POTENTIAL ACCELERATOR IMPROVEMENTS REQUIRED FOR THE TEVATRON UPGRADE AT FERMILAB

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ABSTRACT

A considerable amount of effort has been dedicated toward understanding what accelerator improvements are required to reach a luminosity per detector exceeding 10^{33} cm^{-2} sec^{-1} at Fermilab. This effort has been popularly named the Tevatron33 project. Collider issues involve long range beam-beam interactions between the 100 or more bunches per beam traveling along separated helical orbits, the necessity of crossing angles at the interaction points, and beam instabilities. The main challenge of the injector chain is to produce more antiprotons at a faster rate. One potential improvement would be to configure the modified antiproton source to recycle the antiprotons left over at the end of each collider store. In this paper the current plan for implementing the Tevatron33 upgrade is reviewed.

I. BEYOND THE MAIN INJECTOR

After the demise of the Superconducting Super Collider, the Fermilab Tevatron Collider again became the highest energy collider in the world. With the discovery of the Top quark, a rich program of excellent high energy physics research has commenced. The possibility of further research aimed at discovering or ruling out the theory of supersymmetry, as well as the search for a possible low mass Higgs particle, has started a grass roots project to increase the Tevatron luminosity to 1×10^{33} cm^{-2} sec^{-1}. This project has been dubbed Tevatron33. The accelerator upgrades required to achieve this luminosity are based on the assumption that the Main Injector upgrade [2] is successfully completed.

The design luminosity of the Main Injector was approximately 1×10^{32} cm^{-2} sec^{-1}. Therefore, the Tevatron33 project calls for a luminosity increase of a factor of 10. The equation describing the luminosity is

$$L = \frac{N_P (N_A B) f_o (\beta_r \gamma_r)}{2\pi \beta^* (\varepsilon_{nP} + \varepsilon_{nA})} H\left(\frac{\beta^*}{\sigma_s}\right) \frac{1}{\sqrt{1 + \frac{2\alpha^2 \sigma_s^2 (\beta_r \gamma_r)}{\beta^* (\varepsilon_{nP} + \varepsilon_{nA})}}} \quad , (1)$$

where N_P is the number of protons per bunch, N_A is the number of antiprotons per bunch, B is the number of bunches per beam, f_o is the revolution frequency of the Tevatron Collider, $\beta_r\gamma_r$ is the relativistic momentum of each beam, β^* is the value of the focusing function at each of the interaction points, ε_n is the transverse normalized rms emittance, σ_s is the rms bunch length, and α is the crossing half angle between the proton and antiproton bunches at the interaction point. The degradation of the luminosity due to the shape of the focusing function around the interaction point coupled with an extended bunch length is referred to as the hour-glass form factor, which has a round beam closed form solution of

$$H(x) = \sqrt{\pi}\, x [1 - \Phi(x)]\, e^{x^2} \quad . \quad (2)$$

The ultimate limit to luminosity in hadron colliders to date has been the beam-beam interaction. This limit has been a total beam-beam linear tune shift ξ of approximately 0.025 (where r_p=1.535×10^{-18} m), and is defined by the equation

$$\xi = \frac{r_p}{4\pi} \frac{N}{\varepsilon_n} N_{IP} \quad . \quad (3)$$

The ratio of the proton bunch intensity to emittance is limited by the total beam-beam tune shift suffered at all interaction regions. Plugging the equation for this tune shift into the equation for luminosity per interaction region yields the result

$$L = \frac{(N_A B)}{N_{IP} \beta^*} \frac{2\xi_{max} f_o (\beta_r \gamma_r)}{r_p \left(1 + \frac{\varepsilon_{nA}}{\varepsilon_{nP}}\right)} \cdots \quad , \quad (4)$$

where the factors whose values can be modified appear in the left fraction. The quantity $N_A B$ is just the total antiproton intensity injected into the Tevatron, independent of bunch spacing. The number of interaction points N_{IP} is determined by the high energy physics community, and β^* is probably limited to 25 cm due to lattice control issues. Table 1 contains a list of the parameters which determine the luminosity in the past, present, and proposed future at Fermilab. Figure 1 is a summary of this luminosity history/proposed future in the form of a "Livingston Plot". It is impressive to note that the Main Injector project ensures the continuation of Fermilab's progress on the exponential curve which has as 2.3 year 1/e time.

II. ANTIPROTON PRODUCTION

Since the initial luminosity of a store depends proportionally on the number of antiprotons available for injection, the key to the proposed luminosity upgrades is to increase the maximum antiproton inventory intensity and also to increase the rate of production (stacking rate) of antiprotons. In addition to creating new antiprotons, the ability to reuse the antiprotons remaining at the end of the previous Tevatron Collider store also increases the luminosity.

Table 1: Parameter values for past, present, and proposed future Tevatron Collider runs. The column labeled MI contains the design numbers for the original Main Injector upgrade project. The column labeled Tevatron* is the replacement for the Main Injector scenario in the situation where the 8 GeV antiproton production storage ring in the Main Injector tunnel is built, allowing antiproton recycling from the previous store and storage of excess stacked antiprotons from the Accumulator ring. The Tevatron33 numbers are accessible after antiprotons stacking rate improvements are successfully implemented in addition to the commissioning of the new ring in the Main Injector tunnel. Invariant emittances quoted are in Fermilab units of 95%, which is 6 times the rms emittance.

Parameter	1988/9	1992/3	1995	MI	Tev*	Tev33
Protons/Bunch (10^9)	70	120	240	380	270	270
Antiprotons/Bunch (10^9)	29	31	55	36	45	66
Proton Emittance (π mmmr)	25	20	20	30	20	18
Antiproton Emittance (π mmmr)	18	12	18	15	15	15
Beta @ IP (cm)	55	35	35	25	25	25
Beam Energy (GeV)	900	900	900	1000	1000	1000
Bunches/Beam	6	6	6	36	36	108
Longitudinal Emittance (eV-s)	6.3	4.5	4.5	3.0	0.5	0.3
RMS Bunch Length (cm)	65	55	55	45	20	15
Interaction Regions	12	2	2	2	2	2
Minimum Bunch Spacing (ns)	3500	3500	3500	395	395	132
Luminosity Form Factors	0.71	0.62	0.62	0.58	0.81	0.88
Luminosity (10^{30} cm^{-2} s^{-1})	1.60	5.42	16.2	123	200	1000
Integrated Luminosity (pb^{-1}/week)	0.32	1.1	3.2	25	40	200
Interactions/Crossing (@ 45mb)	0.25	0.85	2.6	3.2	5.2	8.7
Total Antiproton Tune Shift	0.026	0.009	0.019	0.020	0.021	0.023
Total Proton Tune Shift	0.015	0.004	0.005	0.004	0.005	0.007
Antiproton Intensity (10^{10})	17	19	33	130	160	710
Loss Rate (10^{10}/hr @ 90mb)	0.62	0.35	1.0	8.0	13	64
Scenario	actual	actual	actual	design	goal	goal

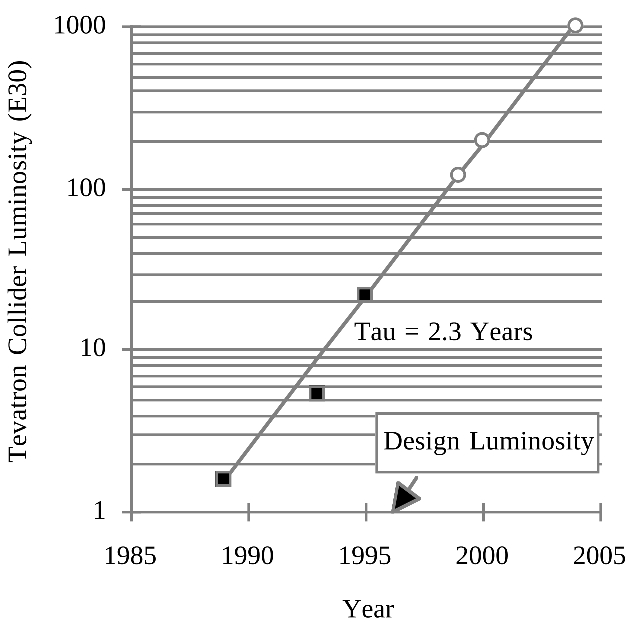

Figure 1: History of Tevatron Collider luminosity as a function of year is contained in the solid squares. The open circles represent design goals for the Main Injector upgrade and the luminosity upgrades presented in this paper (Tevatron* and Tevatron33).

The present Accumulator storage ring employs stochastic cooling to stack antiprotons. Because the cooling electronics can only tolerate a maximum intensity much less than that needed to achieve the Tevatron33 luminosity goal, it is necessary to build an addition storage ring to store the excess antiprotons. Recycling of the antiprotons left over at the end of the previous store can also be made possible by an additional storage ring. Since enhanced reliability is yet a third way to achieve higher effective stacking rates, the present plan is to build this additional ring in the Main Injector tunnel [3] with permanent magnets. This ring has an energy of 8 GeV and employs electron cooling for antiproton stacking and recycling. The electron cooling can also be applied to the protons before injection into the Tevatron.

Recycling of the antiprotons remaining at the end of the previous store is possible because one of the dominant sources of luminosity loss during the store is proton emittance growth due to intrabeam scattering. A numerical simulation of the evolution of the luminosity, beam emittances and intensities has been compared to observations in figure 2. Since the agreement is excellent, the model was applied to the projected parameters for Tevatron33 operations (see figures 3 through 5). Note that the longitudinal emittance of the antiproton bunches has exceeded the longitudinal admittance of the Main Injector, which is 0.5 eV-s. Therefore, deceleration of the antiprotons back down to 8 GeV for recycling is impossible unless the inverse of coalescing [4], called decoalescing, is employed at 150 GeV.

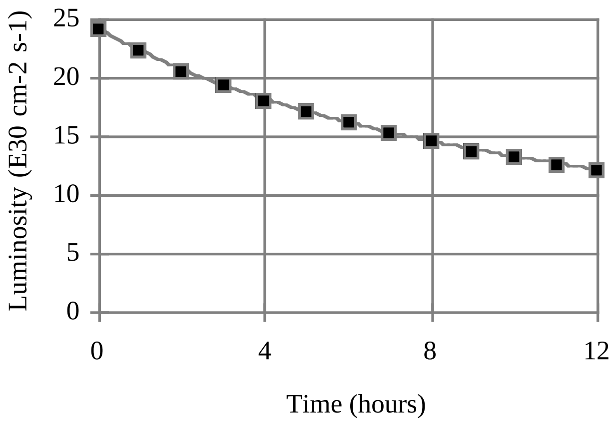

Figure 2: Comparison of measured luminosity (boxes) and a numerical simulation of the evolution of luminosity, beam emittances and intensities.

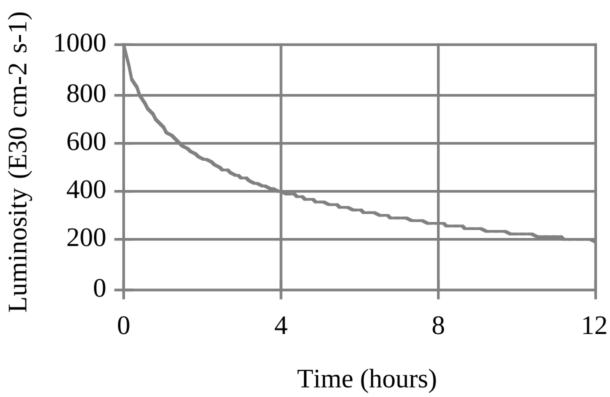

Figure 3: Tevatron33 numerical model prediction.

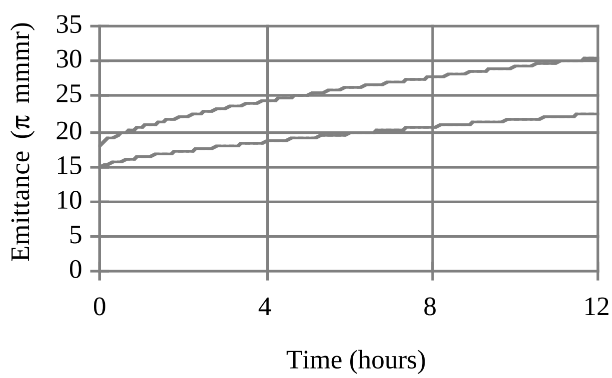

Figure 4: Tevatron33 numerical model predictions.

The initial usage of the permanent magnet storage ring in the Main Injector tunnel for antiproton storage and recycling is called Tevatron*. In that scenario no attempt is made to increase the rate at which new antiprotons are produced in order to achieve a luminosity twice that of the original Main Injector upgrade goal. Table 2 contains the results of calculations of the effect of antiproton recycling on the required stacking rate. Note that recycling alone is responsible for the luminosity increase needed for Tevatron*.

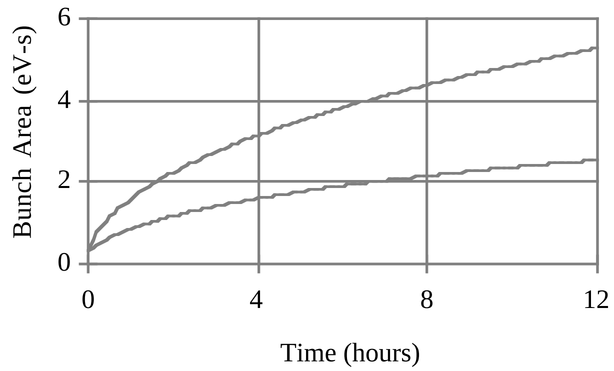

Figure 5: Application of the numerical model to Tevatron33 parameters.

There are a number of methods by which the factor of 5 improvement in stacking rate over that of the Main Injector design of 15×10^{10}/hr is achievable for Tevatron33 operations. The presently favored scheme is to increase the number of proton bunches delivered to the antiproton production target every 2 seconds. The implementation of this concept will require the development of a novel kicker magnet and improvements in the ability of the target and downstream optical system to handle the increased energy density and beam pulse length. Another method which will be employed in the years of adiabatic improvements leading up to Tevatron33 luminosities is the increase in the momentum aperture of the Debuncher ring [5]. Preliminary calculations show that an antiproton capture efficiency improvement exceeding 25% is achievable.

Table 2: Calculation of the required stacking rate of new antiprotons in the 3 upgrade scenarios.

Parameter	MI	Tev*	Tev33
Store Duration (hrs)	12	8	4
Antiproton Remaining (% Inj)	60	70	80
Recycling Efficiency (%)	0	90	90
Injection Eff. to LowBeta (%)	95	95	95
Usable Stack Required (10^{10})	137	168	747
Antiprotons Recycled (10^{10})	0	100	511
New Antiprotons Required (10^{10})	137	68	236
Required Stacking Rate (10^{10}/hr)	11	8	59

III. REFERENCES

[1] Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy.

[2] D. Bogert, "The Status of the Main Injector Project", this proceedings.

[3] G. Jackson and G.W. Foster, "Storage Ring for Enhanced Antiproton Production at Fermilab", this proceedings.

[4] J. Dey, et al., "Improvement in Bunch Coalescing in the Fermilab Main Ring", this proceedings.

[5] D. Olivieri, private communication.