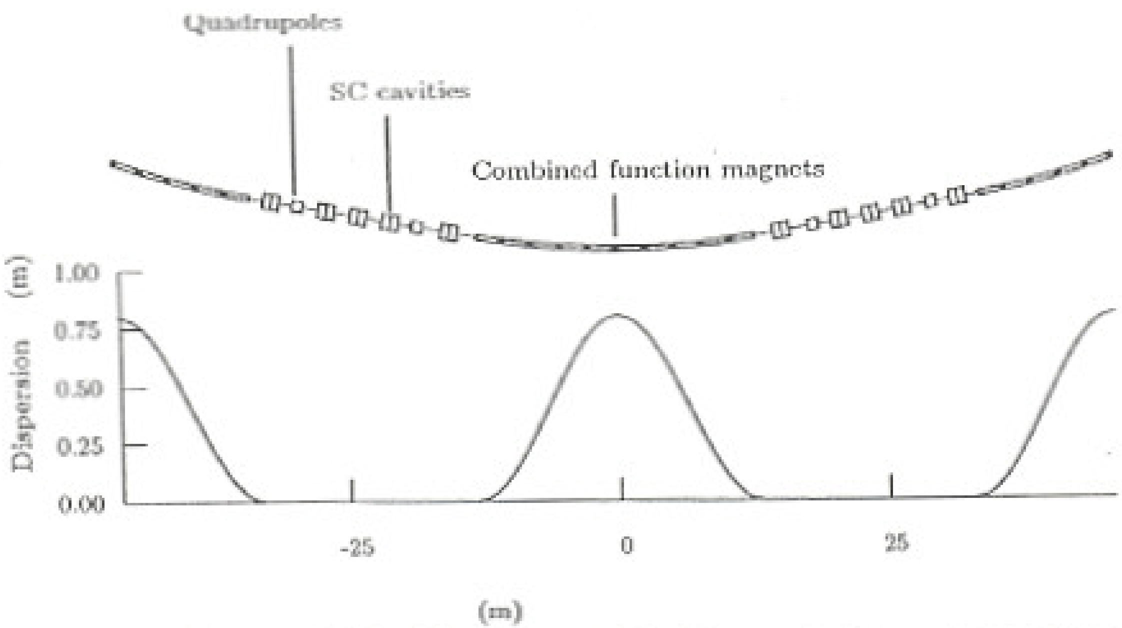


Figure 1. Combined function magnets bend the muons in the arcs. Superconducting RF cavities accelerate muons in the straight sections. Two quadrupoles per straight section provide focusing. The straight sections are dispersion free.

Table 1. Combined function magnet cell parameters. Five cells make up an a[r]
18 arcs form the ring.

Cell length	m	5.28
Combined Dipole length	m	2.24
Combined Dipole $B_{central}$	T	0.9
Combined Dipole Gradient	T/m	20.2
Pure Dipole Length	m	0.4
Pure Dipole B	T	1.8
Momentum	GeV/c	20
Phase advance/cell	deg	72
beta max	m	8.1
Dispersion max	m	0.392
Normalized Trans. Acceptance	π mm rad	4

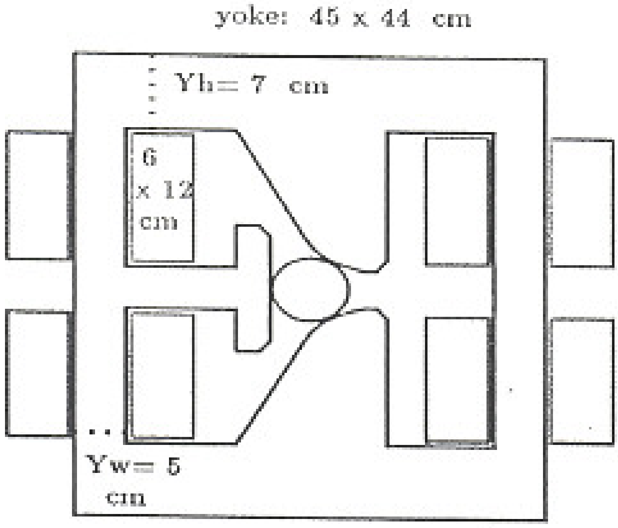
Table 2. Straight section lattice parameters. There are two quadrapoles per straigh

ϕ	$L_{cell}/2$	L_{quad}	dB/dx	a	β_{max}	σ_{max}	B_{pole}	U_{mag}/quad
77^0	11 m	1 m	7.54 T/m	5.8 cm	36.6 m	.0195 m	0.44 T	$\approx$ 3000 J

Superconducting RF parameters.

Frequency	201	MHz
Gap	.75	m
Gradient	15	MV/m
Stored Energy	900	Joules
Muons per train	5×10^{12}	
Orbits (4 to 20 GeV/c)	12	
No. of RF Cavities	160	
RF Total	1800	MV
ΔU_{beam}	110	Joules
Energy Loading	.082	
Voltage Drop	.041	
Muon Acceleration Time	37	μsec
Muon Survival	.83	

COMBINED FUNCTION MAGNETS

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4    --> 20 GeV
19%  --> 95% B Field
11   --> 72 degrees
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61 degrees in 37 uSEC --> 4600 Hz

18 26.5 meter magnets
gradient changes inside the magnet
number of ends are minimized
100 kJoule stored in each

$$B = \frac{\mu_0 N I}{h} \to I = \frac{Bh}{\mu_0 N} = 52\,\mathrm{kA}; \qquad W = .5\,L\,I^2 \to L = 2W/I^2 = 80\,\mu\mathrm{H}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \to C = \frac{1}{L\,(2\pi f)^2} = 15\,\mu\mathrm{F}; \; W = .5\,C\,V^2 \to V = \sqrt{2W/C} = 120\,\mathrm{kV}$$

120 kV is big
center tap the SCR stacks --> +-60 kV

Bring coils out side slots;
leaving pole faces continuous

COPPER LOSSES = 8 + 170 = 178 kilowatts

Four 5 cm square copper conductors each 5300 cm long have a total power dissipation of 130 kilowatts/magnet. Eighteen magnets give a total loss of 2340 kilowatts. But the neutrino factory runs at 30 Hz. Thirty half cycles of 109 μsec per second gives a duty factor of 300 and a total $I^2 R$ loss of 8000 watts. Muons are orbited in opposite directions on alternate cycles. If this proves too cumbersome, the duty cycle factor could be lowered to 150.

$$R = \frac{5300\ (1.8\,\mu\Omega\text{-cm})}{(4)\,(5^2)} = 95\,\mu\Omega; \qquad P = I^2 R \int_0^{2\pi} \cos^2(\theta)\, d\theta = 130\,000 \text{ w/magnet}$$

Find the skin depth of copper at 4600 Hz to see if .25 mm (30 gauge) wire is useable.

$$\text{Skin Depth} = \delta = \sqrt{\rho \,/\, \pi\, f\, \mu_0} = \sqrt{1.8 \times 10^{-8} \,/\, \pi\, 4600\, \mu_0} = 0.97\text{mm}$$

Now calculate the dissipation due to eddy currents in this .25 mm wide conductor, which will consist of transposed strands to reduce this loss [22, 12]. To get an idea, take the maximum B-field during a cycle to be that generated by a 0.025m radius conductor carrying 26000 amps. The eddy current loss in a rectangular conductor made of transposed square wires .25 mm wide (sometimes called Litz wire [23])

with a perpendicular magnetic field is as follows. The width of the wire is w and $B = \mu_0\, I/2\pi r = 0.2$ Tesla.

$$P = [\text{Volume}]\frac{(2\pi\, f\, B\, w)^2}{24\rho} = [4\ .05^2\ 53]\ \frac{(2\pi\ 4600\ .2\ .00025)^2}{(24)\, 1.8 \times 10^{-8}} = 2800 \text{ kilowatts} \qquad (7)$$

Multiply by 18 magnets and divide by a duty factor of 300 to get an eddy current loss in the copper of 170 kilowatts. Stainless steel water cooling tubes will dissipate a similar amount of power [7]. Alloy titanium cooling tubes would dissipate less.

IRON EDDY CURRENT LOSSES = 350 kilowatts

Do the eddy current losses [22] in the 100 micron thick iron laminations. Take a quarter meter square area, a 26.5 meter length, and an average field of 1.1 Tesla.

$$P = [\text{Vol}]\frac{(2\pi\, f\, B\, t)^2}{24\rho} = [(26.5)\ (.5^2)]\ \frac{(2\pi\ 2600\ 1.1\ .0001)^2}{(24)\,47\times 10^{-8}} = 5900\ \text{kw}$$

Multiply by 18 magnets and divide by a duty factor of 300 to get an eddy current loss in the iron laminations of 350 kilowatts or 700 watts/m of magnet. So the iron will need some cooling. The ring only ramps 30 time per second, so the $\int \mathbf{H}{\cdot}d\mathbf{B}$ hysteresis losses will be low, even more so because of the low coercive force, H_c, of grain oriented silicon steel.

Table 4. Approximate permeabilities of soft magnetic materials. The permeability is $B/\mu_0 H$. Grain oriented silicon steel has a much higher permeability parallel (‖) to its rolling direction than in the perpendicular (⊥) direction [16, 17].

Material	1.0 Tesla	1.5 Tesla	1.8 Tesla
1008 Steel	3000	2000	200
Grain Oriented (‖)	40000	30000	3000
Grain Oriented (⊥)	4000	1000	
NKK Super E-Core	20000	300	50
Metglas 2605SA1	300000	10000	1

The skin depth [14] of a 100 micron thick lamination is given by

$$\text{Skin Depth} = \delta = \sqrt{\rho\,/\,\pi\, f\, \mu} = \sqrt{47\times 10^{-8}\,/\,\pi\, 4600\ 1000\ \mu_0} = 160\mu\text{m}$$

Take $\mu = 1000\mu_0$ as a limit on magnetic saturation and hence energy storage in the yoke. Next estimate the fraction of the inductance of the yoke that remains after eddy currents shield the laminations [15]. The lamination thickness is t.

$$L/L_0 = (\delta/t)\,(\sinh(t/\delta) + \sin(t/\delta))\,/\,(\cosh(t/\delta) + \cos(t/\delta)) = 0.995$$

A PULSED SYNCHROTRON FOR MUON ACCELERATION AT A NEUTRINO FACTORY

- Historically synchrotrons have provided economical acceleration.
- Accelerate muons from 4 to 20 GeV/c in a 917m ring.
- 12 orbits in 37 microseconds; 83% muon survival.
- 1.8 GV of 201 MHz, 15 MV/m Superconducting RF (11 MV/m already achieved).
- 18 magnets with ±20 T/m alternating gradients.
- 180 ±6000 Volt, 52000 Amp, 4600 Hz LC Circuits.
- 100 micron thick, grain oriented silicon steel laminations.
- Tiny duty cycle, only accelerates 30 times per second.
- Under a megawatt of eddy current losses for the ring.
- See: D. Summers et al., PAC2003, hep-ex/0305070; R. Palmer et al., www-mucool.fnal.gov/mcnotes/public/pdf/muc0259/muc0259.pdf.