STATUS AND FUTURE OF THE TEVATRON

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The Fermilab Tevatron proton-antiproton collider is nearing the completion of a long physics run at 1.8 TeV in the center-of-mass with a goal of delivering 100 pb^{-1} each to the CDF and D0 detectors. An 800 GeV fixed target run is scheduled to begin in 1996. Recent performance of the accelerator complex, culminating in the reliable delivery of integrated luminosity in excess of 2 pb^{-1} per week, is presented. The prospects for improving the delivery of integrated luminosity to a level in excess of 10 pb^{-1} per week for the next collider run, presently scheduled to begin with the completion of the Main Injector project, will be presented. Finally, ideas related to extending the luminosity beyond the stated goals of the Main Injector, as well as possible alternate directions for the continuation of Fermilab's successful accelerator R&D program, will be discussed.

I. INTRODUCTION

The Fermilab accelerator complex consists of a 400 MeV Linac, an 8 GeV Booster, a 150 GeV Main Ring, a 900 GeV superconducting Tevatron and associated transfer and extraction beamlines. In addition, there is an Antiproton Source that contains two 8 GeV synchrotrons, the Debuncher and Accumulator. The Main Ring supplies the 120 GeV proton beam to generate antiprotons that are then accumulated in the Antiproton source. The complex has two major modes of running, collider and fixed target. In the former mode, beams of protons and antiprotons are brought into collisions at a center of mass energy of 1800 GeV. In the latter mode, protons are accelerated to 800 GeV and delivered to a number of experiments at the ends of various extraction beamlines. Typically fixed target running alternates with collider running every year or two.

Fermilab is coming to the end of a collider running period that has been designated as Run 1b. Since the initial commissioning of the Tevatron as the world's highest energy proton-antiproton collider in 1985, there have been four collider runs, i.e. the 1987 Run, the 88-89 Run, Run 1a in 1992 and the current Run 1b. There has been a steady increase in the delivered luminosity every run from the 0.07 pb^{-1} delivered in the first three month long collider run in 1987. In the 88-89 Run typical initial luminosities of 0.16 x 10^{31} $cm^{-2}sec^{-1}$ were seen and the integrated luminosity in that 14 month run was 9.6 pb^{-1}. At that point the luminosity in the Tevatron was limited by the beam-beam tune shift. The installation of electrostatic separators prior to Run 1a reduced the number of beam crossings from twelve to two. This enabled the Tevatron to reach typical luminosities of 0.54 x 10^{31} $cm^{-2}sec^{-1}$ and integrate a total of 32 pb^{-1} at two interaction regions (B0 and D0). The collider luminosity was now limited by the available proton beam that could be injected in the Booster and, hence, be used for antiproton production and for proton injection into the Tevatron. The limit in the Booster was due to space charge effects at injection from the 200 MeV linac. The Linac Upgrade project increased this injection energy to 400 MeV, thereby improving the performance of the collider complex. This improved performance has been demonstrated in Run 1b which has seen typical luminosities of 1.89 x 10^{31} $cm^{-2}sec^{-1}$ and which has already delivered more than 100 pb^{-1} to each of the two experiments at the two interaction regions.

Run 1b is presently scheduled to end on July 24, 1995. The next collider run, Run II, will start after the commissioning of the new Main Injector synchrotron. Between the end of Run 1b and then, there is scheduled a total of 68 weeks of Tevatron fixed target running at an energy of 800 GeV as welll as the Tevatron collider studies needed for the success of Run II.

At present the luminosities delivered by the collider are limited by the proton beam intensity coming out of the Main Ring. The Main Injector synchrotron is designed to replace the Main Ring and alleviate these limits. The proton bunch intensities in the Tevatron are expected to increase modestly and the antiprotons injected into the Tevatron increase much more. This is expected to generate another factor of five increase in delivered luminosity. After this, no more gains can be made from increasing the proton bunch intensities in the Tevatron. However further increases in the antiproton accumulation rate can give a factor of up to ten increase in delivered luminosity, i.e. greater than 10^{33} $cm^{-2}sec^{-1}$ typical initial luminosities and 200 pb^{-1} integrated luminosity per week. Ideas for achieving this goal are lumped under the name TEVATRON33.

There is significant effort at Fermilab to look at the very far future and R&D effort is going on looking at the feasibility of higher energy proton-proton colliders, muon colliders and other projects. This work is of a very speculative nature, but it is hoped that project proposals will result for the next generation of high energy accelerators.

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II. RUN 1B STATUS

A. *Stacking and storing choreography*

During collider runs the accelerator complex has two distinct operational modes, i.e. "shot setup" and "stacking and storing". At the end of a store, the beam is aborted out of the Tevatron and shot setup starts. The antiproton beam transfers between the Accumulator and Main Ring and between the Main Ring and Tevatron are checked using "reverse protons". Then the Tevatron is loaded with six intense proton bunches and six intense antiproton bunches. Each intense bunch is generated by coalescing eleven bunches in the Main Ring at flattop. The proton and antiproton bunches are injected onto electrostatically separated orbits. Beam is then accelerated to Tevatron flattop. Strong focusing low beta quadrupoles either side of each interaction region squeeze down the beam spot size and the beams are then brought into collisions at the centers of the two collider detectors. At this point the Tevatron provides collisions at the two experiments, and the Main Ring and the Antiproton Source are reconfigured to produce and accumulate antiprotons. Shot setup typically takes 2.5 hours and the stores last about 16 hours. The luminosity lifetime is such that the luminosity drops by a factor of three during a typical store. It should be pointed out that the exact daily schedule depends on many factors, including component failures. On average the collider provides luminosity for the experiments about two thirds of the time.

B. *Luminosity Formula*

The luminosity in a synchrotron collider is given by

$$\boxed{L = \frac{fN_p(BN_{\bar{p}})}{2\pi(\sigma_p^2+\sigma_{\bar{p}}^2)}F(\sigma_z/\beta^*) = \frac{3\gamma fN_p(BN_{\bar{p}})}{\beta^*(\varepsilon_p+\varepsilon_{\bar{p}})}F(\sigma_z/\beta^*)}$$

At Fermilab, the convention used is 95%, normalized emittances. For emittances that are roughly equal this equation factorizes as follows

$$L \quad \propto \quad (N_p/\varepsilon_p)\ \ x\ \ (BN_{\bar{p}})$$

i.e. that the luminosity is proportional the product of the phase space density of the proton bunches and the number of antiprotons in the collider for a particular store. The ultimate particle phase density is limited by the beam-beam tune shift in the Tevatron. At the design operating point, this limit is approximately 1.5 x 10^{10} particles per π mm-mrad. The integrated luminosity depends on the initial luminosity and the luminosity lifetime. The length of a store depends on being able to replenish the accumulator stack for antiprotons used in a shot setup and on maximizing to total integrated luminosity delivered to the experiments.

C. *Run 1b highlights*

The Linac upgrade was completed by October 1993 and the accelerator startup began. The Tevatron saw some beam by November, 1993. Between then and July 1994 collider performance was well below what was expected and indeed even below the performance during Run 1a. The problem was finally traced down to a badly rolled low beta quadrupole in the B0 interaction region. This caused the Tevatron beams to be badly coupled leading to large emittances and low initial luminosities. Once this was corrected the performance improved by a factor of three. In October and November, 1994 there was an obstacle in the Main Ring. This obstacle was a sliver of metal that would stand up in the beam every so often as the Main Ring ramped. This reduced performance by 20% and was eventually found by very careful detective work. In February of 1995, additional coalescing RF cavities were installed in the Main Ring and the resulting increased RF voltage improved bunch coalescing significantly. Also, a 2-4 GHz stochastic core cooling system was recommissioned in the antiproton accumulator. When used in conjunction with the standard 4-8 GHz system, there was a marked improvement in the antiproton accumulation rate.

D. *Run 1b Performance*

The present performance in Run 1b is a factor of 3.5 better than in Run 1a. This improvement results from injecting more protons and antiprotons into the Tevatron. Figure 1 shows the steady increase in beam intensities. Data from both Run 1a (before store number 4500) and Run 1b is shown. The figure shows that both the proton and antiproton intensities have gone up by a factor of almost two. Given that there has been no significant increase in emittances, this increased intensity has directly translated into improved performance. After store 5400 the coalescing RF upgrade was made operational and a 10% improvement in proton and 20% improvement in antiproton intensities is seen. With typical proton and antiproton emittances of 24π and 13π mm-mrad the single bunch proton and antiproton phase space densities are 1.0 x 10^{10} and 0.6 x 10^{10} particles per π mm-mrad respectively. Comparing these numbers with the beam-beam limit of 1.5 x 10^{10} particles per π mm-mrad indicates that the number of bunches used in collider operation will have to be increased to get significantly more luminosity.

Figure 1: Proton & Antiproton Bunch Intensities

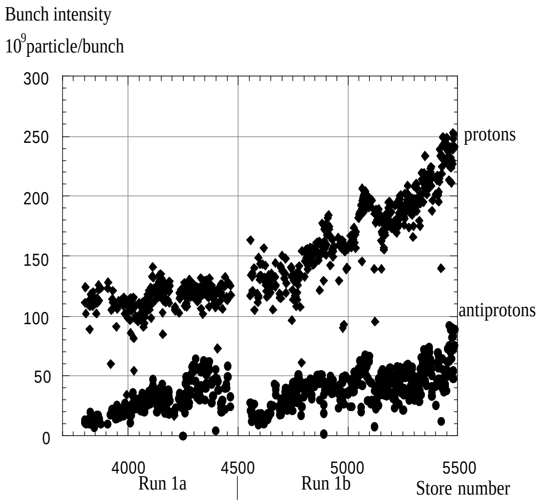

Figure 2: Peak Luminosity Evolution

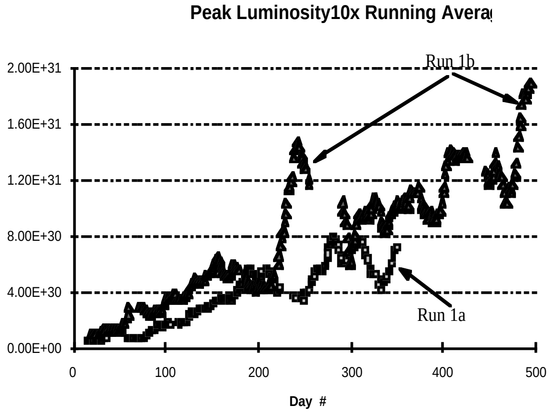

Figure 3: Luminosity per store hour (nb^{-1}/hour)

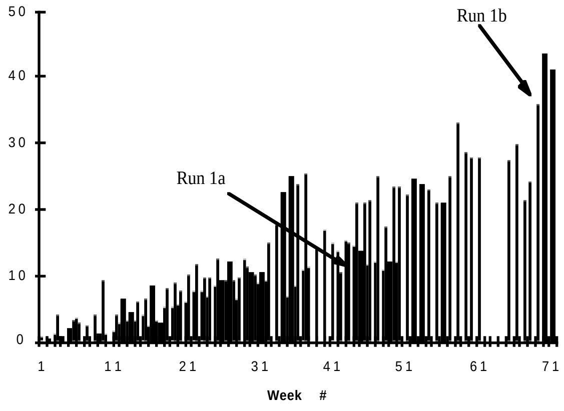

Figure 2 shows the evolution of peak luminosity as a function of days into Run 1b. The Run 1a data is also shown for comparison. The displayed luminosity is a ten times running average and it is seen that recently initial luminosities of 2 x 10^{31} $cm^{-2}sec^{-1}$ are regularly obtained.

Figure 3 shows the luminosity delivered per store hour. This plot is a good measure of performance because the downtime of machines and store length effects are factored out. It is seen that in the last few weeks the per store hour delivered luminosity is greater than 40 nb^{-1} per hour, a number that compares favorably with the 70 nb^{-1} that was delivered in the entire 1987 run. The per store hour luminosity in Run 1a was 11 nb^{-1} per hour.

Table I shows the actual and expected (Run II, Run II+ and TEV33) evolution of parameters at Fermilab. After a slow start, Run 1b has been very successful, delivering greater than 100 pb^{-1} so far. Luminosities of greater than 2 x 10^{31} $cm^{-2}sec^{-1}$ are regularly achieved and the machine reliability has been excellent. It is expected that modest improvements, at the level of 10-20%, to the present performance will be seen by the end of the run. The run goal of 130 pb^{-1} will be easily achieved by the end of the run. Further statistics may be found in reference [1].

III. FERMILAB III

Fermilab III is the generic name given to all the improvements to the accelerator complex that are needed for Run II. The major part of Fermilab III is, of course, the construction and commissioning of a new synchrotron, the Main Injector [2]. Equally important to the success of Fermilab III is the design and construction of new components and the improvements to existing components that are needed to fully exploit the design capabilities of this new ring.

From the discussion above on the Run 1b status, it is seen that the machine performance is now being limited by Main Ring. The Main Ring limits both the proton bunch intensities and the antiprotons accumulated, and hence the antiproton bunch intensity. The Main Injector is designed to alleviate these constraints. Table I shows how Tevatron parameters will change as a result of the Main Injector. The Run II column represents the standard collider parameters using the Main Injctor. Run II+ shows the improvements that can be achieved using new low beta systems and a higher frequency RF system in the Tevatron collider. The Main Injector is in its own enclosure and this has the added benefit of eliminating the backgrounds due to Main Ring losses at the collider experiments. In addition, the Main Injector is also designed to extract beam for fixed target experiments at 120 GeV during collider operation.

Table I: Fermilab Collider Parameters

Collider Parameters	**88-89 Run**	**Run 1a**	**Run 1b**	**Run II**	**Run II +**	**TEV33**
Protons/bunch (10^{10})	7.00	12.00	22.50	33.00	33.00	24.00
Antiprotons/bunch (10^{10})	2.90	3.10	6.50	3.60	3.60	10.00
Proton emittance (π mm-mr)	25	20	22	30	25	18
Antiproton emittance (π mm-mr)	18	12	14	20	20	18
Beta* at interaction point (meters)	0.55	0.35	0.35	0.35	0.25	0.25
Energy (GeV)	900	900	900	1000	1000	1000
Number of bunches	6	6	6	36	36	108
Bunch length (RMS , meters)	0.65	0.55	0.55	0.43	0.17	0.26
Form factor	0.71	0.62	0.62	0.70	0.86	0.75
Typical luminosity (10^{31} $cm^{-2}sec^{-1}$)	0.16	0.54	1.89	8.29	14.20	104.00
Best luminosity (10^{31} $cm^{-2}sec^{-1}$)	0.21	0.92	2.31	12.40	20.00	157.00
Integrated Luminosity (pb^{-1}/ week)	0.32	1.09	3.82	16.72	28.66	210.62
Bunch spacing (nsec)	3000	3000	3000	396	396	132
Interactions/crossing (@ 45 mb)	0.25	0.85	2.98	2.17	3.72	9.13
Antiproton tune shift	0.025	0.009	0.015	0.016	0.016	0.020
Proton tune shift	0.014	0.004	0.007	0.003	0.003	0.008
Average luminosity lifetime (hours)	20	17	15	14	14	13
Typical Antiproton Stack (10^{10})	70	120	180	300	300	900
Antiproton stacking rate (10^{10}/hour)	1.5	3.0	4.5	16	16	80

A. *Fermilab III Physics Goals*

The physics goals of Fermilab III are

1. Tevatron Collider:
    - precision measurement of of W and top masses
    - b meson production rates of 10^{10} per year
    - search for new phenomena at high mass, high P_T
    - peak luminosities in excess of 5 x $10^{31}cm^{-2}s^{-1}$ (see Table 1 for Run II collider parameters)
    - delivered luminosities greater than 10 pb^{-1}/week
    - 2 TeV energy in the center of mass

2. Main Injector fixed target.
    - short and long baseline neutrino oscillations
    - rare K decays
    - greater than 3 x 10^{13} protons per pulse @ 120GeV, 2 second repetition

3. Tevatron fixed target
    - quark spectroscopy
    - greater than 6 x 10^{13} protons per pulse @ 1000 GeV, 60 second repetition

B. *Accelerator Performance Issues*

Fermilab III has an ambitious set of physics goals. In order to realize these goals the accelerator complex will have perform better than at present. Some of the needed performance criteria are discussed here.

In the Antiproton Source the stacking rate will have to increase by a factor of three. This will require more protons on the production target and a target beam sweeping system will have to be implemented in order to achieve the needed antiproton stacking rate. Run II will have 36 x 36 bunch operation and the Antiproton Source will have to deliver 36 ensembles of up to 11 bunches.

For collider operation, the Main Injector will need to deliver 5 x 10^{12}, 120 GeV proton batches to the antiproton production target every 1.5 seconds with 20 π mm-mrad transverse emittance and less than 0.5 eV-sec longitudinal emittance per bunch. In addition, the Main Injector will have to supply intense proton and antiproton bunches to the Tevatron. For the Main Injector fixed target operation, various different scenarios are needed such that the needs of the fixed target experiments and the antiproton source are simultaneously satisfied. Most of these needs require a pulse repetition rate of about two seconds and proton beam intensities of 3 x 10^{13} proton per pulse. For the Tevatron fixed target operation, the Main Injector will supply two pulses of 3 x 10^{13} protons to fill the Tevatron to an intensity of 6 x 10^{13}..

In collider mode the Tevatron will accept 36 bunches of protons and antiprotons and accelerate them to 1 TeV. Beam-beam effects, both short and long range, may become important at this time. In fixed target mode the Tevatron will have to accelerate and extract 6 x 10^{13} protons per pulse.

In collider mode the Fermilab III beam intensities will be a factor of ten larger and in fixed target a factor of three larger than at present. Understanding of beam dynamics and stability will be essential. For the past few years, and continuing until Fermilab III is fully commissioned, there has been a program to design, build and commission active beam damper systems for the various accelerators at Fermilab. This work is critical for the success of the Fermilab III upgrade. In addition there will have to be considerable work done on the accelerator control system to ensure that the various beam transfer scenarios are operational and the accelerator systems are easy to debug.

D. Main injector Schedule

The construction of the Main Injector is progressing well. It will be completed and beam commissioning will start in February 1998. Commissioning for Run II will start in January 1999 with beams for antiproton production. Run II is expected to provide colliding beams for experiments by March 1999 and 120 GeV fixed target beams by the middle of August 1999.

IV. BEYOND FERMILAB III

The Main Injector and the associated Fermilab III upgrade are expected to be fully operational in the year 2000. At this point there are still further improvements in collider performance that may be contemplated. In additional novel accelerator concepts using some parts of the existing accelerator complex are being actively discussed.

A. High Frequency RF in the Tevatron

One way to get as much as a 70% increase in luminosity in the Tevatron collider is to reduce the bunch lengths at collisions in conjunction with new low beta systems to further lower the β^* at the interaction regions. The smaller bunch lengths are most easily achieved by installing a higher frequency, 159 MHz, RF system in the Tevatron. The parameter set for such an option is shown in Table 1 under column Run II+. There is a large increase in the delivered luminosity from 16 to 28 pb^{-1} per week. One important parameter in the table is the interactions at the experiments per beam crossing. This number is uncomfortably large for the HEP detectors. One way to reduce this parameter is to increase the number of bunches in the Tevatron. This will not increase the overall luminosity, indeed it may even reduce the luminosity if a crossing angle is required, but it will reduce the interaction per crossing. This scenario may produce better physics on tape at the collider experiments.

B. TEVATRON33

After Fermilab III is fully operational luminosities of 10^{32} $cm^{-2}sec^{-1}$ will be routine. Looking at the collider parameters in Table 1 it is seen the protons bunch intensity is near the beam-beam limit. The only gain left is to increase the antiproton bunch intensity to the same limit. This requires a factor of ten more antiprotons and hence an antiproton stacking rate that is the same factor of ten larger. Ideas to effect this and increase luminosity to 10^{33} $cm^{-2}sec^{-1}$ range are lumped under the name TEVATRON33 [3]. The improved antiproton accumulation rate is achieved by building a new synchrotron called the "Recycler" in the Main Injector tunnel. This at present is thought to be a permanent magnet ring utilizing electron cooling to achieve very small emittances. In addition the antiproton production rate can be increased by targeting more than one batch of protons from the Main Injector onto the production target or by using a linear debuncher to accept a larger momentum bite out of the antiproton production target. The parameters of the TEVATRON33 upgrade are given in Table 1.

C. 2020

Fermilab is actively pursuing an R&D program to look at the very far future. A large fraction of this R&D is being done in collaboration with other laboratories and institutions. Amongst the ideas being discussed are higher energy "Tevatron" colliders, a very high energy proton-proton collider, muon colliders and TeV scale e^+e^- linear colliders. It is hoped that these discussions will coalesce into proposals that can be presented to the US HEP community.

[1] "Fermilab Collider Run 1b Statistics", V. Bharadwaj et al, proceedings this conference.

[2] "The Fermilab Injector Complex", D. Bogert, proceedings this conference.

[3] "Potential Accelerator Improvements Required for the Tevatron Upgrade at Fermilab", G. Jackson & G. W. Foster, proceedings this conference.