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 $>2 \times 10^{11}$ $\bar{p}$/hr, cooling and stacking of $>2 \times 10^{12}$ $\bar{p}$ in 10 hr. Control of emittance growth mechanisms yields collisions with luminosity $>2 \times 10^{12}$ cm^{-2}s^{-1} in each store and luminosity lifetime $>10$ hr. Nb$_3$Sn 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 $\sqrt{s}$ for three cases: Tevatron ($\sqrt{s} = 2$ TeV), LHC ($\sqrt{s} = 14$ TeV), and Petavac ($\sqrt{s} = 100$ 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$_3$Sn wire [2] and to develop coil technology for use in high-field dipoles. A succession of innovations in Nb$_3$Sn 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$_3$Sn 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 $\sim 17$ 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$\rightarrow$6 K.

Figure 1: Parton luminosity vs. parton collision energy $\sqrt{\tau}$ for the gg channel in Tevatron, LHC, and Petavac.
The dipole incorporates a pair of horizontal flux plates of magnetic steel which separates the central coil windings from the top/bottom windings. It 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$_3$Sn 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 $pp$ 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, $\beta^* = 0.5$ m, $\beta_{\text{max}} = 9.6$ km. The luminosity is directly related to the total beam-beam tune shift $\xi$ produced by head-on and long-range tune shifts:

$$\xi = N_{br} \frac{r_0}{4\pi} \frac{N_p}{\epsilon} L = \frac{3\gamma \xi}{\beta^*} (Bf) N_p \frac{F(\sigma_i / \beta^*)}{(1 + \epsilon_p / \epsilon_p)}$$

where $f=$ revolution frequency, $B= $ number of bunches, $\xi= $ 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 $3 \times 10^{32}$ 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 beambeam tune shift [10]. Ref. 10 showed that two opposite electron lenses can be located to separately correct the tune shift $\xi_n$ on each individual bunch in each beam. An a.c. dipole can be used to continuously measure $\xi_n$ for each bunch [11]. Using such dynamic correction of all $\xi_n$, 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 $\sigma \sim 100$ mb, a luminosity of $10^{35}$ cm$^{-1}$s$^{-1}$ would consume $\bar{p}$s at a rate $\bar{N}_p \sim 7 \times 10^{13}$ $\bar{p}$/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 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.
BEAM SEPARATION

A bunch spacing of 20 ns produces 85 interactions per bunch crossing at luminosity $10^{35} \text{ cm}^{-2}\text{s}^{-1}$. Bunches are separated everywhere except at IPs using 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 $\sim200 \mu\text{rad}$ 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

$$P = \frac{2}{3} \frac{e^{2} \cdot c \cdot \beta^{4} \cdot \gamma^{4}}{4 \cdot \pi \cdot \epsilon_{o} \cdot \rho^{2}}$$

At luminosity $10^{35} \text{ cm}^{-2}\text{s}^{-1}$, 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.

CONCLUSIONS

A single-ring proton-antiproton collider could be built using 16.5 T Nb$_{3}$Sn technology, and used to produce high-luminosity100 TeV collisions in the existing SSC tunnel. Substantiating the design will require development of full-length Nb$_{3}$Sn 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.

REFERENCES