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Fermilab Collider: Performance and Plans

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Fermilab Collider: Performance and Plans

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Abstract

The Fermilab collider program has completed its first physics run with two major detectors, CDF and D0. Recent performance of the Fermilab accelelerator complex during Run Ia is presented, along with plans to improve the luminosity of the collider. The beam-beam tune shift limitations of previous runs have been avoided by the successful implementation of electrostatic separators in the Tevatron. The simultaneous operation of two high luminosity sections is provided by two matched low beta inserts. The Antiproton Source has increased its performance over the previous run as measured by stack size and stacking rate. The Linac will be upgraded from 200 MeV to 400 MeV in order to lessen the space charge tune shift upon injection into the Booster and provide proton beams with increased intensity with the same emittance. Higher luminosity requires more bunches in the Tevatron to again avoid the limitation due to the beam-beam interaction. Until it is replaced with the Main Injector, the Main Ring will remain as the most significant bottleneck on the performance of the collider.

Current Performance

Goals for Run Ia

The primary accelerator goal for the most recent Tevatron collider run, Run Ia, was to deliver an integrated luminosity of 25 pb^{-1} to both the CDF and D0 detectors by the spring of 1993.

Secondary goals for the accelerators were:

1) integrated luminosity of 1 pb^{-1} per week,
2) typical initial luminosity of 5×10^{30} cm^{-2} sec^{-1}, and
3) efficient operation of both the CDF and D0 detectors simultaneously with antiproton production.

Highlights of Run Ia

Machine turn-on started April 20, 1992 and beam was injected onto separated orbits on May 26. The low beta insertions were commissioned along with the separators, and six proton bunches were colliding with six antiptoron bunches with an energy of 900 GeV per beam with sufficient luminosity at the start of Run Ia on August 31, 1992. Run Ia ended on May 31, 1993. The average initial luminosity over the last five months of the run was 5.4 x 10^{30} cm^{-2} sec^{-1} after scraping. The average integraged luminosity over the same period was 1.01 pb^{-1} per week. The total lumonisity delivered to CDF was 31.7 pb^{-1}, and that delivered to D0 was comparable.

Initial and Integrated Luminosity

The initial luminosity delivered to the detectors routinely exceeded 5×10^{30} cm^{-2} sec^{-1}. This is demonstrated in Figure 1 which shows the initial luminosity for both the most recent run (labeled 1992) and the previous run (labeled 1988). The "10X Running Average" means that the initial luminosities for a particular store and the nine previous stores are summed, divided by ten, and plotted. This averaging removes much of the scatter from store to store and presents a clearer picture of the underlying performance of the accelerator complex. The initial luminosity is recorded after scraping the beams to reduce the backgrounds at the two detectors. The record initial luminosity for the run was 9.22×10^{30} $cm^{-2}sec^{-1}$; however, this value does not appear in Figure 1 due to the averaging. The CDF luminosity is displayed; the luminosity for D0 is comparable. The luminosity lifetime at the beginning of a store was typically 12 to 16 hours, and it increased about 0.3 hour per hour during the store.

Figure 2 shows the integrated luminosity for each week and for the entire run, for both the most recent run and the previous run. The integrated luminosity for Run Ia was 31.7 pb^{-1}. The plateau near week 22 is due to a scheduled shutdown. The goal of 1000 nb^{-1} per week was exceeded a dozen times, and one week achieved 2.33 pb^{-1}. The decrease in weekly integrated luminosity after week 33 was primarily due to a change in programmatic emphasis: namely, once the Run Ia goal of 25 pb^{-1} was achieved, the emphasis shifted from strictly producing integrated luminosity to performing machine studies appropriate for the next run, Run Ib.

Figure 2 shows the integrated luminosity delivered to CDF. Approximately 70% of this was logged to tape. D0 logged about 20% less than CDF primarily due to the

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Figure 1. 1992 & 1988 Initial Tevatron Luminosity (10X Running Average)

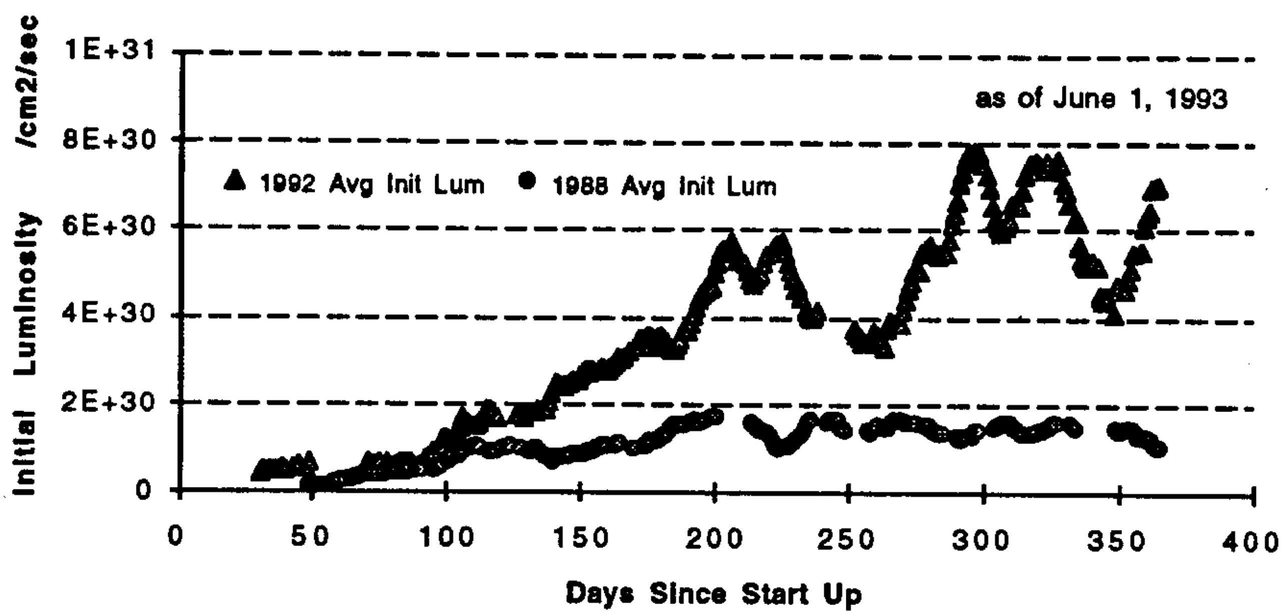
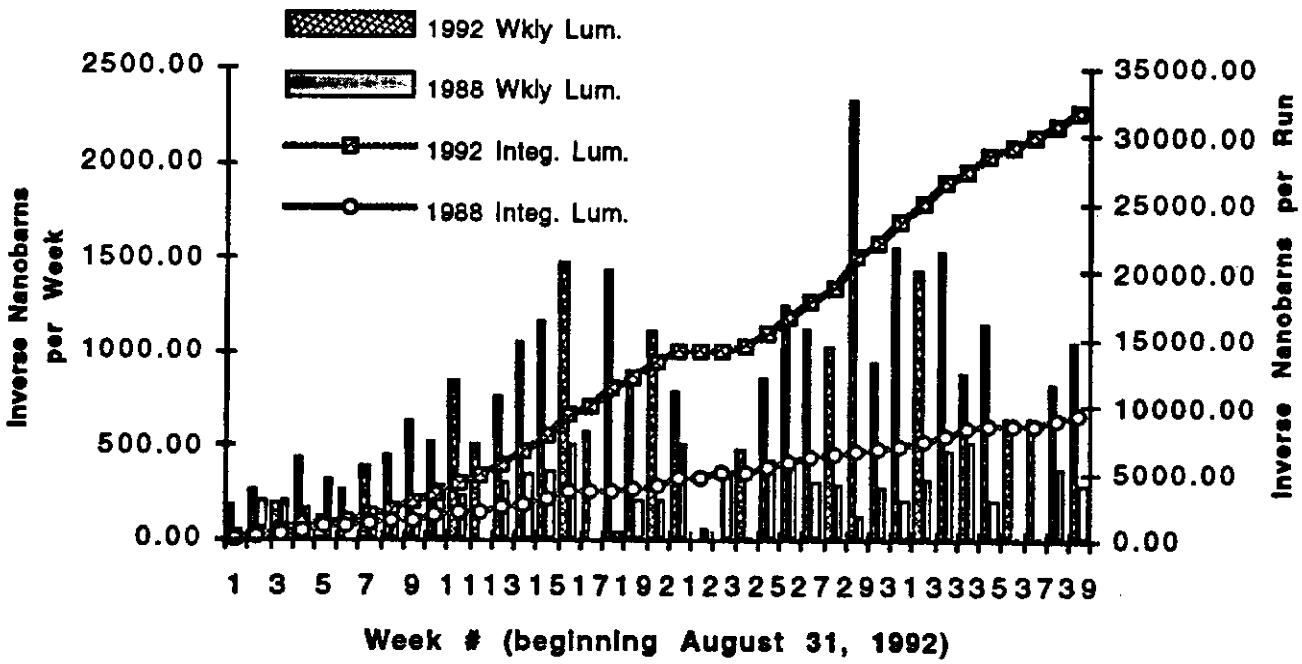


Figure 2. 1992 & 1988 Tevatron Integrated Luminosity



blanking required when Main Ring beam passes through the D0 detector during antiproton stacking. The concern that the D0 detector may not be able to run at all during stacking has been put to rest, but efforts to reduce this inefficiency continue.

Tevatron Improvements

In the previous run, with no separators and 6 bunches per beam, the beams collided 12 times per revolution. This resulted in a beam-beam tune shift which severely limited the proton brightness, and consequently the luminosity. (Brightness is the intensity divided by the emittance.) The implementation of separators in the Tevatron allow the beams to collide only at the two detector locations. The subsequent increases in the proton brightness (intensity / emittance) and the luminosity are given in the table. The gain realized in proton brightness contributing directly to luminosity was a factor of 2.7:

$120 \times 10^9 / 16\,\pi$ mm-mrad in Run Ia vs.
$70 \times 10^9 / 25\,\pi$ mm-mrad for the previous run.

The separators in the Tevatron provide two-dimensional helical orbits, not one-dimensional pretzel-like orbits (in the horizontal plane only) as in other accelerators. The separators functioned very well with only one spark in the first 3000 hours of system operation. The separators have been used to scan the beams through one another, and a summary of these results may be found in D. Siergiej et al., in the Proceedings of the Particle Accelerator Conference 1993, Washington D.C.

The helical orbits allow the use of families of trim sextupoles (both normal and skew) for adjusting the tunes and coupling of the proton and antiprotons beams independently. When sextupoles are used in this manner, they are called "feeddown sextupoles".

Another important Tevatron advance was the improved persistent current compensation during the initial stages of acceleration. Lack of proper compensation results in increased emittances for either the antiprotons or protons, or intensity loss, any of which degrade the initial luminosity.

Antiproton Source Improvements

The improvements in the Antiproton Source - especially the Accumulator stacktail system - have resulted in increased stacking rates. The improvements consisted of:

1) Using circuit board layouts instead of 3 dimensional loops for the kicker arrays provided mechanical tolerances of 75 μm instead of 750 μm,
2) The installation of microwave dampers in the kicker tanks to absorb undesired modes, and
3) The number of kicker tanks was increased from 3 to 10.

The development of techniques for stabilizing large antiproton stacks has been necessary. Clearing electrodes have been used to help expel trapped ions which are the primary problem. However, the clearing electrodes alone are not enough. Counter circulating protons, and bunching of the antiproton core have also been found to have a stabilizing influence. Some of the observations of the effects of trapped ions in the Antiproton Source were presented by P. Zhou and P. Colestock, S. Werkema et al., and A. Gerasimov, at the Particle Accelerator Conference 1993, Washington D.C.

Other Antiproton Source improvements included changes to the Debuncher cooling system and improved Debuncher to Accumulator transfer efficiency; these gave a factor of 1.3 gain in stacking rate. Improved rf curves for antiproton unstacking resulted in better longitudinal emittance preservation. This preservation is important due to the limited momentum aperture in the Main Ring.

With these improvements, the production rate exceeded 14 antiprotons per 10^6 protons on target. The stacking rate was typically 4.5×10^{10} antiprotons / hour at modest stacks and 3.5×10^{10} antiprotons / hour at stacks exceeding 10^{12}. The largest antiproton stack used for a store was 1.5×10^{12}, and the most number of antiprotons stacked in a week was 4.04×10^{12}.

Main Ring Improvements

Longitudinal instabilities in the Main Ring limit the efficiency of coalescing. (Coalescing is the process by which several - typically 11 - bunches are combined into a single high intensity bunch.) By speeding up the process of coalescing, so that the instability does not have time to develop, the intensity of the coalesced bunches has been increased from 80×10^9 to greater than 125×10^9. The "speeded up process" is called "snap coalescing". For additional details, refer to X. Lu and G. Jackson, and I. Kourbanis et al., to be published in the Proceedings of the Particle Accelerator Conference 1993, Washington D.C.

Additional Main Ring improvements included a feed forward system to reduce injection oscillations of antiprotons.

Collider Upgrade Plans

Overview

The table presents the plan for the upgrade of the collider. As noted previously, the most recent run (Run Ia) provided 1 pb^{-1} per week with a typical initial luminosity in excess of 5×10^{30} cm^{-2} sec^{-1}. (This exceeds the original Tevatron

I project goal by a factor of five.) The shutdown following Run Ia allows the final installation and commissioning of the Linac upgrade, and the installation of the cold compressors in the Tevatron. The integrated luminosity per week is expected to double in Run Ib which is scheduled to begin in the fall of 1993. Run II is not expected to provide much more integrated luminosity per week, but the energy of the Tevatron will be raised and the number of interactions per crossing will be greatly reduced by using 36 instead of 6 bunches per beam. Finally, a factor of five increase in the integrated luminosity will be provided by the Main Injector.

The form factor in the table describes the reduction in the luminosity which occurs when the bunch length is comparable to the beta function. It approaches 1.00 if the beta function is much larger than the bunch length. However, this is not the case for the actual case presented in the Tevatron as seen in the table where typically one only obtains about 2/3 of the luminosity one would naively expect from the bunch intensities, emittances and crossing rate.

Linac Upgrade

The Linac upgrade project will be completed in 1993. The kinetic energy of the H^- ions provided by the Linac will be increased from 200 MeV to 400 MeV. This is accomplished by replacing the last four sections of the present drift tube linac with seven side coupled cavity sections. The first 100 MeV of energy will still be provided by the original (20+ year-old) drift tube linac tanks. The beam will be transported to the Booster with a new 400 MeV beam transfer line. The calculated reduction in the space charge tune shift limit for injection into the Booster decreases by a factor of 1.75 which in principle allows for an equivalent increase in the proton intensity delivered by the Booster. However, the full utilization of this factor will not be attained until the Main Ring is replaced with the Main Injector.

Lower Temperature

Cold compressors and new valve boxes are to be installed in the 24 helium refrigerators for the Tevatron in the summer of 1993. These changes to the cryogenic system allow for subatmospheric operation of the helium system and a subsequent reduction of the temperature of the superconducting cable in the Tevatron magnets from 4.5^oK to 3.5^oK. Low temperature tests with half of the Tevatron have shown that this decrease in temperature is expected to raise the short sample limit of the cable and allow the beam energy of the Tevatron to be raised from 900 GeV to 1 TeV for collider operations. Run Ib will be used to gain experience with lower temperature operation, and the increase in energy is expected to become operational for Run II as shown in the table.

Multibunch Kickers

As the table shows, the Main Injector will result in typical initial luminosities in excess of $5x10^{31}$ $cm^{-2}sec^{-1}$. The present collider operates with 6 proton and 6 antiproton bunches colliding at the two detectors, CDF and D0. For the present configuration, the minimum spacing between bunches is 185 buckets. For the present typical initial luminosity, $5x10^{30}$ cm^{-2} sec^{-1}, the number of interactions in the detectors per bunch crossing is 0.79 (assuming a cross section of 45 mbarns). For Run Ib, typical initial luminosities are expected to exceed $1x10^{31}$ cm^{-2} sec^{-1}. Since the number of bunches per beam will remain at 6, the number of interactions per crossing will exceed 1.57. Certain types of physics - not including the discovery of the top quark - are done more efficiently if the number of interactions per crossing is kept below one. For Run II, the number of bunches per beam will be increased to 36, in order to reduce the number of interactions per crossing to 0.26. For this configuration, the minimum spacing between bunches will be 21 buckets.

With the Main Injector, the typical initial luminosity will exceed $5x10^{31}$ cm^{-2} sec^{-1}, and the number of interactions per crossing will exceed 1.31, again exceeding one. If the physics program requires it, some modest improvements to the Antiproton Source and the Tevatron can provide 99 bunches per beam with 7 bucket spacing. This would keep the number of interactions per crossing near one for luminosities of 1×10^{32} cm^{-2} sec^{-1}.

Additional details of bunch loading schemes can be found in J. Holt et al., to be published in the Proceedings of the Particle Accelerator Conference 1993, Washington D.C.

Antiproton Source

There are several improvements needed in the Antiproton Source to realize the upgrades given in the table. An h=4 rf system in the Accumulator will allow the delivery of 36 rather than 6 bunches. Improvements in Debuncher cooling include rebuilding the pickups to allow for 2 - 4 GHz operation and cooling the pickups to 20 ^oK. Increases in the apertures of the Accumulator, Debuncher and the beam transfer lines are also being evaluated. Finally, the Main Injector will deliver sufficient intensity at 120 GeV to the antiproton production target that the target is not expected to survive the shock. R&D on a beam sweeping system has begun.

Main Injector

The purpose of the Main Injector is to remove the Main Ring bottleneck in the delivery of high intensity proton and antiproton beams to the Tevatron. The Main Injector will remove backgrounds from the CDF and (especially) the D0 detector, since the Main Ring - which shares the tunnel with the detectors - will no longer be used. The Main Injector will allow for test beams and fixed target physics year round.

Most of the wetlands mitigation has been completed for the Main Injector. Groundbreaking for the project was March 22, 1993 and civil construction for the MI-60 enclosure and service building has begun. This building is at the point of tangency between the Tevatron and the Main Injector and will contain the rf for the new accelerator. This building also services the principle access point to the Main Injector tunnel. The R&D for the project has produced several dipoles which have met the required field quality. A prototype 200 kWatt power amplifier has been tested, and tests of the R&D dipole power supply (1,000 V / 10,000 Amps) will begin in the summer of 1993.

The funding profile in the President's FY94 Budget Request allows initiation of operations with the Main Injector in the summer of 1998.

Summary

The Tevatron Collider ran beautifully for Run Ia, and its luminosity goals were all met or exceeded. Fermilab is continuing along a path which will increase the luminosity by another factor of ten over the remainder of the decade. The Tevatron complex offers challenging research opportunities, both in the coming decade and into the 21st century.

Final Note

The author wishes to thank all the many accelerator and high energy physics collaborators who have contributed to the work summarized in this paper, although only a few of their contributions are mentioned by name. Each individual's professional contributions to the team effort have made it a pleasure to describe an ongoing success story as stunning as the Fermilab Collider.

Table of Fermilab Collider Upgrade Parameters

	1989	Ia	Ib	II	Main Injector	
Protons/bunch	7.0×10^{10}	1.2×10^{11}	1.5×10^{11}	1.5×10^{11}	3.3×10^{11}	
Pbars/bunch	2.9×10^{10}	3.6×10^{10}	4.5×10^{10}	7.5×10^{9}	3.7×10^{10}	
Proton emittance	25	16	16	16	30	mm-mrad
Pbar emittance	18	16	16	16	22	mm-mrad
Beta at IP	0.55	0.50	0.35	0.35	0.5	m
Beam Energy	900	900	900	1000	1000	GeV
Number of Bunches	6	6	6	36	36	
Bunch length (rms)	0.65	0.5	0.5	0.5	0.65	m
Form Factor	0.71	0.76	0.65	0.65	0.68	
Luminosity*	1.60×10^{30}	5.37×10^{30}	1.03×10^{31}	1.15×10^{31}	5.60×10^{31}	$cm^{-2}sec^{-1}$
Integrated Luminosity	0.32	1.08	2.08	2.31	11.28	pb^{-1}/week
Bunch spacing	3000	3000	3000	396	396	nsec
Interactions / crossing (@ 45 mbarn)	0.25	0.84	1.62	0.30	1.47	
Antiproton tune shift	0.025	0.011	0.014	0.014	0.016	
Proton tune shift	0.014	0.003	0.004	0.001	0.002	
What's New?		Separators, D0 Detector, Pbar Improvements	Linac	Faster Kickers and Cold Compressors	Main Injector	

*Typical luminosity at the beginning of a store; translates to integrated luminosity with a 33% duty factor.