PETAVAC: 100 TeV PROTON-ANTIPROTON COLLIDER IN SSC TUNNEL

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Abstract

Recent developments in accelerator physics and superconducting magnet technology make it reasonable to extend proton-antiproton colliding beams from the 2 TeV of the Tevatron to 100 TeV in the existing SSC tunnel. The antiproton source and collider scenarios at the Tevatron yield accumulation of >2 x 10^{11} $\bar{p}$ /hr, cooling and stacking of >2 x 10^{12} $\bar{p}$ in 10 hr. Control of emittance growth mechanisms yields collisions with luminosity >2 x 10^{32} $cm^{-2}s^{-1}$ in each store and luminosity lifetime >10 hr. Nb_3Sn dipole development has yielded field strength >16 T, and 4-m-long coils using this technology have been tested successfully. We present a conceptual for a 100 TeV collider in which a single 16 T magnet ring is located in the SSC tunnel, and discuss issues from synchrotron radiation, electron cloud effect, and beam separation.

INTRODUCTION

Proton-antiproton colliding beams have produced two generations of discovery for high energy physics: the discovery of the electroweak bosons, the discovery of the top quark, and currently the search for the Higgs boson and supersymmetry. The Large Hadron Collider (LHC) at CERN will become the new center of effort for discovery, with a collision energy of 14 TeV and a design luminosity of 10^{34} $cm^{-2}s^{-1}$.

It takes a decade to prepare the technology and physics case for a next-generation collider, Today, at the dawn of the LHC era, it is appropriate to examine the options for next-generation facilities, and to examine the physics potential and its requirements for accelerator physics and related technology for each option. The International Linear Collider (ILC), the Compact Linear Collider (CLIC), a multi-TeV muon collider, and Machine X are all under discussion. Most of these proposed facilities would provide one or another complementary look at the energy scale to be opened by LHC, but none would make it possible to extend significantly beyond that scale.

Here we examine the case for a $p\bar{p}$ collider of 100 TeV energy and 10^{35} $cm^{-2}s^{-1}$ luminosity: the technology for a 16.5 T magnet ring, control of synchrotron light emitted by the beams, the elimination of subsidiary bunch crossings, the luminosity scaled from Tevatron performance, the SSC tunnel in Waxahatchie, and the physics potential of hadron collisions at 100 TeV.

CONTEXT FOR HIGH ENERGY PHYSICS

In high energy hadron collisions, scattering of constituent quarks and gluons is described by the parton distribution functions $f(x,Q^2)$. Dutta [1] has used the CTEQ6 distribution functions to calculate the parton luminosity for the *gg* production channel as a function of the parton center-of-mass energy τ for three cases: Tevatron (√s = 2 TeV), LHC (√s = 14 TeV), and Petavac (√s = 100 TeV).

Figure 1 shows that 100 TeV $p\bar{p}$ collisions provide the same factor increase of mass reach for new physics compared to LHC as LHC does compared to Tevatron.

16 TESLA DIPOLE TECHNOLOGY

For the past decade there has been a sustained program to develop high-performance multi-filament Nb_3Sn wire [2] and to develop coil technology for using it in high-field dipoles. A succession of innovations in Nb_3Sn coil technology has led to the successful testing of a short-model dipole to a central field strength of 16 Tesla, retaining 95% of the short-sample performance in its wire [3]. Techniques have been developed for control of Lorentz stress, preloading of windings [4,5], control of low-field instability [6], compact insulation [7], and suppression of persistent-current multipoles at injection field [8].

The LHC Accelerator R&D Program (LARP) has recently successfully fabricated and tested a racetrack dipole containing 3.6 m long Nb_3Sn racetrack coils [10]. While much development remains to be done, the above work lays a solid foundation for developing collider dipoles and quadrupoles with maximum field up to ~17 T.

In order to explore the parameters of such magnets for a Petavac, preliminary designs have been developed for a 16.5 Tesla dipole and a 450 T/m dipole, shown in Figure 2. All lattice magnets have cold aperture of diameter 60 mm and are designed to operate using supercritical He cooling with temperature cycle 4→6 K.

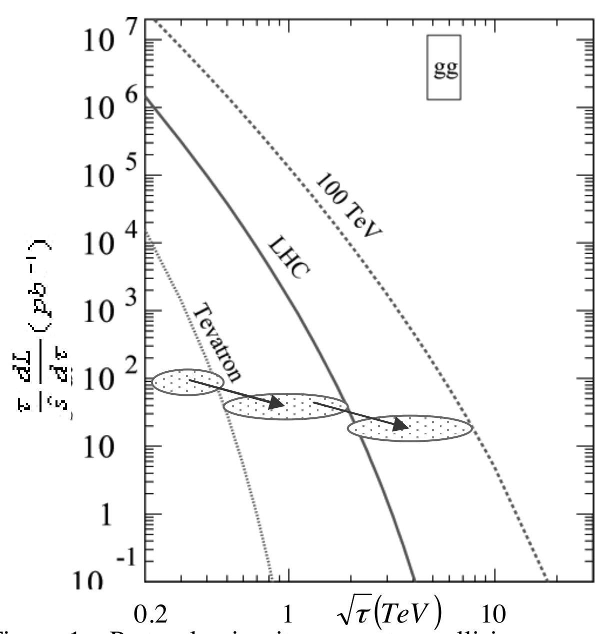

Figure 1: Parton luminosity *vs.* parton collision energy √τ for the gg channel in Tevatron, LHC, and Petavac.

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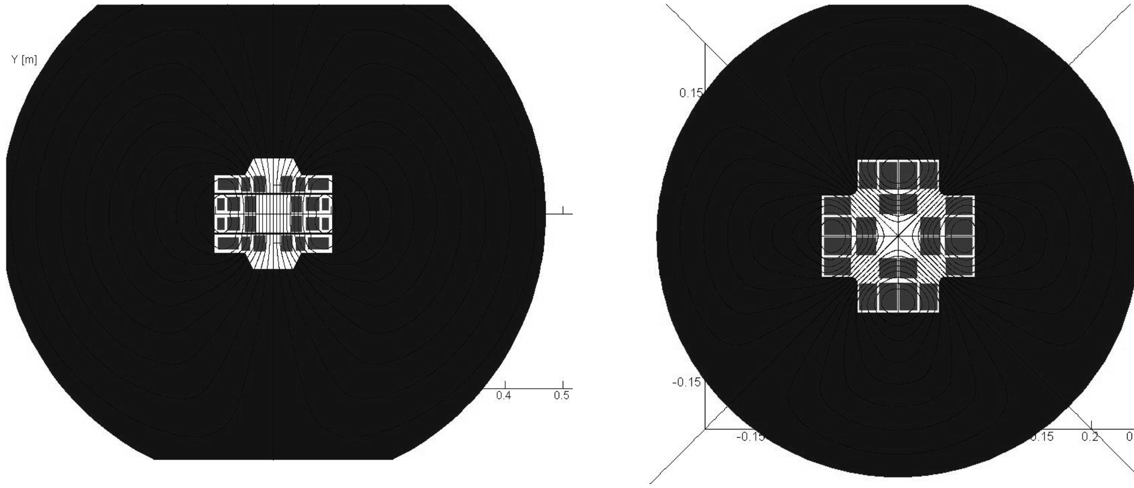

Figure 2: Cross sections of preliminary designs for 16.5 T dipole and 450 T/m quadrupole for 100 TeV collider.

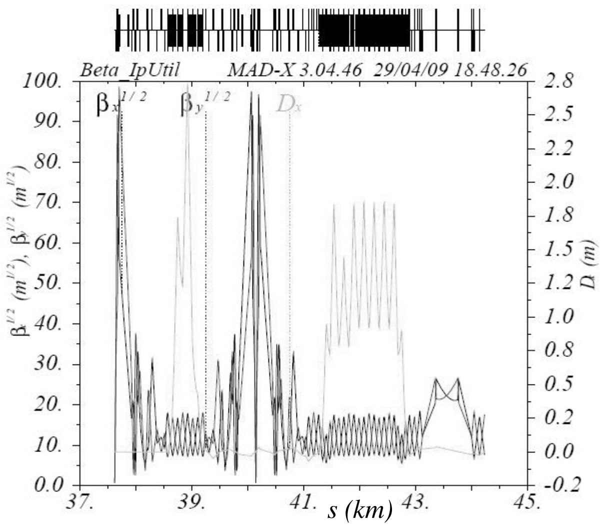

Figure 3: Lattice functions of Petavac, showing two low-beta insertions, dispersion matching, and one utility cell.

The dipole incorporates a pair of horizontal flux plates of magnetic steel which separates the central coil windingss from the top/bottom windings. It is is unsaturated at injection field and so imposes a strong dipole boundary condition that suppresses the multipoles from persistent currents in the superconducting strands. This provision is important to provide for a ~10:1 working range between injection and collision field strength.

It is interesting to note that the total cross-sectional area (80 cm^2) of Nb_3Sn superconductor in the coil of the 16 Tesla dipole is the same as the total quantity of NbTi superconductor required in the two magnet rings of LHC.

100 TEV COLLIDER IN SSC TUNNEL

A single storage ring of the above magnets in the SSC tunnel would support $\bar{p}p$ colliding beams at $\sqrt{s} = 100\,TeV$. The boring of the SSC tunnel was ~80% complete at the time when the project was cancelled. A superferric 5 TeV injector would be located in the same tunnel as Petavac, with bypasses in the two long straight sections.

The lattice is assumed to be similar to that of either SSC or LHC. An example lattice has been prepared, and is summarized in Fig. 3 which shows the betatron functions $\sqrt{\beta}$ and the dispersion D_x through one of the long SSC straight sections, then the dispersion-matching section and the first utility cell of the asymptotic lattice. For the lattice shown, β^*= 0.5 m, β_{max}= 9.6 km. The luminosity is directly related to the total beam-beam tune shift ξ produced by head-on and long-range tune shifts:

$$\xi = N_{IR} \frac{r_0}{4\pi} \frac{N_p}{\varepsilon} \qquad L = \frac{3\gamma\xi}{\beta^*}(Bf)N_{\bar{p}} \frac{F(\sigma_\ell / \beta^*)}{(1 + \varepsilon_{\bar{p}} / \varepsilon_p)} \quad (1)$$

where f= revolution frequency, B= number of bunches, ξ= beam-beam tune shift on the proton bunches, $\gamma = E/m_p$.

The luminosity increases adiabatically with energy ($\propto\gamma$) so that the present Tevatron luminosity of 3x10^{32} cm^{-2}s^{-1} would translate into a Petavac luminosity $L \sim 10^{34}$ cm^{-2}s^{-1}.

Over the past decade an electron lens system has been developed to compensate microscopically for the beam-beam tune shift [10]. Ref. 10 showed that two opposite electron lenses can be located to separately correct the tune shift ξ_n on each individual bunch in each beam. An a.c. dipole can be used to continuously measure ξ_n for each bunch [11]. Using such dynamic correction of all ξ_n to a common value it should be possible to operate at a luminosity of 10^{35} cm^{-2}s^{-1} with long lifetime.

The sustainable luminosity will be limited by the production rate of antiprotons to replace those lost in collisions. With a total cross section σ~ 100 mb, a luminosity of 10^{35}cm^{-1}s^{-1} would consume $\bar{p}$ s at a rate $\dot{N}_{\bar{p}}$~ 7x10^{13} $\bar{p}$ /hr, with a store time ~8 h. This would require ~100 greater accumulation rate than the Tevatron source.

For highest luminosity it will be necessary to control the electron cloud effect. For Petavac a clearing electrode is supported along the side wall of the beam tube and runs through the entire lattice. The electrode is biased +20 V, which is sufficient to clear the electron cloud produced by each bunch before the next bunch arrives.

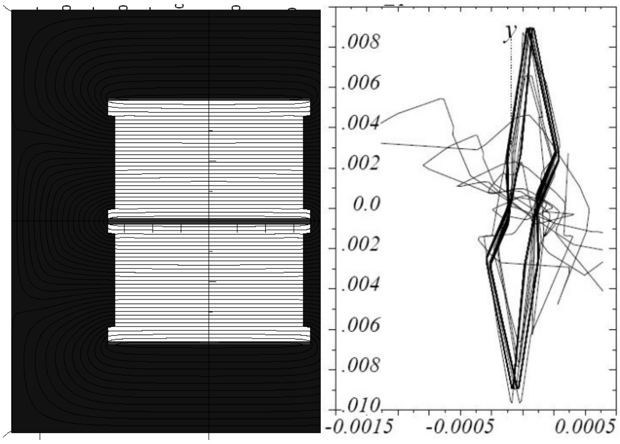

Figure 4: Vertical pretzel separation of beams: a) 1 T thin-septum dipole; b) separated orbits around the lattice.

BEAM SEPARATION

A bunch spacing of 20 ns produces 85 interactions per bunch crossing at luminosity 10^{35} $cm^{-2}s^{-1}$. Bunches are separated everywhere except at IPs using by locating a pair of 1 T thin-septum superferric septum magnets, shown in Fig. 4, flanking each intersection point (IP). The septum produces a horizontal magnetic field in the upper half-aperture, and reverse in the lower half-aperture. The two beams cross with ~200 μrad vertical angle at each IP and traverse a vertical pretzel everywhere else in the lattice. A small horizontal separation is introduced using electrostatic septa to provide supplementary separation.

SYNCHROTRON RADIATION

An obvious concern for a 100 TeV collider concept is synchrotron radiation. The power radiated into synchrotron radiation is

$$P = \frac{2}{3} \cdot \frac{e^2 \cdot c}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{\beta^4 \cdot \gamma^4}{\rho^2} \qquad (2)$$

At luminosity $10^{35}cm^{-2}s^{-1}$, the power radiated in one 20 m dipole is 1600 W! Were this to be intercepted on a cryogenic surface it would be unfeasible to refrigerate.

The spectrum of synchrotron light also hardens with energy: with peak at critical energy $E_c \sim \gamma^3$. The critical energy for LHC is 44 eV (hard UV, reflect from surfaces); for Petavac it is 4.4 keV (X-rays, absorb).

Photon stops are used in synchrotron light sources to localize the interception of synchrotron light of power comparable to that in Petavac. Figure 5 shows a design for a photon stop that would absorb the light emitted by both Petavac beams at room temperature. Operation of the blade at room temperature requires cold/warm/cold insertion between each 20 m dipole. The central portion of the device contains a double-blade which is hinged at each end and connected at its center to a linear actuator. During injection the actuators are retracted parallel to the wall so that full aperture is available for the injected beams. The actuator is moved in as the beam is accelerated. It intercepts all light radiated in the flanking pair of dipoles.

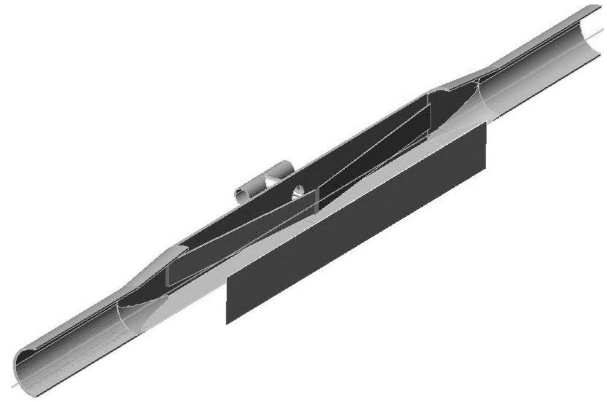

Figure 5: Photon stop to intercept synchrotron radiation at room temperature insertion between dipoles.

The warm-cold transitions in each photon stop consist of a ceramic tube with a sputtered film of copper on its inner surface. The 50 μm thick Cu film (skin depth at 1 MHz), dominates the heat budget of the photon stop. The calculated heat load of each photon stop is 6 W/dipole, giving a total cryogenic heat load that is comparable to that in LHC. Synchrotron radiation damps the beam emittance in all dimensions with time constant 45 min.

CONCLUSIONS

A single-ring proton-antiproton collider could be built using 16.5 T Nb_3Sn technology, and used to produce high-luminosity100 TeV collisions in the existing SSC tunnel. Substantiating the design will require development of full-length Nb_3Sn collider magnets and high-power photon stops and optimization of antiproton source design. There appear to be no fundamental barriers to attaining the required performance.

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