AN OVERVIEW OF TEVATRON COLLIDER RUN II AT FERMILAB

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Abstract

The Run II era at Fermilab began in March 2001. Many changes to the accelerator complex were made to support the Tevatron proton-antiproton collider operation with peak luminosities of 2-4 $\times 10^{32}$ cm^{-2} s^{-1} while delivering greater than 5 fb^{-1} of integrated luminosity before the LHC begins its physics program. This report describes the current status of Run II operations and the machine performances needed to achieve our goals.

Introduction

The Fermilab accelerator complex underwent many modifications in preparation for Run II. The most notable changes include: the construction of the Main Injector, which replaces the Main Ring from Run I; the construction of the Recycler Ring, which will be used for storing antiprotons produced in the pbar source, as well as the antiprotons remaining in the Tevatron after an physics store; increasing the Tevatron beam energy from 900 GeV to 980 GeV; operating the Tevatron as a 36×36 bunch collider. The current Fermilab complex is depicted in Figure 1. More detailed information about the Run II program can be found in [1].

Proton Source

The proton source consists of a 25 keV H^- source, a 750 keV Cockcroft-Walton accelerator, a 400 MeV linac to accelerate the H^-, and the 8 GeV Booster synchrotron.
Many of the components are now 30 years old, and maintaining these machines is a priority for Run II operation.

Main Injector

The Main Injector is a new 150 GeV synchrotron occupying a new tunnel. The Main Injector replaces the Main Ring that resided in the Tevatron tunnel. The principal advantage of the Main Injector is the ability to provide a higher repetition rate to support antiproton production while simultaneously providing protons for fixed-target operations. The various operating modes of the Main Injector include: providing up to 5×10^{12} 120 GeV protons per pulse for antiproton production with 2.0 second cycle time; accelerating protons and antiprotons to 150 GeV for injection into the Tevatron, transferring 8 GeV antiprotons from the Accumulator to the Recycler; providing 8 GeV (and eventually 120 GeV) protons for neutrino production. Additionally for the Tevatron, the Main Injector RF cavity system coalesces several proton or pbar 53 MHz bunches at 150 GeV into a single, higher intensity bunch within a 53 MHz bucket. In current typical running, 7 proton bunches are coalesced with 90% efficiency into a single 270-300 $\times10^9$ bunch. Seven to eleven antiproton bunches, depending upon extraction from the Accumulator, are coalesced with 80-90% efficiency into single bunches with 25-35 $\times10^9$ particles.

Pbar Source

Fast and efficient antiproton production is a key factor for the success of Run II. Lattice modifications and stochastic cooling tank upgrades in the Debuncher and Accumulator are necessary to take advantage of the higher repetition rate allowed by the Main Injector. The antiproton stacking rate varies inversely with the stack size, starting at 11×10^{10}/hr and falling to 6×10^{10}/hr as the typical 140×10^{10} stack intensity is reached. The transverse emittance of the antiproton stack varies linearly with the stack size. Figure 2 illustrates recent improvements in the Accumulator lattice and core cooling systems that provide 5-12 π mm-mrad transverse emittance (95% normalized) for stack sizes normally used for making store in the Tevatron.

Table 1 shows the current and expected values for key antiproton production parameters for Run IIa. Our short-term plans to increase the stacking rate include: raising the proton intensity on the production target, decreasing the cycle time, and improving the production efficiency. At present, the Debuncher cooling system limits the cycle time. The production efficiency is hoped to increase by at least a factor of two by: 1) increasing the operating gradient of the Li lens which focuses secondaries leaving the production target; 2) increasing the dynamic aperture of the transfer line between the target station and the Debuncher.

	Current	Run IIa Goal
Protons/pulse on target (E12)	4.2-4.5	5
Stacking cycle repetition rate (sec)	2.5	< 2
Maximum stacking rate (E10/hr)	12.4	18
Max stack size (E10)	190	165

Table 1: Current typical and desired parameters for Run IIa antiproton production.

Recycler

The Recycler is a combined-function permanent magnet storage ring in the Main Injector tunnel used for storing 8 GeV antiprotons. Whereas the Accumulator stacking rate decreases as stack size increases, the stacking rate and efficiency of the Recycler should be independent of the beam intensity in the ring. Consequently, the overall antiproton production rate would benefit by occasionally transferring small stacks from the Accumulator to the Recycler in order to maintain higher stacking rates in the Accumulator. Eventually, antiprotons remaining in the Tevatron after a store (50-70% of the initial intensity) will be not be aborted, but "recycled" by decelerating them in the Tevatron and Main Injector, and added to an existing Recycler stack.

Currently, the Recycler is still being commissioned and is not integrated into collider operations. Antiproton transfer efficiency from the Main Injector to the Recycler has exceeded 90%. Recycler stacking efficiency has averaged approximately 70%, but problems with RF manipulations have been identified and work is underway to correct them. Changing fields from Main Injector ramping distort the Recycler orbit and tunes. Magnetic shielding has greatly improved the situation, but active correction of Recycler tunes during Main Injector ramping cycles is planned.

The stochastic cooling systems have been commissioned, but are not yet optimized. Nonetheless, the Recycler has achieved a 10 π mm-mrad/hr transverse cooling rate for antiprotons. The measured heating rate is 3-4 π mm-mrad/hr, and is consistent with that measured with protons.

This heating rate is consistent with that from beam-gas interactions at the current vacuum levels in the Recycler. Antiproton beam lifetime of 110 hours has been attained for 40×10^{10} antiprotons with cooling systems on and Main Injector ramping.

Additional work on the Recycler will be completed before it can be integrated into operations by the end of 2003. The number of ion pumps will be doubled to reduce the heating rate from beam-gas scattering by a factor of 3-4. Goals for the Recycler are to store 200×10^{10} antiprotons with better than 200 hour lifetime and cooled to transverse emittances less than 10 π mm-mrad.

Tevatron

In Run I, the Tevatron operated as a 6×6 collider with a beam energy of 900 GeV. For Run II, the maximum energy has increased to 980 GeV, and 36 proton and antiproton bunches populate the machine. Figure 3 shows the evolution of Tevatron peak luminosities so far in Run II. Table 2 shows various parameters that affect peak luminosity. Although progress is being made, peak luminosity is more than a factor of 2 below expectations for performance early in Run II.

	Typical Values	Run IIa/IIb Goal
Antiproton Efficiency: Accumulator to start of store	58%	80%
Antiproton intensity / bunch (E9)	25	30
Proton intensity / bunch (E9)	180	270
Transverse Emittance (π mm-mrad, 95% normalized)	18-22 (average)	20 proton 16 antiproton
Bunch length RMS Proton/antiproton (ns)	2.0/1.8	1.4
Peak Luminosity (E31 cm^{-2} s^{-1})	3.6	8.1/40

Table 2: Status of various parameters influencing Tevatron luminosity. Bunch intensities and sizes refer to conditions at start of physics stores.

Two problems limiting Tevatron performance are a transverse instability for large intensity proton bunches and worse than expected consequences from beam-beam effects. As proton intensities reached ~200×10^9 / bunch, transverse instabilities have been observed at 150 GeV, up the ramp, or at 980 GeV. We now believe the instability is a single bunch, weak head-tail phenomenon. The instability causes Schottky power to rise quickly ~200 ms, and mainly results in a rapid increase of both proton and antiproton transverse emittances. We can prevent or control the instability by raising chromaticities to higher than desired values (8 units at 150 GeV, to 20 units during collisions). We also intentionally limit the proton beam intensity to ~240×10^9 / bunch at injection, which results in ~170×10^9 / bunch for collisions. A bunch-by-bunch transverse damper system recently constructed has demonstrated that it can damp transverse oscillations and allow us to lower chromaticity at 150 GeV. We will continue to commission the system and explore its capabilities. Using octupole magnets to provide a nonlinear tune spread has also shown promise in preventing the instability and allowing lower chromaticities.

The transverse instability and beam-beam effects both contribute to poor beam lifetimes at 150 GeV. During injections, the proton bunches are first injected onto the Tevatron central orbit. Beam lifetime is satisfactory at 10-20 hours. However, once electrostatic separators are ramped to put the protons onto a helical orbit prior to antiproton injections, the lifetime drops to approximately 2 hours.

Lowering the chromaticity can improve lifetime, but the head-tail instability prevents chromaticities lower than 8 units at typical beam intensities without the transverse dampers. Beam-beam effects drastically reduce the antiproton lifetimes to 1-3 hours during injections; without protons in the machine, the antiproton lifetime is approximately 20 hours on their helical orbit. We cannot expand the separation between the proton and antiproton helical orbits because of a physical aperture restriction in Lambertson dipoles for a now redundant abort system. During the shutdown in early 2003, these magnets will be replaced with larger aperture dipoles that will allow implementation of helical orbits with greater beam-beam separation.

Beam-beam effects at 980 GeV have caused antiproton beam loss and larger than expected transverse emittance growth. As proton intensity was raised during early 2002, a sudden 10-20% antiproton beam loss started occurring at a particular moment of the low beta squeeze. The loss happened when the beam-beam separation reached a minimum while moving the beams to the helical orbits used for collisions. Fortunately, the electrostatic separator ramps could be modified to increase the minimum beam-beam separation. The beam loss was eliminated, and luminosity immediately benefited as a result.

The observed beam-beam effects have led to lower luminosity lifetimes. Typically, luminosity lifetime in the first 2 hours of Tevatron stores is 9-11 hours when a lifetime of 20 hours is expected. The beam-beam effects cause tune shifts of the antiprotons that depend upon the bunch position within a train. The bunches within a train suffer larger transverse emittance growth (5-7 π mm-mrad) compared to the minimal emittance growth for the bunches on the ends of the trains. One solution is to adjust the base tunes to minimize the emittance growth for the majority of the antiproton bunches; another is to use an electron lens to provide bunch-by-bunch compensation of the beam-beam tune shifts.

The Tevatron Electron Lens (TEL) was designed for compensation of the beam-beam tune shift felt by the antiprotons from the much more intense proton beam. The TEL can fire short 10 keV electron beam pulses coincident in time with the antiprotons close to their orbit. The TEL is not yet used operationally for compensation, but in studies with protons only, it has achieved tune shifts up to 0.009 while maintaining 100 hour beam lifetime.

The TEL has been used to remove DC beam from the abort gaps. Some phenomenon, not yet understood, has been causing beam to leak out of the RF buckets continuously. This DC beam can spread around the entire ring, including the abort gaps, before losing energy by synchrotron radiation and being lost on a collimator. However, enough beam can build up in the gaps that when an abort kicker fires, the beam in the gap gets knocked into nearby superconducting magnets and cause a quench. The TEL can remove beam in the abort gap by firing its electron beam every 7 Tevatron orbits to excite a resonance. The operation has been very successful in preventing magnet quenches on aborts and it also reduces a source of background at the B0 collision hall.

Beyond Run IIa

The current accelerator configuration is capable of supporting a peak Tevatron luminosity of 6-8 $\times 10^{31}$ cm^{-2} s^{-1}. Reaching peak luminosities above 10^{32} cm^{-2} s^{-1} requires additional improvements to produce and stack a greater number of antiprotons. A well-functioning Recycler is a prerequisite. Increasing the number of protons striking the antiproton production target will be obtained by "slip-stacking" two Booster batches of protons in the Main Injector. Stacks of up to 500 $\times 10^{10}$ antiprotons may be attainable by implementing electron cooling in the Recycler.

The Run II plan calls for decreasing the bunch spacing in the Tevatron to 132 ns once the luminosity reaches a level where the experiments suffer from too many interactions per crossing. This mode would require faster injection kickers and additional separators to generate a crossing angle at the interaction points. However, the stronger than expected beam-beam effects already observed at 396 ns bunch spacing have forced us to consider alternative plans such as using 264 ns bunch spacing or continuing with 36×36 operation with a luminosity-leveling scheme.

Summary

Fermilab Tevatron Collider Run II began in March 2001 after many modifications were made to the accelerator complex. Progress has been slower than expected, but the performance has improved recently. Tevatron peak luminosities are now consistently above Run I values, and more than 90 pb^{-1} have been delivered to the two collider experiments. Two problems affecting Tevatron performance are: 1) a weak head-tail instability for large proton intensities; 2) stronger than expected beam-beam effects that degrade antiproton intensity and emittances. The Recycler Ring should be integrated into operations by the end of 2003.

References

[1] Run II Handbook, http://www-bd.fnal.gov/lug/runII_handbook/RunII_index.html.

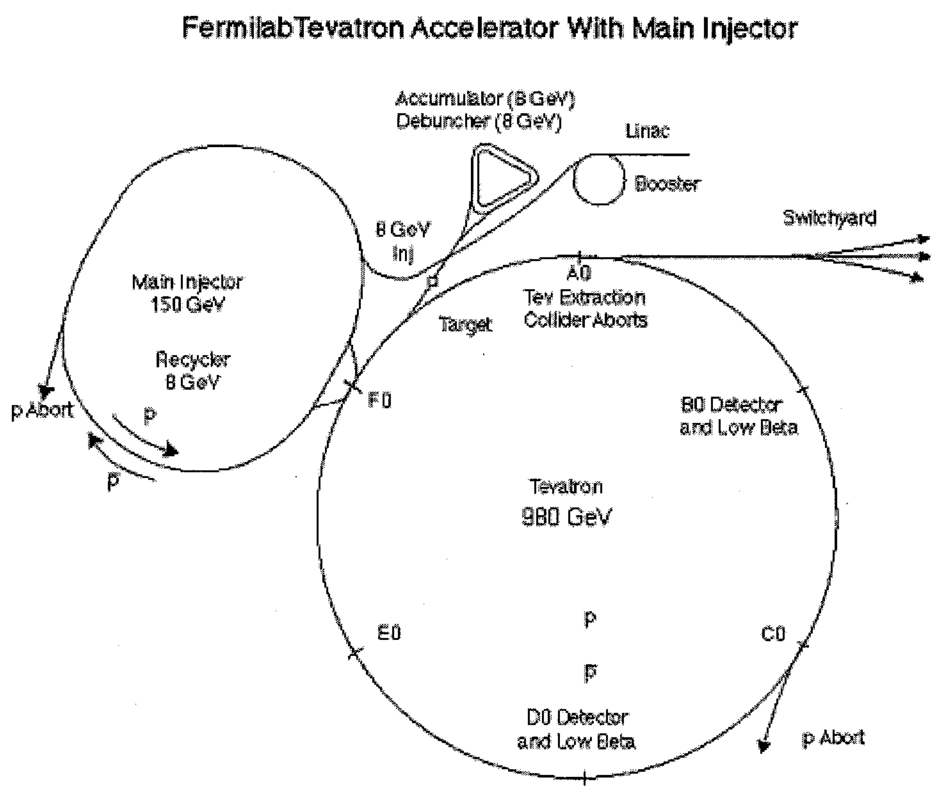

Figure 1: A schematic of the Fermilab accelerator complex for Run II operation.

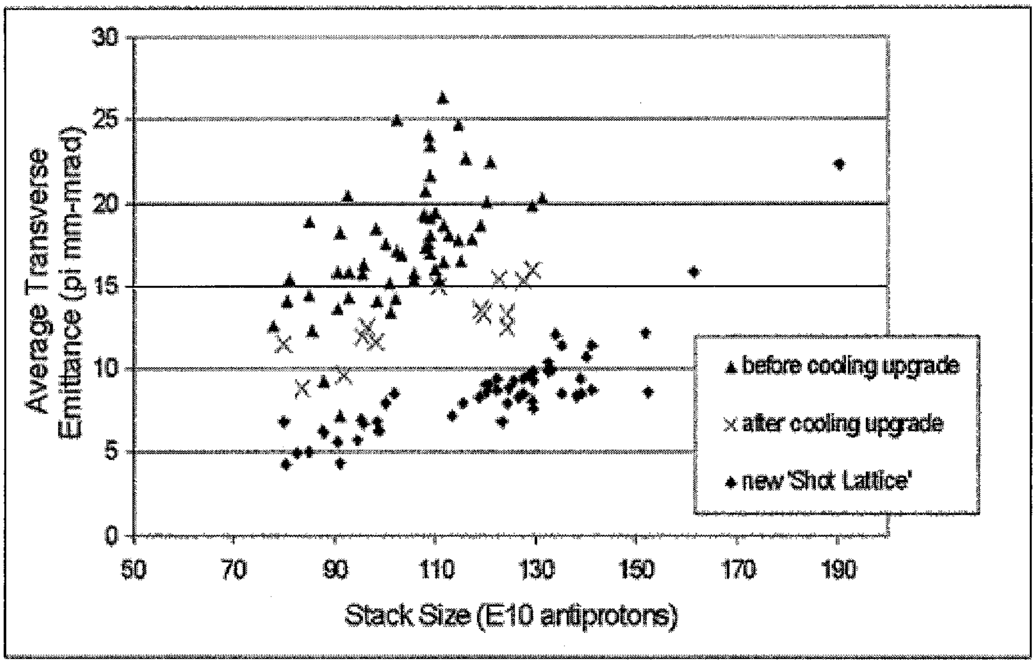

Figure 2: Normalized 95% transverse emittances of antiprotons in the Accumulator versus stack sizes: before core cooling upgrade (triangles), after core cooling upgrade (crosses), after core cooling upgrade with new lattice in transfers for Tevatron stores (diamonds).

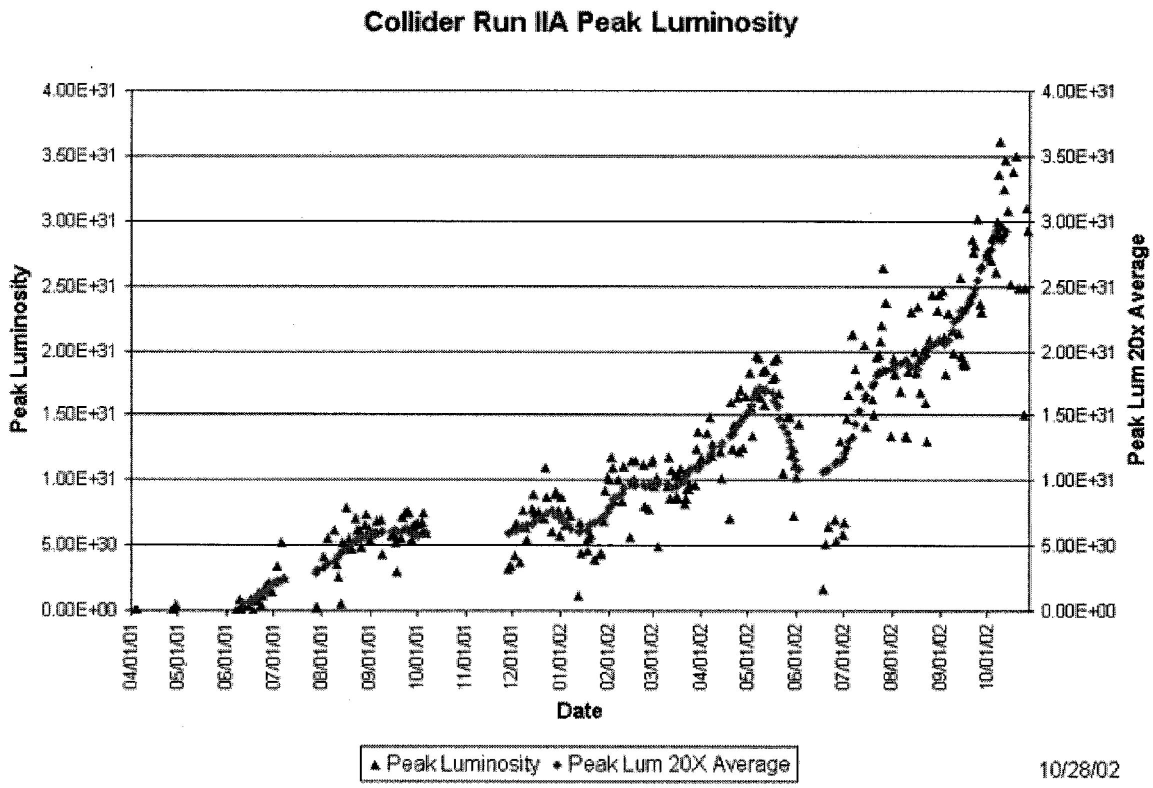

Figure 3: Tevatron peak luminosities versus time in Run II.