COOLING FOR A HIGH LUMINOSITY 100 TeV PROTON ANTIPROTON COLLIDER

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Abstract

A 10^{34} cm^{-2} s^{-1} luminosity 100 TeV proton-antiproton collider is explored. The cross section for many high mass states is 10x higher in $p\bar{p}$ than pp collisions. Antiquarks for production can come directly from an antiproton rather than indirectly from gluon splitting. The higher cross sections reduce the synchrotron radiation in superconducting magnets and the vacuum system, because lower beam currents can produce the same rare event rates. Events are also more central, allowing a shorter detector with less space between quadrupole triplets and a smaller β^* for higher luminosity. To keep up with the antiproton burn rate, a Fermilab-like antiproton source would be adapted to disperse the beam into 12 different momentum channels, using electrostatic septa, to increase antiproton momentum capture 12x. At Fermilab, antiprotons were stochastically cooled in one debuncher and one accumulator ring. Because the stochastic cooling time scales as the number of particles, 12 independent cooling systems would be used, each one with one debuncher/momentum equalizer ring and two accumulator rings. One electron cooling ring would follow the stochastic cooling rings. Finally antiprotons in the collider ring would be recycled during runs without leaving the collider ring, by joining them to new bunches with snap bunch coalescence and longitudinal synchrotron damping.

INTRODUCTION

With the recent discovery of the Higgs boson [1] the standard model of particle physics is complete, but exploration will continue to search for beyond the standard model (BSM) physics. Colliders beyond $\sqrt{s}$ =14 TeV are necessary to fully explore new BSM physics, and this provides a great motivation for the future construction of a high energy $p\bar{p}$ collider [2, 3]. A 200 km circumference ring with 8 T NbTi magnets is chosen [4]. The tunnel is 2.5× longer than the twin 40 km tunnels proposed for the International Linear Collider. The center of mass energy considered would be 100 TeV with a luminosity of 10^{34} cm^{-2} s^{-1}. Energy frontier pp [5, 6] and $\mu^+\mu^-$ [7] colliders have also been proposed.

Synchrotron radiation of about 2 Megawatts per ring becomes a problem with circular 100 TeV pp colliders [8]. A $p\bar{p}$ collider represents a large advantage with respect to a pp collider in the point that the cross section for higher mass is around 10 times larger, which allows the collider to run with lower beam currents while still producing the same high mass event rate as pp. See Figs. 1 and 2. Synchrotron radiation in superconducting magnets and the vacuum system is reduced as well as detector radiation damage.

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Some important aspects to achieve high luminosity are identified in this study, such as increased momentum acceptance in a Fermilab-like antiproton source, and studies of higher antiproton cooling rates.

PROTON ANTIPROTON COLLIDERS

Proton antiproton colliders have been used at CERN [9], Fermilab [10], and GSI Darmstadt [11].

In $p\bar{p}$ collisions, antiquarks for production can come directly from an antiproton rather than indirectly from gluon splitting as is observed in Fig. 1, which shows the main process for W′ production in $q\bar{q}$ and qq collisions.

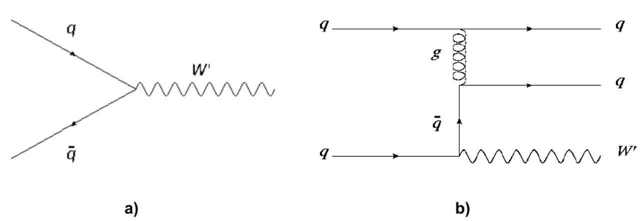

Figure 1: Feynman diagrams for W′ production in (a) $q\bar{q}$ collision, and (b) qq collision (t channel). The two final state quarks cross in the u channel, which is not shown.

In $p\bar{p}$ collisions, the cross section for most high mass states is greater than in pp collisions [2], as can observed in the Fig. 2, where the cross section is around 10x higher in $p\bar{p}$ collisions in W′ production as an example. It is important to note that the higher cross sections allow the collider to be run at lower beam currents and luminosities, which reduces synchrotron radiation in the collider's superconducting magnets and vacuum system. In addition, one beam pipe of magnets is shared by both beams, reducing costs with respect to the two beam pipes required for a pp collider, as well as simplifying the interaction region.

LUMINOSITY REQUIREMENTS

A main goal is to achieve a luminosity of 10^{34} cm^{-2} s^{-1}. As a starting point, take as reference the Tevatron collider. The luminosity can be scaled as:

$L_{scaled} = E_{increased} \times f_{decreased} \times L_{current}$ =
(50 TeV / 0.98 TeV) x (6.28 km/200 km) x (3.4 x 10^{32} cm^{-2} s^{-1}) =
5.2 x 10^{32} cm^{-2} s^{-1}
where f is collision frequency.

Thus, with 20 times more bunches a luminosity of 10^{34} cm^{-2} s^{-1} is achieved. The antiproton burn rate for a 100 TeV $p\bar{p}$ collider, with total cross section σ = 150 mbarn, is σL = 540 x 10^{10} /hr. The Fermilab Debuncher ring cooled 40

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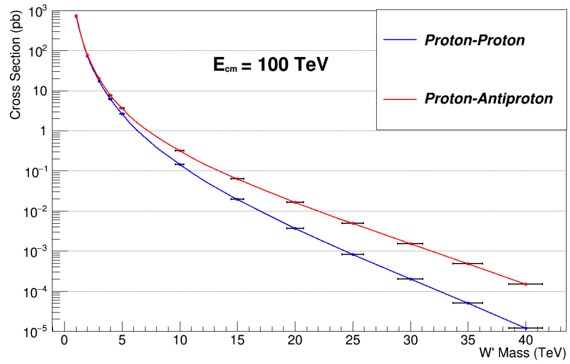

Figure 2: W′ cross section as a function of the mass using pp and $p\bar{p}$ collisions with E$_{\text{cm}}$ = 100 TeV using MadGraph [12].

x 10^{10} $\bar{p}$/hr, thus the number of antiprotons needed is 13.5 times more. The Fermilab Accumulator ring followed the Debuncher and cooled 25 x 10^{10} $\bar{p}$/hr. Providing more time for Accumulator ring deposition orbit longitudinal and transverse cooling might improve the Accumulator ring stacking rate [13].

ANTIPROTON CAPTURE AND COOLING

For the Tevatron, antiprotons were created by hitting an Inconel (a low expansion nickel-iron alloy) target with a beam of 120 GeV protons, producing antiprotons with a momentum peak of 8.9 GeV/c. Many antiprotons were rejected because of the momentum acceptance (8.9 ±2% GeV/c). Our goal is to collect more antiprotons from a Fermilab-like target station (8.9 ± 24% GeV/c), instead of creating more antiprotons. Thus, to keep up with the high luminosity antiproton burn rate, one or more dipoles would be adapted to spread the antiprotons into 12 different momentum channels using 11 electrostatic septa. The Fermilab Fixed Target Switchyard used eight electrostatic septa strings to deliver beam to nine primary slow spill users and one fast spill user [14]. A linear Fixed Field, Alternating Gradient channel [15] might be used to transport the 8.9 ± 24% GeV/c beam until it could be split.

At Fermilab, antiprotons were stochastically precooled in the Debuncher ring during 2.2 s, with transverse emittance reduction from 300 to 30 μm, then sent them to the Accumulator ring to be stochastically cooled and stored. There, the transverse emittance was reduced from 30 to 3 μm. The stochastic cooling time scales as the number of particles [16],

$$\tau \approx N \times 10^{-8}\text{s}. \quad (1)$$

Thus, to cool 12x more antiprotons, 12 independent cooling systems [17] would be implemented as shown in Fig. 3. Each system would have a debuncher/momentum equalizer, which would use RF cavities to reduce the 2% momentum spread by decelerating fast antiprotons and accelerating slow ones. In addition the central momenta of all 12 channels would be equalized. The debuncher would alternately feed two accumulator rings. This doubles the time in the accumulator ring deposition orbit for more cooling and reduces required stack sizes. Hopefully, two accumulator rings can keep up with one 40 x 10^{10} $\bar{p}$/hr debuncher output rate. A single electron cooling ring follows the stochastic cooling. Electrons can cool large numbers of low emittance antiprotons in one ring [18].

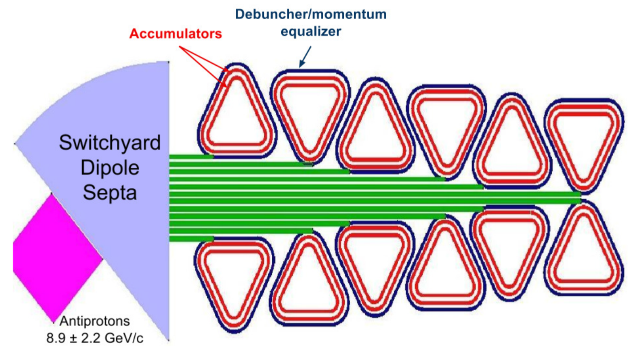

Figure 3: Independent cooling systems to cool more antiprotons. The 8.9 ± 2.2 GeV/c beam is spread by a bending magnet system and separated into 12 momentum channels using 11 electrostatic septa strings. Each debuncher ring phase rotates the beam to the lower the momentum spread and also ramps the beam central momenta up or down to 8.9 GeV/c. Each debuncher alternately outputs antiprotons to one of two associated accumulator rings.

COLLIDER PARAMETERS

For the 100 TeV $p\bar{p}$ collider, the 200 km ring could be constructed at CERN and connected to the LHC tunnel. For antiproton production, a Fermilab-like antiproton source would be adapted to the new collider with 12 debuncher and 24 accumulator rings for stochastic cooling. The 27 km LHC ring would serve as the Main Injector Ring. Table 1 lists the main parameters for the Tevatron, the LHC, a 100 TeV (pp) Future Circular Collider FCC-hh, and this100 TeV $p\bar{p}$ collider [6, 10, 19–21].

INTERACTION REGION

Events from $p\bar{p}$ collisions are more central than from pp collisions, allowing a shorter detector and quadrupole triplet focal length. Note that $\beta^* \beta_{\max}$ is proportional to f^2, where f is the focal length. The focal length is the distance from the center of the quadrupole triplet that focuses the beam to the interaction point as shown in Fig. 4. The luminosity is proportional to $1/\beta^*$ and the quadrupole bores are proportional to $\sqrt{\beta_{\max}}$. High luminosity and small quadrupole bores are desirable. The IR optics can be much improved with one rather than two rings. One beam can pass through a smaller quadrupole bore than two separated beams [24].

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Table 1: Parameter List for the Tevatron, the LHC, the Future Circular Collider FCC-hh, and the 100 TeV $p\bar{p}$ Proposed Here

Collider Parameters	**Tevatron**	**LHC**	**FCC-hh**	**100 TeV $p\bar{p}$**	**Unit**
Luminosity (L)	3.4 x 10^{32}	1.0 x 10^{34}	5.0 x 10^{34}	1.0 x 10^{34}	$cm^{-2}s^{-1}$
Energy Center of Mass (E_{cm})	1.96	14	100	100	TeV
Magnetic Field (B)	4.3	8.3	16	8	T
Circumference (C)	6.28	27	100	200	km
Collision Frequency (f)	0.048	40	40	1.08	MHz
Lorentz Gamma Factor (γ)	1044	7460	53304	53304	
Number of Bunches (N_B)	36	2808	10600	720	
Number of Protons/Bunch (N_p)	29 x 10^{10}	11.5 x 10^{10}	10 x 10^{10}	29 x 10^{10}	
Number of Antiprotons/Bunch (N_a)	8 x 10^{10}			8 x 10^{10}	
Normalized RMS Transverse Emittance (ε_N)	3.0 (protons)	3.75	2.2	3.0 (protons)	μm
	1.5 (antiprotons)			1.5 (antiprotons)	μm
Betatron Function at IP (β^*)	0.28	0.55	1.1	0.3	m
Beam Size at IP (σ)	33 (protons)	16.6	6.8	4.1 (protons)	μm
	29 (antiprotons)			2.9 (antiprotons)	μm
Beam-Beam Tune Shift per IP (ξ)	0.012 (protons)	0.003	0.005	0.012 (protons)	
	0.006 (antiprotons)			0.006 (antiprotons)	
Number of IPs (N_{IP})	2	4	2	2	
Hourglass Factor (H)	0.65	1	1	1	
Energy loss per turn (U_0)	0.0000095	0.0067	4.6	2.3	MeV
Longitudinal Emittance Damping Time (τ_ε)	305	13	0.5	2.0	h
Transverse Emittance Damping Time (τ_x)	610	26	1.0	4.0	h

IR parameters for a 100 TeV pp collider [23] are taken as reference to get a smaller L* (distance from the interaction point to the first quadrupole) by using the hard-edge model for quadrupoles. The beta values (β_x, β_y) are plotted as a function of the longitudinal coordinate s in Fig. 4.. The average value of β^* obtained correspond to 0.3 m. A gradient of 225 T/m could be provided by Nb_3Sn superconducting quadrupoles [25].

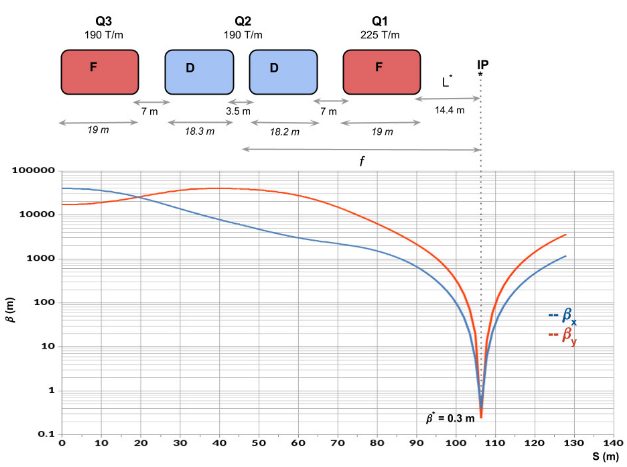

Figure 4: Betatron function distributions for the Interaction Region.

BUNCH RECYCLING

Antiprotons in the collider ring would be recycled without leaving the collider ring. This would increase the availability of antiprotons by a factor of about two. To allow this, the beam energy would have to be occasionally lowered as was done at the S$p\bar{p}$S ramping run [26]. Continuous (trickle charge) injection improved integrated luminosity at PEP-II [27]. Snap bunch coalescence [28] would be used to join new and old antiproton bunches, and then synchrotron damping would make the joined bunches smaller. Final antiproton cooling would be done by synchrotron damping in the collider ring, with longitudinal and transverse damping times of 2 and 4 hours, respectively.

CONCLUSION

A high luminosity proton-antiproton collider presents a promising future. It offers some advantages with respect to a proton-proton collider in terms of cross section for many high mass states, which are about 10x higher. This avoids high beam currents and reduces synchrotron radiation in superconducting magnets and the vacuum system. For antiproton production, Fermilab had a powerful antiproton source, which would be implemented and extended to capture and store 12 times more antiprotons, with 36 independent cooling rings. The antiproton yield increases by a factor of about 20 due to reduced accumulator ring losses.. Recycling antiprotons in the collider ring yields another factor of about two. A total of roughly 40 times more antiprotons than at the Tevatron may be enough to support two 100 TeV interaction points with a luminosity of 10^{34} cm^{-2} s^{-1} at each IP.

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