

A 233 km Tunnel for Lepton and Hadron Colliders

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Abstract. A decade ago, a cost analysis was conducted to bore a 233 km circumference Very Large Hadron Collider (VLHC) tunnel passing through Fermilab. Here we outline implementations of e^+e^- , $p\bar{p}$, and $\mu^+\mu^-$ collider rings in this tunnel using recent technological innovations. The 240 and 500 GeV e^+e^- colliders employ Crab Waist Crossings, ultra low emittance damped bunches, short vertical IP focal lengths, superconducting RF, and low coercivity, grain oriented silicon steel/concrete dipoles. Some details are also provided for a high luminosity 240 GeV e^+e^- collider and 1.75 TeV muon accelerator in a Fermilab site filler tunnel. The 40 TeV $p\bar{p}$ collider uses the high intensity Fermilab \bar{p} source, exploits high cross sections for $p\bar{p}$ production of high mass states, and uses 2 Tesla ultra low carbon steel/YBCO superconducting magnets run with liquid neon. The 35 TeV muon ring ramps the 2 Tesla superconducting magnets at 9 Hz every 0.4 seconds, uses 250 GV of superconducting RF to accelerate muons from 1.75 to 17.5 TeV in 63 orbits with 71% survival, and mitigates neutrino radiation with phase shifting, roller coaster motion in a FODO lattice.

Keywords: electron positron collider, proton antiproton collider, muon collider

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INTRODUCTION

In 2001, a cost estimate [1] for boring a 233 km circumference tunnel in northern Illinois was made for the proposed Very Large Hadron Collider (VLHC [2]). Level 12 foot and 16 foot diameter tunnels were estimated to cost \$2.55 billion and \$2.94 billion, respectively. Included were a shotcrete lined tunnel, caverns, vertical access shafts, and 25% contingency. Since then inflation has increased prices, but more automation has been added to tunneling in pulling tunnel boring machines forward and in placing rock stabilization bolts [3]. Here we outline how such a tunnel might be used by lepton and hadron colliders over many years. We examine circular 240 and 500 GeV e^+e^- colliders [3, 4], a 40 TeV $p\bar{p}$ collider, and a 35 TeV $\mu^+\mu^-$ collider [3, 5]. The recent observation of a 126 GeV/ c^2 boson [6] provides motivation for 240 GeV $e^+e^- \rightarrow Z^0h^0$ [7] and 126 GeV $\mu^+\mu^- \rightarrow h^0$ [8] colliders .

240 and 500 GeV e^+e^- Ring Colliders

A crab waist crossing [9] as developed for the next generation of B factories is employed to extend the energy of circular e^+e^- colliders beyond LEP. Low emittance bunches from precision damping rings for the proposed International Linear Collider (ILC [10]) are used as well the short vertical focal length ILC collision region optics.

A beam crossing angle is introduced to allow short focal length, β_y^* , collision optics. The horizontal emittance of the beam is driven by quantum fluctuations in synchrotron radiation [11]. The vertical emittance is lowered until the tune-tune shift limit, ξ_y , is reached. The crossing angle independent luminosity is given by [3, 9]:

$$L = 2.167 \times 10^{34} E(\text{GeV}) I(\text{Amps}) \xi_y / \beta_y^* (\text{cm}). \quad (1)$$

Preliminary parameters for three high energy, high luminosity machines are given in Table 1. One of the 240 GeV machines fits in a Fermilab site filler ring. A 120 mm bore Nb₃Sn quadrupole [12] may be useful in getting the beam to fit into the final focus.

However, some beam particles are lost due to beamstrahlung tails when the momentum changes so much that the ring and Interaction Point (IP) can no longer transport the particles. Equation 2 shown below is used to calculate luminosities under these conditions [13]. L is luminosity, h is the hourglass factor, η is momentum acceptance, ξ_y is the vertical beam-beam tune shift, E_0 is the beam energy, ϵ_y is the vertical geometric emittance, P is the synchrotron radiation power for both beams, R is the ring radius, and R_b is the bending radius. To still attain reasonable luminosities we use a large ring, increase the normal ring/IP $\eta = 1\%$ momentum acceptance to $\eta = 3\%$ gaining a factor of

TABLE 1. Strawman parameters for three e^+e^- colliders which exploit the crab waist crossing [9].

Parameter Name (Units)				Formulae
e^+, e^- energy (GeV)	120, 120	120, 120	250, 250	
Ring Circumference: C (km)	15	233	233	
Ring Radius: R (meters)	2400	37, 100	37, 100	$R = C / 2\pi$
Bending radius: ρ (meters)	1900	29, 000	29, 000	
Relativistic γ	235, 000	235, 000	489, 000	$E / m = (120, 250) / 0.000511$
Collision frequency: f_0 (kHz)	65.1	978	52.8	$(\text{Bunches} / \text{beam}) c / 2\pi R$
Half crossing angle: θ (mr)	34	34	34	
Bunch length (mm)	6.67	6.67	6.67	
σ_x, σ_y IP beam size (μm)	8.5, 0.0244	8.5, 0.0244	8.5, 0.0115	$\sigma = \sqrt{\varepsilon\beta^*}$
IP β_x^*, β_y^* (cm)	2, 0.06	2, 0.06	2, 0.06	
Geometric emittance: ε_x (nm)	3.6	3.6	3.6	$\sim (\text{Lattice Type}) \gamma^2 (\ell_{\text{half cell}} / \rho)^3$ [11]
Geometric emittance: ε_y (nm)	0.00099	0.00099	0.00022	
Norm. emit.: $\varepsilon_x^N, \varepsilon_y^N$ (mm-mrad)	846, 0.235	846, 0.235	1760, 0.108	$\varepsilon^N = \gamma\varepsilon$
Beam-beam tune shift: ξ_x	0.0014	0.0014	0.0007	$r_e N / 4\pi\varepsilon_x^N \approx 2r_e N\beta_x^* / (\pi\gamma\sigma_x^2\theta^2)$ [9]
Beam-beam tune shift: ξ_y	0.20	0.20	0.23 [4]	$r_e N / 4\pi\varepsilon_y^N \approx r_e N\beta_y^* / (2\pi\gamma\sigma_y\sigma_x\theta)$ [9]
No. of bunches / beam	3	700	41	
Particles / bunch [4]	4.85×10^{11}	4.85×10^{11}	4.85×10^{11}	$\delta N_2 = 2N_2\sigma_x / (\theta\sigma_z) = 3.63 \times 10^{10}$ [9]
Dipole field (Tesla)	0.21	0.014	0.029	$B = (120, 250) / .3\rho$ (meters)
Current / beam (Amps)	0.00505	0.07	0.0041	1.6×10^{-19} (particles/beam) $c / 2\pi R$
E loss / orbit (GeV)	9.7	0.63	11.9	$8.85 \times 10^{-5} E^4 (\text{GeV}) / \rho (\text{m})$
Synch rad power (MW/beam)	49	44	49	$8.85 \times 10^{-2} E^4 (\text{GeV}) I (\text{amps}) / \rho (\text{m})$
Total synch wall power (MW)	198	176	198	
IP $\beta_x^{\text{max}}, \beta_y^{\text{max}}$ (km)	40, 250	40, 250	40, 250	
IP $\sigma_x^{\text{max}}, \sigma_y^{\text{max}}$ (mm)	12, 0.5	12, 0.5	12, 0.23	$\sigma^{\text{max}} = \sqrt{\varepsilon\beta^{\text{max}}}$
IP Sextupole Strength (1/m) ²	0.0007	0.0007	0.0007	$K_2 = [1 / (2\theta\beta_y^{\text{max}}\beta_x^*)] \sqrt{\beta_x^* / \beta_x^{\text{max}}}$ [9]
Luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	4.4×10^{34}	6.1×10^{35}	7.6×10^{34}	$L = N_1 (\delta N_2) f_0 / (4\pi\sigma_x\sigma_y)$

$3^{2/3} = 2.08$, and employ the ILC vertical emittance. Luminosity scales linearly with ring circumference for fixed synchrotron power. There is experience with 3% momentum acceptance rings [14], which would need to be designed to minimize synchrotron radiation losses. A large momentum acceptance IP design would be new, probably allocating more real estate to sextupoles and less to quadrupoles, if it can be built without too much of an increase in focal length. The nominal normalized ILC vertical emittance is 0.04 mm-mrad. This yields geometric emittances of 0.000170 nm and 0.000082 nm for 120 GeV ($\gamma = 235,000$) and 250 GeV ($\gamma = 489,000$) beams, respectively. Results are in Table 2. The luminosity might also be improved by refreshing the beam at up to a few times per second instead of the roughly 12 minute interval [7] required by radiative Bhabba scattering. Table 2 shows refresh times that add 10% to power requirements beyond synchrotron radiation. Finally, Reference [13] notes that a crab waist crossing would add a further factor of $2^{2/3} = 1.6$ to the luminosities shown in the last line of Table 2.

$$\frac{L}{10^{34} \text{cm}^{-2} \text{s}^{-1}} \approx \frac{100 h \eta^{2/3} \xi_y^{1/3}}{(E_0 / 100 \text{ GeV})^{13/3} (\varepsilon_y / \text{nm})^{1/3}} \times \left(\frac{P}{100 \text{ MW}} \right) \left(\frac{2\pi R}{100 \text{ km}} \right) \frac{R_b}{R} \quad (2)$$

The dipoles for this 233 km circumference ring have a magnetic field four times lower than used at the CERN LEP machine. To maintain good field quality, particularly at injection, a soft magnetic material is needed. Grain oriented silicon steel [15] is chosen for the dipoles because its coercivity is 1/5 that of ultra low carbon steel [16]. Horizontal bands sandwich the top and bottom of C shaped laminations to permit a high permeability path in the entire flux return circuit. Putting concrete in between laminations provides space for the four bands. If an even lower coercivity material is absolutely required, hydrogen annealed mu metal (77% nickel, 16% iron) might suffice.

TABLE 2. Strawman parameters for three e^+e^- colliders including beamstrahlung tail limitations [13]. A beam refresh time of a second or less might improve luminosity but is not included in Equation 2 values on the last line.

Parameter Name (Units)				Formulae
$E_0 : e^+, e^-$ energy (GeV)	120, 120	120, 120	250, 250	
Ring Circumference: C (km)	15	233	233	
Ring Radius: R (km)	2.4	37.1	37.1	$R = C / 2\pi$
Bending radius: R_b (km)	1.9	29	29	
Hourglass factor, h	0.8	0.8	0.8	
Ring and IP momentum acceptance η	0.03	0.03	0.03	
Relativistic γ	235,000	235,000	489,000	$E/m = (120, 250)/0.000511$
Norm. emit.: ϵ_y^N (mm-mrad)	0.04	0.04	0.04	$\epsilon^N = \gamma\epsilon$
Geometric emittance: ϵ_y (nm)	0.000170	0.000170	0.000082	
Beam-beam tune shift: ξ_y	0.15	0.15	0.15	$r_e N / 4\pi\epsilon_y^N$
E loss / orbit (GeV)	9.7	0.63	11.9	$8.85 \times 10^{-5} E^4(\text{GeV})/R_b(\text{m})$
Beam refresh time (seconds)	0.006	1.5	0.16	$10 \times (E_0/E_{\text{loss/orbit}})(C/300,000)$
Synch rad power, both beams (MW)	100	100	100	$8.85 \times 10^{-2} E^4(\text{GeV})I(\text{amps})/R_b(\text{m})$
Luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	4.0×10^{34}	6.3×10^{35}	3.3×10^{34}	Equation 2 [13]

Energy Frontier 40 TeV $p\bar{p}$ Collider

A 40 TeV $p\bar{p}$ collider fits in the 233 km tunnel with 2 Tesla H-frame dipoles. Ultra low carbon steel [16] is used for the dipoles. The low coercivity/hysteresis loss of this steel permits reuse of these magnets for a muon collider. The magnet coils consist of 52 turns of 4mm wide YBCO superconducting ribbon. Each ribbon carries 500 amps for a total of 26,000 ampere/turns. The coils are cooled with liquid neon at 25K [3].

The Tevatron luminosity [17] of $4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ is scaled to yield:

$$L = (20/37) (4 \times 10^{32}) = 2.16 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}. \quad (3)$$

The factor of 20 increase comes from the energy increase and the factor of 37 decrease comes from lowering the

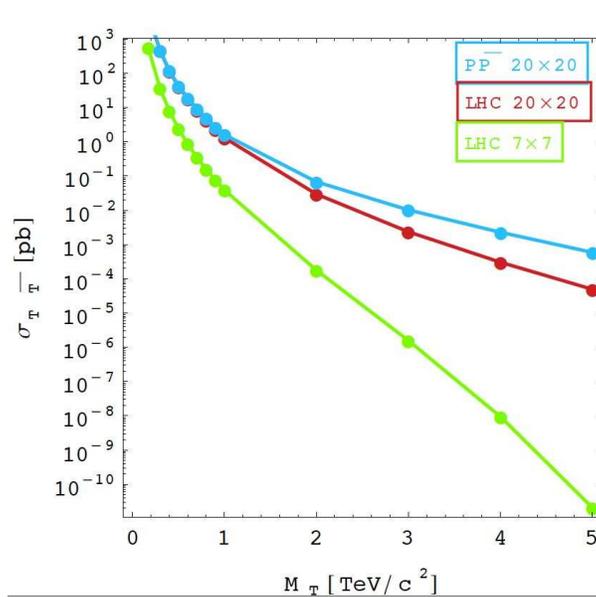


FIGURE 1. $p\bar{p}$ and pp cross sections are generated [19] for a particle similar to the top quark as a function of mass.

collision frequency due to the larger ring. As shown in Fig. 1, the $p\bar{p}$ cross section for many high mass states is an order of magnitude larger than the pp cross section. Thus, for high mass objects near threshold, this collider, with the Tevatron \bar{p} source, has 2x more events and 5x less background than the Superconducting Super Collider (SSC) pp design with a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The cross section for $p\bar{p}$ collisions does rise from 80 to 120 mb as \sqrt{s} goes from 2 to 40 TeV. But this increased \bar{p} burn rate might be ameliorated by adding a second, parallel \bar{p} accumulator ring. The current limitation on the Tevatron \bar{p} source is the accumulator ring with a \bar{p} stacking rate of $26 \times 10^{10} \bar{p}/\text{hour}$ [18]. The debuncher ring can supply $40 \times 10^{10} \bar{p}/\text{hour}$.

Energy Frontier 35 TeV $\mu^+\mu^-$ Collider

First we calculate the neutrino radiation ($\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ and $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$) for a ring with 17.5 TeV muons [20]. A 17.5 TeV muon lifetime is 0.364 s and $\gamma = 165,000$.

$$\tau = \gamma \tau_{\mu^\pm} = \frac{17.5 \text{ TeV}}{105.7 \text{ MeV}} 2.2 \times 10^{-6} \text{ s} = 0.364 \text{ s} \quad (4)$$

$$D_{\text{exit}}^{\text{ave}} [\text{Sievert}] = 2.9 \times 10^{-24} \times \frac{N_\mu (E_\mu [\text{TeV}])^3}{D[\text{m}]} = 2.9 \times 10^{-24} \times \frac{(1.1 \times 10^{20}) (17.5 \text{ TeV})^3}{300 \text{ m}} = 0.0057 \text{ Sv/yr} \quad (5)$$

The ring is 300 m underground. Two bunches of 2×10^{12} muons are produced every 0.364 seconds giving 1.1×10^{20} muons per 10^7 second accelerator year. The radiation dose, which equals the yearly dose from background, is too high, 0.0057 Sieverts/year or 570 mrem/year. A neutrino from the three body decay of a 17.5 TeV/c muon has a 20 MeV/c transverse momentum and a 5.8 TeV/c forward momentum yielding a rather small opening angle of $(20 \times 10^6)/(5.8 \times 10^{12}) = 3.4 \mu \text{ rad}$. So we dilute the radiation with a roller coaster motion [21] in FODO lattice arcs similar to the Tevatron helical lattice motion [22]. A rise or fall of 1 cm over a distance of 20 m leads to a 500 $\mu \text{ rad}$ angle, 150 times larger than angle from muon decay. The radiation dose falls by this factor to 4 mrem/year, equivalent to eating one banana a day. Vertical bumps are used to phase shift the roller coaster motion a few times a day. A similar phase shifting, helical lattice is used in straight sections.

Now we see if beam power and energy losses in magnets are plausible. The same magnets are used for muon acceleration as were used for the $p\bar{p}$ machine. The beam power for 4×10^{12} 17.5 TeV muons is:

$$P = \frac{(4 \times 10^{12})(17.5 \times 10^{12})(1.6 \times 10^{-19})}{0.364 \text{ s}} = 31 \text{ MW}. \quad (6)$$

The ultra low carbon steel eddy current losses are [23]:

$$P = [\text{Duty Factor}][\text{Volume}] \frac{(2\pi f B w)^2}{24\rho} = 14 \text{ MW}, \quad (7)$$

where the duty factor due to the flat top is 0.30, the steel volume is $15,000 \text{ m}^3$, the frequency is 9 Hz, the magnetic field averages 0.9 Tesla in the steel, the lamination width is 0.0005 m, and the resistivity of the steel is $9.6 \times 10^{-9} \text{ n}\Omega\text{-m}$. Using the Steinmetz Law [24] the hysteresis loss is:

$$\text{Energy/cycle} = (.001)(9000 \text{ gauss})^{1.6} = 2100 \text{ ergs/cc} \quad (8)$$

$$P = (\text{Vol/cycle}) (2100 \text{ ergs/cc}) (10^{-7} \text{ joules/erg}) = 9 \text{ MW}, \quad (9)$$

where the volume is $15,000 \text{ m}^3$ times 10^6 cc/m^3 and the cycle time is 0.364 seconds. Tests of YBCO superconductor ramping at 9 Hz are showing progress [25].

Next, we accelerate muons [26] in a Fermilab site filler ring to 1.75 TeV, and then to 17.5 TeV in the 233 km circumference ring using 2 Tesla dipoles, 250 GV of superconducting RF, and 63 orbits. Phase/frequency locked magnetrons [27] might supply power for the RF, if they can be developed as a more efficient alternative to klystrons.

$$\text{SURVIVAL} = \prod_{N=1}^{63} \exp \left[\frac{-2\pi R m_{\mu^\pm}}{[1625 + (250N)] c \tau} \right] = 71\% \quad (10)$$

A final focus system has been worked out for a 30 TeV, round beam, muon collider [28]. The IP beta function, β^* , is 0.48 cm. Quadrupole gradients are below 400 T/m and peak fields are below 15 T. Twelve meters is kept free for a detector. Total length of this final focus system is 2 km. Initially the acceleration ring is used as a 35 TeV collider with two detectors to give a luminosity of:

$$L = \frac{\gamma N^2 f_0}{4\pi \epsilon^N \beta^*} = \frac{165,000 (2 \times 10^{12})^2 2575}{4\pi (25 \times 10^{-4} \text{ cm}) 0.48} = 1.1 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \quad (11)$$

A smaller collision ring with higher field dipole magnets, higher collision rates, and higher luminosity could be added as an upgrade. Progress is being made on $\epsilon^N = 25$ mm-mrad cooled muon bunches but more work remains [29].

SUMMARY

A site filler ring at Fermilab permits 240 GeV e^+e^- and 3.5 TeV $\mu^+\mu^-$ colliders. The 233 km tunnel would be used by a series of machines sequentially over many decades. The tunnel would first be filled with 140 gauss dipoles for the 240 GeV e^+e^- machine aimed at producing one million $e^+e^- \rightarrow Z^0 h^0$ reactions per year. The Tevatron \bar{p} source gives a competitive event rate with a 40 TeV energy frontier hadron collider based on 2 T dipole magnets. Muon acceleration from 1.75 to 17.5 TeV with 250 GV of RF and 2 T dipole magnets with 9 Hz ramped superconducting coils looks promising. Neutrino radiation might be rasterized. A 35 TeV muon collider would have 70x the center of mass energy of the ILC, while using half the RF of the ILC.

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