AN e^+e^- TOP FACTORY IN A 50 + 50 TeV HADRON COLLIDER TUNNEL

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Abstract

We present the parameters of an e+e- collider sized for the tunnel of a 50 + 50 TeV superferric hadron collider[1]. Assuming a diameter of 170 km and a maximum radiated power of 100 MW, this collider should have a maximum energy of 500 - 600 GeV (c.m.) and should be able to produce a luminosity L = 0.9.1033 cm-2sec-1 at a center of mass energy of 360 GeV, (somewhat less at higher or lower energies) which would make it useful for producing top quarks or light Higgs bosons. Design problems include the very low field magnets, synchrotron radiation power, beam stability, and heat removal systems. Preliminary magnet, vacuum chamber and cooling designs are presented along with possible construction techniques, and some costing algorithms. We also consider an ep collider with 70 GeV electrons and 5 TeV protons as an injector.

1 PARAMETERS

We have considered an e^+e^- collider[2] located in the tunnel of a 50 + 50 TeV hadron collider, which could operate at energies sufficient to study $e^+e^- \rightarrow t\bar{t}$ and light Higgs production[3]. If this facility was operated as an ep collider, a c.m. energy of $\sqrt{s}$ = 7 TeV could be reached.

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 consists either of a single ring, 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, or of two rings. 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 $\pi/2$. We assume that wiggler magnets, installed in wiggler insertions where H has four times the arc value, are used to make the horizontal emittance a factor of ten larger than its equilibrium value without wigglers. Table II shows the proposed variation of phase advances and 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 favor 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 is indeed possible to achieve the strong variation of the beam radii with E by adjusting the phase advance in steps and using emittance wigglers.

Table I: The Parameters of a Very Large Lepton Collider

Beam energy E /GeV	180
Circumference C /m	531000
Luminosity L /$cm^{-2}s^{-1}$	9.15E+32
Beam-beam tune shift $\xi_x = \xi_y$	0.03
Beta functions at IP $\beta_x^* : \beta_y^*$ /m	1.0 : 0.05
Beam emittances $\varepsilon_x : \varepsilon_y$ /nm	32.5 : 1.7
Beam radii at IP $\sigma_x^* : \sigma_y^*$ /μm	180 : 9.01
Bunch population N	8.04E+11
Total current / beam I_b /mA	37.2
Number of bunches /beam k	512
Bending radius ρ /m	72628
Injection Energy E_{inj} / GeV	50
Dipole fields $B_{max} : B_{inj}$ /mT	8.3 : 2.3
Phase advance / cell $\mu/2\pi$	0.125
Arc tune Q	258
Cell Length L_p /m	249
Beta functions in arcs $\beta_{max} : \beta_{min}$ /m	488 : 218
Beam radii $\sigma_x : \sigma_y$ /mm	4.3 : 2.8
Synchrotron radiation loss U_s /MeV	1376
Aperture radii $A_x : A_y$ /mm for 10σ	53 : 38
Center of mass energy spread σ_E /GeV	0.26
RF voltage V_{RF} /MV	1616
Total generator power P_g /MW	102

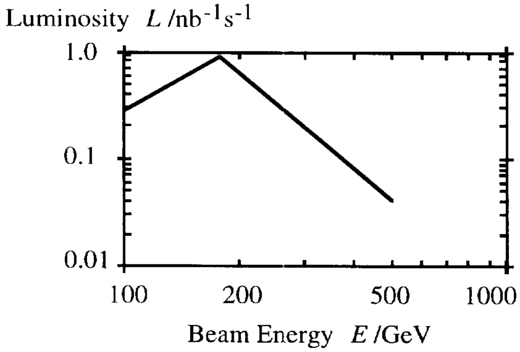

Figure 1, The energy dependence of the luminosity

The aperture limited luminosity is given by the expression $L_a = \pi f k \xi \sigma_x^* \sigma_y^* \gamma^2 / r_e^2 \beta_y^*$, 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. If power limited, $L_P = (3/16\pi)\xi\rho P / r_e^2 E_e \beta_y^* \gamma^3$, 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, σ_E ~0.26 GeV, in the center of mass at the $t\bar{t}$, would be useful for high resolution studies of threshold behavior and may be better than other collider options.

The polarization time is about 19 hours at 180 GeV, and comparable to the typical duration of a physics fill. The tolerance on the closed orbit harmonic at the spin tune is very tight, even with Siberian snakes. Therefore, no useful degree of polarization is expected.

The requirements that all three degrees of freedom are damped by synchrotron radiation imposes constraints on the length of all quadrupoles, as does nonlinear radiation damping [3].

Table II. Luminosity L, proposed phase advances $\mu/2\pi$ in the arc cells, emittance increase factors F_ε with wiggler magnets and circumferential RF voltage V as functions of the beam energy E, (L, I and V are evaluated at the lower end of the energy range).

E /GeV	L /nb^{-1}s^{-1}	$\mu/2\pi$	I /mA	F_ε	V /GV
100→136	0.28	0.0625	21	4→2.2	0.2
136→180	0.52	0.0833	29	5.2→3	0.7
180→250	0.92	0.125	39	10→1	1.8
250→335	0.34	0.25	10	8→1	5.3

2. RF SYSTEM

Table II also shows the total current in one beam I, the luminosity L, and the total circumferential RF voltage V as a function of energy. The total RF generator power at the cavity windows increases proportional to E^5 up to 180 GeV. There it reaches 100 MW, and remains at that value for higher energies by design, although the required voltage continues to rise as E^4. Above 250 GeV, the RF voltage and the length of the RF system, assuming ~6 MV/m, become absurd.

Current technology limits input power to superconducting cavities to about 500 kW. Using a very reasonable gradient of 6 MV/m in a superconducting cell with 0.425 m active length, operating at a synchronous angle of 31.6° and matched at 160 mA beam loading gives 3 cells per cavity for 588 kW input power. Klystrons providing 1.7 MW at 350 MHz determine 3 cavities per klystron and 70 klystrons for 1.4 GV synchrotron loss. This system should benefit from expected improvements in RF coupler and window technology, superconducting gradients and klystron power.

Instabilities related to higher order monopole and multipole modes can be managed by aggressive higher order mode damping techniques, which are available. Coupled bunch longitudinal instabilities, exacerbated by cavity detuning being comparable to the revolution frequency are a concern.

3 MAGNET ISSUES

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, and stabilized against thermal expansion with materials like invar. 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 ~2.3 mT, (assuming E_{inj} = 50 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.

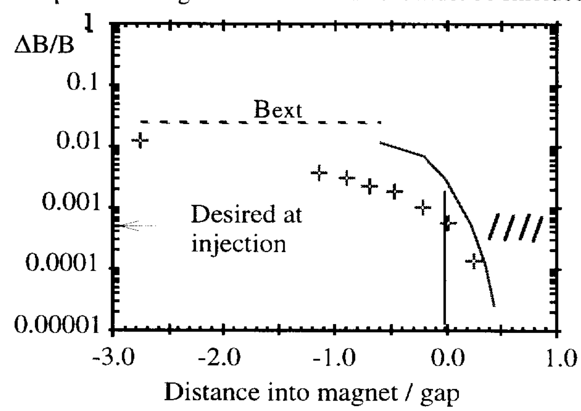

Figure 2, Measured error fields after degaussing, with parametrizations of Brown and Spencer. ΔB/B = (measured field) / (field at injection), which is equivalent to the measured field in mT. The hatched line shows level of residual fields.

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. The magnet was degaussed by exciting it at 60 Hz, with slowly decreasing amplitude from 700 A-turns to zero. The results are shown in Figure 2, above, compared with Brown and Spencer[5].

Since the total mass of iron required is ~ 20 kg/m the magnet will rely on an external support structure against mechanical motion and thermal expansion. Possible component dimensions are shown in Figure 3.

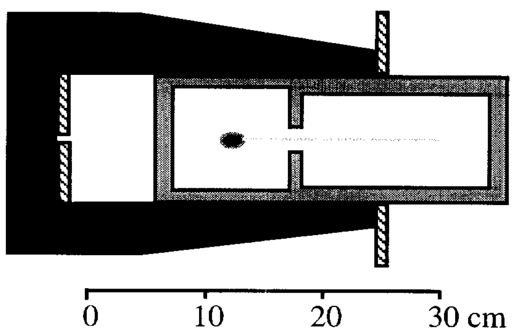

Fig 2. Dipole yoke, 4 conductors and vacuum chamber

4 VACUUM ISSUES

The vacuum system is defined by the comparatively small amount of photoproduced gas per unit length, and the large radius of the ring, which makes the vacuum chamber effectively straight between discrete absorbers. The average photodesorption of gas per meter by synchrotron light is given by $Q_{gas}/\mathrm{m}=24.2EI\eta/2\pi R$ [6], where Q_{gas} is the gas load in Torr-L/s, 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 $\mathrm{Ls^{-1}m^{-1}}$.

We consider a vacuum chamber with a beam channel and a antechannel containing NEG strips, discrete absorbers and ion pumps. The slot impedance is a concern for beam stability. OFHC copper absorbers 0.6m long protruding into the antechannel would protect the vacuum chamber from synchrotron radiation. With discrete absorbers the gas load and ionizing radiation would be localized and handled more efficiently. Each absorber would intercept 19 kW of power with a surface temperature rise of 150 ^{o}C. Bulk water temperature rise in the absorber with 4 gpm of water flow would be 18 ^{o}C.

Since the machine would be far underground and distances would be large, we have considered sinking the 200 W/m of synchrotron power directly into the rock by taking the cooling water from the synchrotron absorbers through an array of pipes extending from the tunnel. Since the conductivity of rock is low but the specific heat is high, heat tends to be absorbed rather than conducted away. The required power can be absorbed by an array of pipes extending on the order of 3 m in one direction from the tunnel, water in the rock would help heat conduction.

We anticipate sharing a ~3 m diameter tunnel with the hadron collider magnets and a two way railroad, with access points to the surface located far apart.

5 COST MINIMIZATION

The cost of the facility is expected to be dominated by the cost of the tunnel, magnet/vacuum systems and RF. Tunnel costs have been estimated at 1000 \$/m from a number of sources[1]. Bending magnet costs for a system of length l should roughly scale like $Bl \propto B\rho \propto E$ for a given magnet cross section, however the very low dipole field permits the use of more compact coil structures which should permit a considerably smaller and lighter stamping than that used in LEP. The RF cost has been roughly estimated at <0.25 \$/V, although R&D directed at producing higher gradients could perhaps reduce this.

6 THE INJECTOR: AN ep COLLIDER

The injector for the hadron and e^+e^- colliders would be a proton ring of 3-5 TeV and an electron ring, both with a circumference of 15 - 30 km. If the >1.8 GV, 100 MW rf system for the e^+e^- collider were installed in the injector ring, an energy E_e ~ 80-100 GeV might be obtained. Use of these rings as an ep collider would thus be possible up to $\sqrt{s}$ ~1000 - 1350 GeV. The power to the vacuum chamber, P_{av} ~8 W/mm, can be cooled with simple water channels on the outside circumference.

7 CONCLUSIONS

An e^+e^- collider could be added to a 50+50 TeV low field hadron facility permitting high energy lepton physics as well as ep physics in an integrated facility.

8 REFERENCES

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