TEVATRON RUN II PERFORMANCE AND PLANS

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Abstract

The Fermilab accelerator complex has been operating Run II for approximately one year. In this mode 36 proton bunches collide with 36 antiproton bunches at 2 interaction regions in the Tevatron at 980 GeV beam energy. The long range goal in Run II is to obtain a total integrated luminosity of 15 pb^{-1}. The current status and performance of the accelerator complex is described, including the Tevatron, Main Injector, Antiproton Source, and Recycler Ring. Future upgrade plans and prospects for reaching the admittedly ambitious long range goal are presented.

1 COLLIDER OPERATIONS AT FERMILAB

There are 2 basic modes during Collider operation: antiproton stacking and "shots." A shot is the process of loading the Tevatron with protons and antiprotons.

In stacking mode, a batch of 84 53MHz proton bunches is extracted from the Booster Ring at 8 GeV and injected into the MI (Main Injector) every 2.2 seconds. These are accelerated to 120 GeV and extracted to the antiproton production target. 8 GeV antiprotons from the production target are then delivered to the Debuncher Ring where they are debunched and stochastically cooled. These are then transferred to the Accumulator Ring where they are stacked and stochastically cooled into a "core."

Every ~14 hours stacking is stopped in preparation for a shot. A batch of 7 53MHz proton bunches is extracted from the Booster, injected into the MI, accelerated to 150 GeV, coalesced into a single bunch, and then injected into the Tevatron. This process is repeated every ~12.5 seconds until 36 proton bunches are loaded into the Tevatron on its central orbit. Electrostatic separators are then turned on in the Tevatron in preparation for antiproton injection. Antiprotons are extracted from the Accumulator in 4 batches of ~7 53MHz bunches, injected into the MI, accelerated to 150 GeV, coalesced into 4 single bunches separated by 396 nsec, and then injected into the Tevatron, counter-rotating with the protons and separated by the helical orbit. This process is repeated 9 times. The beam in the Tevatron is then accelerated to 980 GeV, a low beta squeeze is executed, and the beams are finally brought into collisions at the 2 IR's (Interaction Regions). An entire shot typically takes ~3 hours from the end of the previous store to the start of the next store. A Collider store generally lasts ~14 hours which is approximately 1 luminosity lifetime.

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2 CURRENT STATUS AND ISSUES

Table 1 lists the current status of important Collider parameters along with the Run IIa goals for 2002.

Table 1: Important Run IIa parameters. Column 2 shows best values on 1/1/2002, column 3 shows best values on 5/25/2002, and column 4 shows goals for 1/1/2003

Parameter	**1/1/02**	**5/25/02**	**1/1/03 goal**
antiproton production rate (E10/hr)	10	11	18
Accumulator core size (E10)	115	120	165
antiproton transfer efficiency	.23	.37	.80
antiprotons/bunch @ low beta (E9)	7.6	10.8	33
protons/bunch @ low beta (E9)	115	196	270
transverse emittance @ low beta (π-mm-mrad)	16.0	16.3	17.5
peak luminosity	0.8	2.0	8.6

Figures 1 and 2 show the peak luminosity and the proton and antiproton intensities at the start of each store for stores from 11/28/01 to 5/25/02. Over the last five months significant gains have been made in increasing the proton intensity at low beta, but increasing the antiproton intensity at low beta has been problematic. There are two major reasons for this: 1) The transverse emittance of the antiprotons in the Accumulator core is large -- about twice as large as it was in Run I for similar core intensities. The transfer efficiency of antiprotons from the Accumulator core to 980 GeV is dramatically reduced because of this large transverse emittance (see Table 1). 2) The long range beam-beam interaction in the Tevatron severely reduces the antiproton lifetime and causes excessive emittance growth at 150 GeV.

Extensive recent studies indicate that the large Accumulator transverse emittance is due to an increase in the IBS (IntraBeam Scattering) contribution to beam heating in the core. The Accumulator lattice was modified between Run II and Run I in order to increase the bandwidth of the stacktail cooling system from 1-2 GHz to 2-4 GHz. This bandwidth increase was necessary to support higher stacking rates for Run II. This lattice modification changed the value of η, the slip factor, from

.023 to .012 in order to avoid Schottky band overlap in the stacktail cooling system.

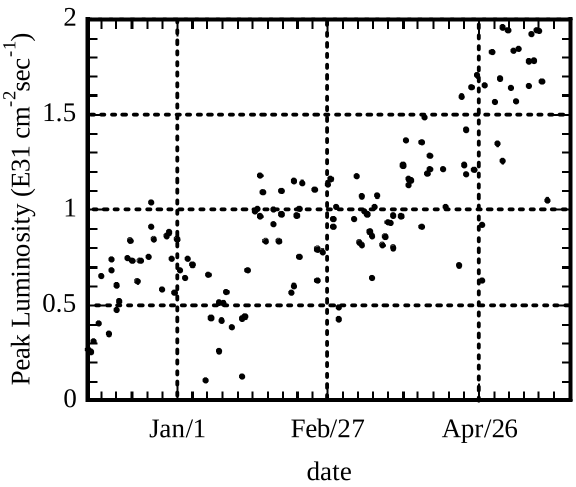

Figure 1: Peak luminosity vs. date for Run II from 11/28/01 to 5/25/02

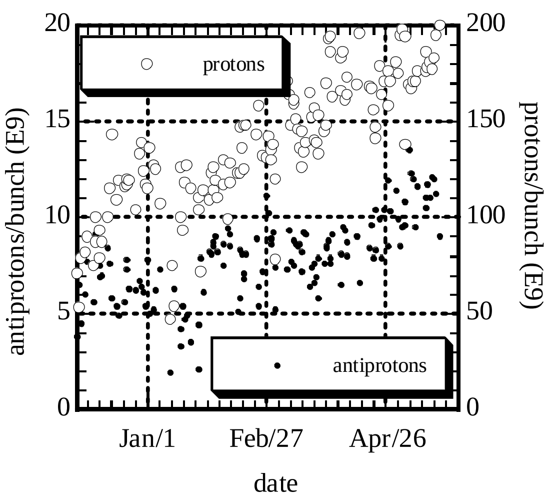

Figure 2: Proton and antiproton intensity at low beta vs. date for Run II from 11/28/01 to 5/25/02

Unfortunately it was not appreciated that this lattice modification also increased the IBS term

$$H = \frac{D^2 + (\beta D' + \alpha D)^2}{\beta}$$

by a factor of 2.5. Here, D is the dispersion function, D' is the derivative of the dispersion, α and β are the normal lattice functions, and H is averaged over the ring.

The plan to mitigate the excessive core heating is twofold. 1) During a 2 week shutdown in early June a new Accumulator core stochastic cooling system will be installed. This system will increase the cooling bandwidth by a factor of 2, thus increasing the cooling rate by a factor of 4. 2) A second Accumulator lattice is being commissioned to be used only during shots. This lattice will reduce the IBS heating term by a factor of 2.5. The Accumulator will therefore be operated at 2 distinct lattices -- one for shots and one for stacking. It takes about 60 seconds to ramp between the two lattices.

The other serious limitation to Run II luminosity is the long range beam-beam interaction in the Tevatron [1]. During Run I the number of parasitic beam-beam crossings was 12; in Run II it is now 72. Even though the beam-beam tune shift is relatively small, ~.003, the lifetime of the antiprotons is dramatically reduced by the presence of protons at 150 GeV in the Tevatron. The typical beam separation on the helix is ~5 beam sigmas. Over the last few months improvements have been made in the helical orbit increasing the separation between protons and antiprotons. This has improved the antiproton lifetime at 150 GeV and the antiproton efficiency during the transition from the injection helix to the collision helix. These modifications have increased the antiproton transfer efficiency (from Accumulator @ 8 GeV to collisions @ 980 GeV) from ~23% to ~37% even while increasing the proton intensity by 70%.

In a shutdown in the Fall of 2002, the limiting aperture in the Tevatron (3 C0 Lambertson magnets) will be removed and replaced with wider aperture dipole magnets, allowing the helix to be opened an additional ~30%. Modification to the lattice at the A0 sector (possibly in the Fall 2002 shutdown) will yield additional improvements in the helix. The completion of longitudinal and transverse dampers in the Tevatron in the summer of 2002 will allow the chromaticity to be reduced (currently it is set at ~10 units). This will increase the 150 GeV lifetime. Also, methods of using the existing octupole circuits to provide differential chromaticity for the protons and antiprotons are being investigated.

3 RECYCLER COMMISSIONING

The Recycler Ring is an 8 GeV antiproton storage ring situated in the MI tunnel enclosure [2] [3]. Its purpose is twofold: 1) provide for final 8 GeV antiproton storage, beyond the Accumulator; 2) allow for reusing the antiprotons which remain at the end of a Tevatron store.

The Accumulator antiproton core size is probably limited to ~200E10 antiprotons. There are two reasons for this. First, as the stack size increases, the efficacy of the core stochastic cooling systems drop (like 1/N). The heating of the core from the stacktail cooling system does not decrease with N, therefore the antiproton stacking rate drops as the core size increases. Second, as the core size increases, trapped ion instabilities become increasing difficult to control. The Recycler has a circumference 7 times larger than the Accumulator, therefore for a given core size, the line charge density is less and it is probably not as sensitive to trapped ions. In addition, electron cooling [4] is planned to be installed and commissioned in the Recycler in 2004, and the cooling rate in this case does not scale like 1/N. Without the Recycler being used for 8 GeV antiproton storage and recycling, peak luminosities in the Tevatron above ~1E32 are probably very difficult to obtain.

Currently luminosity in Run IIa is being produced with antiprotons delivered from the Accumulator. The Recycler is still in a commissioning stage but steady improvements in performance is being made. Figure 3 shows the antiproton transfer efficiency from the Accumulator to Recycler for a recent series of 3 transfers.

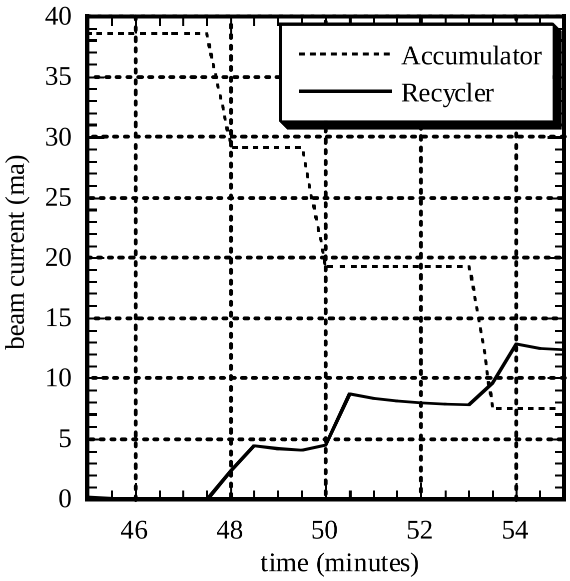

Figure 3: Antiproton transfer efficiency from Accumulator to Recycler. Efficiency here is ~39%.

The major known problems confronting Recycler commissioners, with proposed solutions, are:

1) Beam lifetime is ~100 hours due to poor vacuum. In the next two shutdowns (June 2002, Fall 2002) the number of ion pumps will be doubled and the entire ring will be baked to >100ºC.

2) The tunes are modulated by stray fields from the MI ramping. During the next two shutdowns more magnetic shielding will be added and ramped power supplies will be installed on some Recycler quadrupole corrector magnets.

3) The injection and extraction apertures are small and the injection line is poorly matched due to an initial design error. Calculations and studies are currently underway to understand and fix these problems.

4) The circulating beam aperture is ~30 π-mm-mrad, while the design is 40 π-mm-mrad. Additional dipole correctors and power supplies are being installed to provide more orbit control.

5) A very fast beam loss just after injection may be a sign of poor field quality, or small dynamic aperture in the Recycler. This is currently under investigation with beam studies.

It is anticipated that the Recycler will be commissioned and fully integrated into Collider operations before the end of 2003.

4 PLANS TO INCREASE ANTIPROTON PRODUCTION RATE

Assuming the number of protons/bunch in the Tevatron is limited by the beam-beam interaction, the only way to increase luminosity substantially is by increasing the number of antiprotons/bunch at collisions. Fermilab has an ambitious plan to increase the antiproton production rate to ~60E10/hr to meet the long term Run II goals. This plan consists of the following upgrades [5].

1) "Slip stacking" in the MI will increase the proton intensity on the antiproton production target by a factor of ~1.8. Under current operations a single batch of 84 bunches of protons is injected into the MI on each antiproton production cycle. With slip stacking two successive batches of protons will be injected into the MI from the Booster on each acceleration cycle. These batches will initially be captured in independently controlled RF systems in the MI. The 2nd batch will then be "slipped" longitudinally with respect to the 1st batch until both batches can be captured by one RF system and then accelerated. This technique has been successfully tested with low intensity proton batches. Further improvements in beam loading compensation on the MI 53 MHz RF cavities will be required to implement this technique for high intensity proton batches.

2) Antiprotons are produced at the production target with a very large angular spread which are then collected and focused by a lithium lens [6]. The collection efficiency increases as the lens gradient increases, but the lens gradient is currently limited by mechanical constraints. That is, the shock wave induced by the ohmic heating of the fast current pulse damages the inner lens septum. Improvements in lens design, fabrication, and filling techniques are underway to try to push the maximum operating gradient from 750 T/m to over 900 T/m.

3) The transverse collection aperture of the beamline downstream of the lithium lens is currently only ~16 π-mm-mrad. Modest improvements in this aperture, primarily in the beamline at the Debuncher injection channel will increase this to >30 π-mm-mrad.

4) The increased antiproton flux into the Accumulator from the above upgrades will require an increase in the Accumulator stacktail stochastic cooling bandwidth from the current 2-4 GHz to 4-8 GHz [7]. With this new cooling system, antiproton transfers from the Accumulator to the Recycler will need to take place at least once every 20 minutes, as a large core intensity will not be maintainable in the Accumulator.

5 132 NSEC OPERATION

For a fixed number of bunches in the Tevatron, as the luminosity increases, the number of interactions per crossing at the IR's increases. This makes it increasingly difficult for the Collider detectors to efficiently trigger on interesting events and increasingly difficult to unambiguously reconstruct interesting events offline. It is thought that much above a peak luminosity of ~1.5E32

$cm^{-2}sec^{-1}$ (average of ~5 inelastic interactions per crossing), Collider detector data acquisition and analysis will become severely compromised due to multiple interactions per crossing for 36 bunch operation (396 nsec bunch separation). This is the motivation for considering operating the Tevatron at 132 nsec bunch separation (140 proton bunches x 100 antiproton bunches).

Figure 4 shows a calculation of the weekly integrated luminosity under three future operational scenarios: 1) 36x36 operation with the Accumulator only; 2) 36x36 operation with the Recycler and "luminosity leveling"; and 3) 140x100 operation with a crossing angle at the IR's. When antiproton production rates exceed ~20E10/hour it might be advantageous to switch to 132 nsec operation. However, 132 nsec operation in the Tevatron introduces additional difficulties which are not trivial to overcome.

1) The long range beam-beam effects will become ~3.8 (140/36) times more severe than they are now for 36 bunch operation. There is not yet a clear plan for mitigating this fundamental problem.

2) Unless the beam-beam effects can be otherwise compensated for, a crossing angle must be introduced at the IR's in order to avoid head-on parasitic bunch crossings on either side of each IR. This is because the electrostatic separators which separate the beams are located outside the 1st set of parasitic bunch crossings. This crossing angle reduces the peak luminosity (for given proton and antiproton intensities), but increases the luminosity lifetime.

3) Collider detector backgrounds are already severe in 36 bunch operation. These backgrounds will probably scale with proton intensity, which will be ~3.8 times higher in 132 nsec operation.

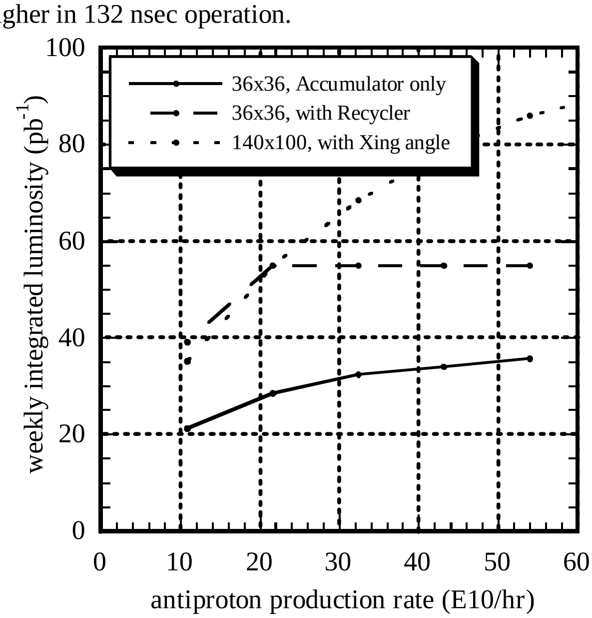

Figure 4: Potential integrated luminosity for future operating scenarios for the Tevatron. Reasonable assumptions on downtime and transfer efficiencies are made in all 3 cases. The 36x36 case with Recycler is luminosity leveled to keep the number of interactions/crossing < 5.

The hardware upgrades required for 132 nsec operation are currently in process.

1) New electrostatic separators are being built to implement a helix with crossing angles at the IR's. A preliminary lattice solution has been developed.

2) The new Tevatron proton injection kickers will require an additional minor upgrade so that the kicker rise time is <132 nsec. Currently the 5 kickers are run as a group of 3 in parallel with a group of 2. The upgrade will be to run them all in parallel.

3) A new 7.5 MHz RF cavity is being built for installation in the MI to support 132 nsec bunch spacing.

4) A TEL (Tevatron Electron Lens) [8] is currently installed in the Tevatron and has been undergoing beam tests for over a year. This device consists of a 10 KV electron beam coaxial with the antiproton beam for 2m in the Tevatron. The electron beam provides a tune shift to the antiprotons which is intended to compensate the proton-induced tuneshift. During recent studies, TEL-induced tune shifts of over .01 have been measured. A second TEL will be installed during the Fall 2002 shutdown so that tune shifts can be controlled in both horizontal and vertical dimensions. The possibility of using the TEL to induce nonlinear tuneshifts, and hence control tune spread, is being investigated [9]. The TEL may eventually be capable of controlling tunespread well enough to reduce the IR crossing angle in 132 nsec operation or compensate for long range beam-beam effects.

6 REFERENCES

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