ONE 233 KM TUNNEL FOR THREE RINGS: e^+e^-, $p\,\bar{p}$, AND $\mu^+\mu^-$*

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Abstract

In 2001, a cost analysis was made to bore a 233 km circumference tunnel in northern Illinois for a Very Large Hadron Collider (VLHC). Here we reaccess and outline the implementations of e^+e^-, $p\,\bar{p}$, and $\mu^+\mu^-$ collider rings in such a tunnel using recent innovations. The 240 and 500 GeV e^+e^- colliders employ a crab waist crossing, ultra low emittance damped bunches, a short vertical Interaction Point (IP) focal length, superconducting RF, and very low coercivity, grain oriented silicon steel/concrete dipoles. 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 Tevatron $\bar{p}$ source, exploits the large cross sections for $p\,\bar{p}$ production of high mass states, and uses 2 Tesla ultra low carbon steel/YBCO superconductor magnets run with liquid neon. The 35 TeV energy frontier muon collider ramps the 2 Tesla superconducting magnets at 9 Hz every 0.36 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 a phase shifting, roller coaster FODO lattice.

INTRODUCTION

Ten years ago, 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, 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]. Observation of a 125 GeV/c^2 Higgs [6] would provide the motivation for 240 GeV $e^+e^- \to Z^0 h$ [7].

240 and 500 GeV e^+e^- Colliders

A crab waist crossing [8] 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 [9]) 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 [10]. The vertical emittance is lowered until the tune-tune shift limit, ξ_y, is reached. The crossing angle independent luminosity is given by [3, 8]:

$$L = 2.167 \times 10^{34}\, \mathrm{E\,(GeV)\; I\,(Amps)}\, \xi_y / \beta_y^*\, \mathrm{(cm)}.$$

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 Nb_3Sn quadrupole [11] may be useful in getting the beam to fit into the final focus.

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 [12] is chosen for the dipoles because its coercivity is 1/5 that of ultra low carbon steel [13]. 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.

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 [13] 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 [14] of $4 \times 10^{32}\,\mathrm{cm^{-2}\,s^{-1}}$ is scaled to yield:

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

The factor of 20 increase comes from the energy increase and the factor of 37 decrease comes from lowering the collision frequency in 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 $p\,p$ 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) $p\,p$ design with a luminosity of $10^{33}\,\mathrm{cm^{-2}\,sec^{-1}}$. 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

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current limitation on the Tevatron $\bar{p}$ source is the accumulator ring with a $\bar{p}$ stacking rate of 26×10^{10} $\bar{p}$/hour [15]. The debuncher ring can supply 40×10^{10} $\bar{p}$/hour.

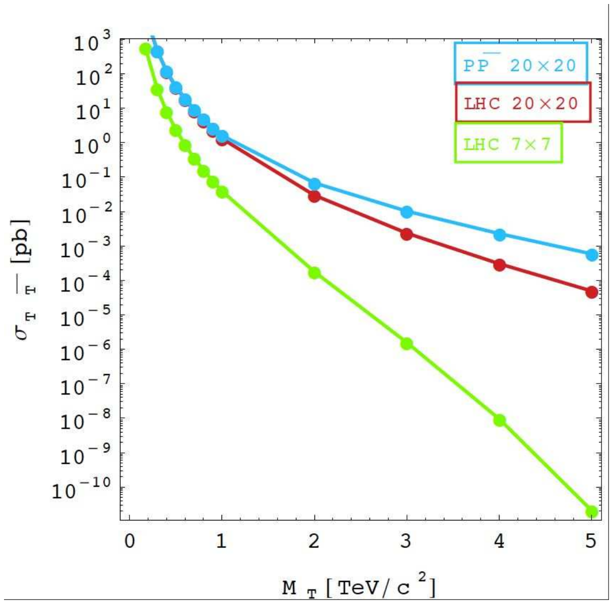

Figure 1: $p\,p$ and $p\,\bar{p}$ cross sections are generated [16] for an object similar to the top quark as a function of mass.

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

First we calculate the neutrino radiation ($\mu^- \to e^-\,\overline{\nu}_e\,\nu_\mu$ and $\mu^+ \to e^+\,\nu_e\,\overline{\nu}_\mu$) for a ring with 17.5 TeV muons [17]. A 17.5 TeV muon lifetime is 0.364 s and γ = 165000.

$$\tau = \gamma\,\tau_{\mu^\pm} = \frac{17.5\,TeV}{105.7\,MeV}\;\; 2.2 \times 10^{-6}\,\mathrm{s} = 0.364\,\mathrm{s}$$

$$D^{ave}_{exit}[\mathrm{Sievert}] = 2.9 \times 10^{-24} \times \frac{N_\mu\,(E_\mu[\mathrm{TeV}])^3}{D[\mathrm{m}]} =$$

$$2.9 \times 10^{-24} \times \frac{(1.1 \times 10^{20})\,(17.5\ \mathrm{TeV})^3}{300\ \mathrm{m}} = 0.0057\ \mathrm{Sv/yr}$$

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 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 μrad. So we dilute the radiation with a roller coaster FODO lattice in arcs similar to the Tevatron helical lattice [18]. A rise or fall of 1 cm over a distance of 20 m leads to a 500 μrad 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 once or twice 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:

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

The ultra low carbon steel eddy current losses are [19]:

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

where the duty factor due to the flat top is 0.30, the steel volume is 15,000 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 9.6×10^{-9} nΩ-m. Using the Steinmetz Law [20] the hysteresis loss is:

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

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

where the volume is 15,000 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 good progress [21].

Next, we accelerate muons [22] 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 [23] might supply power for the RF, if they can be developed as a more efficient alternative to klystrons.

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

A final focus system has been worked out for a 30 TeV, round beam, muon collider [24]. 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:

$$L = \frac{\gamma N^2 f_0}{4\pi\epsilon^N\beta^*} = \frac{165000\,(2 \times 10^{12})^2\,2575}{4\pi\,(25 \times 10^{-4}\ \mathrm{cm})\,0.48} = \frac{1.1 \times 10^{35}}{\mathrm{cm}^2\,\mathrm{s}}$$

SUMMARY

A starter ring on the Fermilab site provides for 240 GeV e^+e^- and 3.5 TeV $\mu^+\mu^-$ collisions. The crab waist crossing [8] may extend the energy reach of e^+e^- beyond LEP. The Tevatron $\bar{p}$ source can run a 40 TeV hadron collider with a competitive event rate. Muon acceleration from 1.75 to 17.5 TeV with 250 GV of RF and 2 T steel magnets with 9 Hz ramped superconductor looks promising. Neutrino radiation can be rasterized. One option for powering these rings is a subcritical, thorium/nuclear waste reactor [25] driven by a fixed field, alternating gradient accelerator.

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Table 1: Parameters for three e^+e^- colliders which exploit the crab waist crossing [8].

Parameter Name (Units)				Equations
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 / 2π
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	(Bunches / beam) c / 2πR
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	$\sigma = \sqrt{\epsilon\,\beta^*}$
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	$\sim$ (Lattice Type) $\gamma^2(\ell_{\text{half cell}}/\rho)^3$ [10]
Geometric emittance: ϵ_y (nm)	0.00099	0.00099	0.00022	
Norm. emit.: $\epsilon^N_x, \epsilon^N_y$ (mm-mrad)	846, 0.235	846, 0.235	1760, 0.108	$\epsilon^N = \gamma\epsilon$
Beam-beam tune shift: ξ_x	0.0014	0.0014	0.0007	$r_e\, N/4\pi\epsilon^N_x \approx 2\, r_e N\beta^*_x/(\pi\gamma\sigma^2_x\,\theta^2)$ [8]
Beam-beam tune shift: ξ_y	0.20	0.20	0.23 [4]	$r_e\, N/4\pi\epsilon^N_y \approx r_e N\beta^*_y/(2\pi\gamma\sigma_y\sigma_z\,\theta)$ [8]
No. of bunches / beam	3	700	41	
Particles / bunch [4]	4.85×10^{11}	4.85×10^{11}	4.85×10^{11}	$\delta N_2 = 2N_2\sigma_x/(\theta\sigma_z) = 3.63\times10^{10}$ [8]
Dipole field (Tesla)	0.21	0.014	0.029	B = (120, 250) /.3ρ (meters)
Current / beam (Amps)	0.00505	0.07	0.0041	1.6×10^{-19} (particles/beam) c / 2πR
E loss / orbit (GeV)	9.7	0.63	11.9	$8.85\times10^{-5}\,E^4(\text{GeV})/\rho(\text{m})$
Synch rad power (MW/ beam)	49	44	49	$8.85\times10^{-2}\,E^4(\text{GeV})\,I(\text{amps})/\rho(\text{m})$
Total synch wall power (MW)	198	176	198	
IP $\beta^{\max}_x$, $\beta^{\max}_y$ (km)	40, 250	40, 250	40, 250	
IP $\sigma^{\max}_x$, $\sigma^{\max}_y$ (mm)	12, 0.5	12, 0.5	12, 0.23	$\sigma^{\max} = \sqrt{\epsilon\,\beta^{\max}}$
IP Sextupole Strength (1/m)^2	0.0007	0.0007	0.0007	$K_2 = [1/(2\,\theta\,\beta^{\max}_y\beta^*_y)]\sqrt{\beta^*_x/\beta^{\max}_x}$ [8]
Luminosity (cm^{-2} s^{-1})	4.4×10^{34}	6.1×10^{35}	7.6×10^{34}	L = $N_1\,(\delta N_2) f_0/(4\pi\sigma_x\,\sigma_y)$

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