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A High Energy e^+e^- Collider in a "Really Large" Tunnel

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ABSTRACT

Recent developments in tunneling technology imply that it is possible to consider much larger tunnels for high energy circular colliders in the future. Tunnels with diameters of 200 km are being considered for a low field hadron collider called the Really Large Hadron Collider (RLHC)[1]. This tunnel might be produced for a cost of about 1000 $/m. An e^+e^- collider in this tunnel could perhaps study $t\bar{t}$ production at threshold with good resolution, Higgs production and e/p collisions at high energy. This note considers some of the parameters and issues of such a machine.

I. PARAMETERS

If a 50 + 50 TeV hadron collider was constructed using superferric magnets, the circumference would be roughly 531,000 m. We have considered an e^+e^- collider[2] located in this tunnel, which could operate at energies sufficient to study $t\bar{t}$ and light Higgs production[3].

The most important parameters of a $t\bar{t}$ factory operating at a beam energy of 180 GeV are shown in Table I. A complete parameter set is on the WWW[4]. We assume a total RF generator power available at the cavity windows of 100 MW, and a superconducting RF system similar to that of LEP operated at a gradient of 5 MV/m. We assume that the collider is operated with pretzels and parasitic beam-beam collisions every quarter betatron wavelength, and have adapted phase advance, arc tune Q and number of bunches k accordingly. We assume that wiggler magnets are used to make the horizontal emittance a factor of 10 higher than its equilibrium value without wigglers. The advantage is a smaller value of the synchrotron tune, the disadvantages are a smaller dispersion in the arcs, a possibly smaller dynamic aperture and a larger momentum spread in the beam. We have not checked that the dynamic aperture is large enough.

We assume that the aperture is filled and that the beam power limit is reached at a beam energy of 180 GeV. If we control the beam size such as to remain at the beam-beam limit over a range of energies, the luminosity is proportional to E^2 for $E \leq 180$ GeV, and proportional to E^{-3} for $E \geq 180$ GeV. We increase the phase advance of the arc cells in steps from $\pi/8$ at 100 GeV to $\pi/2$ at 250 GeV. In order to satisfy the pretzel condition, all phase advances are integral fractions of π. In order to limit the emittance variation at the higher energies, we start reducing the number of bunches in steps of two from 335 GeV. We use emittance wigglers to adjust the beam size at the intermediate energies. Table II shows the proposed variation of phase advances, number of bunches, and

Table I: The Parameters of a $t\bar{t}$ Collider

Beam energy E /GeV	180
Circumference C /m	531000
Beam-beam tune shift $\xi_x = \xi_y$	0.03
Amplitude functions at IP $\beta_x^* : \beta_y^*$ /m	1.0 : 0.03
Emittance blowup factor F_ε	10
Horizontal emittance ε_x /m	3.49E-8
Beam radii at IP $\sigma_x^* : \sigma_y^*$ /mm	187 : 9.35
Luminosity L /cm^{-2}s^{-1}	9.15E+32
Bunch population N	8.61E+11
Total current / beam I_b /mA	39.1
Number of bunches /beam k	512
Photodesorbed gas Q_{gas} /torr L sec^{-1}	6.8E-4
Bending radius ρ /m	72628
Average arc radius R /m	81964
Average collider radius $C/2\pi$ /m	84511
Dipole fields $B_{max} : B_{inj}$ /mT	8 : 1
Phase advance / cell $\mu/2\pi$	0.125
Arc tune Q	248
Cell Length L_p /m	260
Amplitude functions $\beta_{max} : \beta_{min}$ /m	508 : 227
Dispersions $D_{max} : D_{min}$ /m	1.67 : 1.14
Beam radii σ_x, σ_y /mm	5.2 : 3.0
Closed orbit allowance $C_x = C_y$ /mm	10
Beam aperture	10σ
Aperture radii $A_x : A_y$ /mm	62 : 40
Synchrotron radiation loss U_s /MeV	1279
Relative energy spread σ_E	1.31E-3
RF Frequency f_{RF} /MHz	351.7
RF voltage V_{RF} /MV	1838
Synchrotron tune Q_s	0.107
Bunch length σ_z /mm	22
Total generator power P_g /MW	100

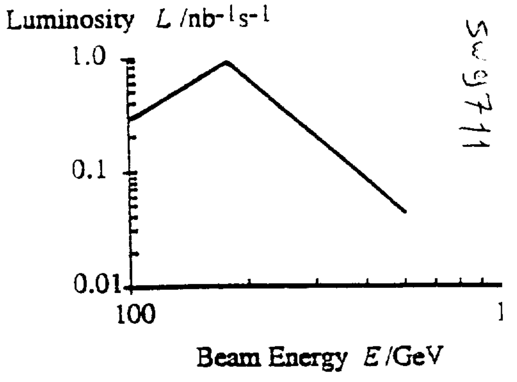

Figure 1, The energy dependence of the luminosity wiggler excitation. At energies below 250 GeV, the desired beam size can often be reached by more than one combination of phase advance $\mu/2\pi$ and emittance increase F_ε. In Table II, we favour higher values of $\mu/2\pi$ and F_ε in order to restrict the variation of the synchrotron tune Q_S with the energy E. It may be seen that it is indeed possible to achieve the strong variation of the beam radii with E by adjusting the phase advance in steps, varying the number of bunches, and using emittance wigglers.

The aperture limited luminosity is given by the expression $L_a = \pi f k \Delta Q \sigma_x{}^* \sigma_y{}^* \gamma^2 / r_e{}^2 \beta y^*$, where the revolution frequency $f \propto 1/\rho$, and the number of bunches $k \propto \rho$ if the bunch spacing is fixed by the hardware required to separate the beams, thus L_a is independent of ρ. The power limited luminosity is $L_P = (3/16\pi) \Delta Q \rho P / r_e{}^2 E_e \beta_y{}^* \gamma^3$, where E_e is the rest mass of the electron and r_e its radius[2]. The maximum luminosity occurs when $L_a = L_P$, and this energy, E_{max}, is proportional to $\rho^{1/5}$. Thus the specific dimensions of the tunnel only weakly affect the operating parameters.

The energy resolution of the collider could be ~0.2 GeV in the center of mass at the $t\bar{t}$, which would be desirable for high resolution studies of threshold behavior.

Table II. Proposed phase advances $\mu/2\pi$ in the arc cells, number k of bunches in one beam, and emittance increase factors F_ε with wiggler magnets as functions of the beam energy E.

E /GeV	$\mu/2\pi$	k	F_ε
100→136	0.0625	512	4→2.2
136→180	0.0833	512	5.2→3.0
180→250	0.125	512	10→1
250→335	0.25	512	8→1
335→370	0.25	256	2→1
370→410	0.25	128	2→1
410→450	0.25	64	2→1
450→500	0.25	32	2→1

TABLE III. Total current in one beam I, luminosity L, synchrotron tune Q_S and circumferential RF voltage V as a function of the beam energy E.

E /GeV	I /mA	L /nb^{-1}s^{-1}	Q_S	V /MV
100	21.7	0.28	0.111	231
136	29.5	0.52	0.083	658
180	39.1	0.92	0.106	1832
250	10.5	0.34	0.056	5266
335	3.3	0.14	0.059	15686
370	2.2	0.11	0.067	23313
410	1.4	0.08	0.077	35101
450	1.0	0.06	0.088	50905
500	0.7	0.04	0.100	77474

II. RF SYSTEMS

Table III shows the total current in one beam I, the luminosity L, the synchrotron tune Q_S and the total circumferential RF voltage V as a function of energy for the collider settings at the lower energy of the ranges shown in Table II. The total RF generator power at the cavity windows is about 5 MW at 100 GeV, then increases proportional to E^5 up to 180 GeV. There it reaches 100 MW, and remains at that value for higher energies. The LEP2 modules consist of four cavities each and deliver a total voltage of 40 MV and a total power of 0.5 MW, limited by the input couplers. Thus about 200 LEP2 modules are needed to supply a beam power of 100 MW. The accelerating voltage needed at 180 GeV is only about 9 MV per module. Above 180 GeV the accelerating gradient rises quickly, the value of 40 MV per module is reached at about 280 GeV. Beyond that energy, the RF voltage and the length of the RF system become absurd.

III. DIPOLE FIELD ERRORS

Since the maximum dipole field required is only 23 mT even for 500 GeV, one could use thin steel laminations separated by large nonmagnetic spacers, as in LEP. Error fields should be on the order of 4×10^{-4} of the dipole fields, and the earth's field is on the order of 0.05 mT, thus it will be necessary to carefully shield this field from the beam, particularly at injection when the dipole field is ~1 mT, (assuming E_{inj} = 20 GeV). If the electron ring was used in combination with the hadron ring for e/p collisions, even larger fields from the superferric magnet and return current must be shielded.

While magnets could be shielded with various materials, and coils could be used to cancel error fields, it seems desirable to examine the magnetic shielding provided passively by the magnet yoke itself. The magnitude of error fields in a dipole due to external fields is well known when the external field is zero. This has been expressed by Fischer[5] as

$$x/h = 0.75 - 0.36 \log_{10}(100\ \Delta B/B)$$

where h is the half gap of the magnet. Brown and Spencer [6] parametrize the error field as

$$\Delta B/B = 1 / (1 + e^S)$$

where $S = C_0 + C_1(x/g) + C_2(x/g)^2 + \ldots + C_5(x/g)^5$, and the constants are given by $C_0 = 0.479$, $C_1 = 1.191$, $C_2 = -1.186$, $C_3 = 1.630$, $C_4 = -1.082$, $C_5 = 0.318$ where g is the full gap. In both paramatri-zations contributions from external fields drop off very rapidly within the magnet gap.

A. Prototype Measurements

In order to evaluate experimentally the degree of shielding one would expect from the normal magnet yoke itself we constructed a prototype of a C magnet from 0.025" laminations spaced by 0.25". This prototype is 0.2 m long and made from magnet laminations cut and glued to make a C magnet with a gap height of 3.81 cm. Measurements were made with a Bartington MAG-01 single axis fluxgate magnetometer[7]. The magnet was degaussed by exciting it

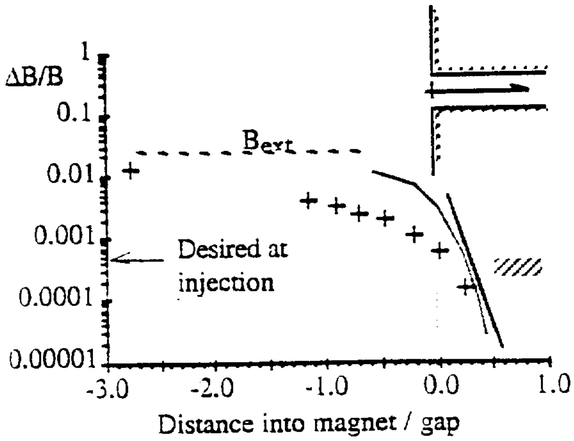

Figure 2. Measured error fields after degaussing, with parametrizations of Fischer (straight) and Brown and Spencer (curved). ΔB/B = (measured field) / (field at injection), which is equivalent to the measured field in mT. Hatched line shows level of remanent fields.

oscillations at 60 Hz, with slowly decreasing amplitude from 700 A-turns to zero.. The results are shown in Figure 2 above compared with models.

Much of the vertical component of the external magnetic field, (about 0.025 mT away from the magnet), is diverted through the magnet yoke within dimensions comparable to the yoke itself. Approaching the physical gap in the magnet, the field tends to drop more rapidly, until it follows the parametrization of Brown and Spencer, and Fischer. Larger fields should be shielded by a similar factor. Remanent magnetic fields, which should be dependent on the magnet history, contributed at the level of ~0.0006 mT, however these should primarily be dipole, which can be corrected externally. Degaussing would be required before injection.

IV. EMITTANCE WIGGLERS

The ratio F_ε of the horizontal equilibrium emittance with and without emittance wigglers is [8]:

$$F_\varepsilon = \frac{1 + \dfrac{N_W\, L_+ \,|B_+|^3\, H_W}{2\pi\, \rho_0\, B_0^3\, H_B}\left(1 + \dfrac{1}{r^2}\right)}{1 + \dfrac{N_W\, L_+ \,|B_+|^2}{2\pi\, \rho_0\, B_0^2}\left(1 + \dfrac{1}{r}\right)} \qquad (1)$$

Here N_W is the number of wigglers, each consisting of three magnets with polarity - + - , L_+ is the length and B_+ is the field of the central + pole, H_W and H_B (generally written with script fonts) are averaged over the wiggler and the dipoles, respectively, ρ_0 is the bending radius, B_0 the field of the dipoles, r is the ratio of the + and - poles of the wiggler $r = B_+/B_-$ and $H = \gamma D_x^2+2\alpha D_x D_x'+\beta D_x'^2$ where the terms are standard lattice functions. In order to restrict the extra synchrotron radiation loss caused by the wigglers, the second term of the denominator of (1) should be small compared to unity. On the other hand the second term in the numerator of (1) should be large compared to unity in order to achieve a large emittance ratio F_ε. The ratio of the second terms of numerator and denominator is $R_W=(B_+/B_0)(H_W/H_B)(1-1/r)$. If the wigglers and main dipoles contribute equally to the synchrotron radiation loss then the emittance ratio becomes $F_\varepsilon=(1+R_W)/2$. Assuming $B_+= 1$ T, the ratio B_+/B_0 becomes about 120 at 180 GeV. The ratio $H_W/H_B = 4$ can be achieved in a wiggler insertion with a dispersion bump[9]. It should therefore be possible to achieve the emittance ratios assumed and to keep the extra synchrotron radiation loss caused by the wigglers small.

V. ARC CELL QUADRUPOLES

Several phenomena impose lower limits on the quadrupole gradient which are lower than the technological limit imposed by the poletip field. Because of these arguments we have assumed that the quadrupole length would be approximately 10 m.

A. Damping Partition Numbers

The variation of the damping partition numbers J with the relative momentum error δ is described by the synchrotron integral I_8[10]. In a machine consisting of FODO cells with total dipole length l_B, quadrupoles of length l_Q, and phase advance μ in both planes, it is given by

$$\frac{dJ_x}{d\delta} = -\frac{dJ_s}{d\delta} = -\frac{l_B}{l_Q}\,\frac{4 + \sin^2 \mu/2}{\sin^2 \mu/2}$$

The reciprocal of $dJ_x/d\delta$ defines the momentum aperture inside which all three degrees of freedom are damped. Wiggler magnets reduce $dJ_x/d\delta$.

B. Nonlinear Radiation Damping

The synchrotron radiation loss in the quadrupoles is proportional to the quadrupole gradient and the trajectory offset $(x^2 + y^2)^{1/2}$ and hence inversely proportional to the length of the quadrupoles. If this loss is large enough, particles with large betatron amplitudes lose enough energy to jump out of the RF bucket. This effect is described by the synchrotron integrals I_{6x} and I_{6y}.[11] This effect, which has been called radiative synchro betatron coupling, is important in LEP2.

VI. VACUUM ISSUES

The vacuum system seems to be defined by: 1) the comparatively small amount of photoproduced gas per unit length, and, 2) the large radius of the ring which makes the vacuum chamber effectively straight between discrete absorbers. The average photodesorption per meter of gas by synchrotron light is given by $Q_{gas}/\mathrm{m}=24.2EI\eta/2\pi R$ [12], where Q_{gas} is the gas load in Torr-L/s, E is the beam energy, I is the beam current, R is the radius, and η is the photodesorption coefficient, roughly 10^{-5} - 10^{-6}. At 180

GeV a pressure of 10^{-9} Torr could be reached with an average pumping speed of ~ 2 $Ls^{-1}m^{-1}$. Discrete absorbers at 100 m intervals would be able to easily handle the gas loads, with no photodisorption in the magnets between the absorbers. The power loading on the absorbers would be a concern, as would the impedance of the slot. With discrete absorbers, all ionizing radiation can be absorbed by local shielding and no distributed shielding should be required.

The vacuum chamber itself could be an aluminum extrusion with a heating/cooling channel and a beam channel separated from a pumping channel by a narrow slot for the synchrotron radiation, as shown in Figure 3. The narrow slot would maintain a constant surface to carry image currents, with Non Evaporable Getters (NEG) and discrete absorbers located behind this boundary. The pumping channel must be wide enough to accommodate the synchrotron fan over 100 m. Note that thermal expansion over this distance during a 100° C bake would be 0.24 m for an Al chamber.

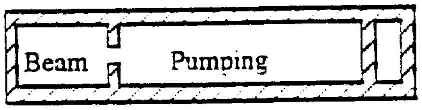

Figure 3. A possible Vacuum chamber geometry.

VII. COST MINIMIZATION

The majority of the circumference will be occupied by weak bending magnets, vacuum chamber and some distributed pumping. It is possible to estimate the cost of materials required for these components from costs for Al extrusions, magnet laminations and NEG getter material.

The primary methods of cost reduction would be automated assembly / installation, and reduction in the number of individual components.[1] For example, since the magnets will probably be remotely movable, horizontal and vertical trim magnets can be replaced by moving quadrupoles. It is probably desirable to minimize the dipole mass, consistent with producing a rigid structure. Cooling of synchrotron losses should be done locally with heat sinks into the ground and magnets could be air cooled.

VIII. CONCLUSIONS

A very preliminary study at the properties of a large e^+e^- collider has shown that the device could be very useful for looking at the $t\bar{t}$ threshold with good energy resolution, although the luminosity of this machine will not quite match that of recent NLC designs. While the machine is large, the majority of the circumference will be filled with very weak magnets and a comparatively simple vacuum system which should be considerably cheaper (per unit length) to construct and install than existing machines. The weak field at injection requires good shielding from the ambient magnetic fields, but this should be provided passively by the magnet yoke. Remanent fields in the dipoles might be significant and require correction. The effective maximum energy of this machine might be around a beam energy of 300 GeV, due to the decreasing luminosity and rapidly rising RF cost.

IX. ACKNOWLEDGEMENTS

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