Issues and Experience with Controlling Beam Loss at the Tevatron Collider

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The Tevatron has operated as a Proton-Antiproton Collider since 1985 and functions very near the quench threshold of the main magnet system. This small quench margin requires that the local level of particle loss remain quite low. Fast events such as the spontaneous discharge of an abort kicker, or an electrostatic separator spark can produce sudden losses that are damaging to the accelerator and experimental equipment. Also, the detectors at the collider experiments are sensitive to more modest beam loss in regards to both equipment damage, and data integrity. Modification of the collider has been necessary both to maximize the lifetime of both beams as well as to protect the accelerator and experiments from residual beam loss. The issues and experience of minimizing beam loss as the luminosity has been increased to its present values will be detailed.

I. INTRODUCTION

The maximum allowable level of losses in the Tevatron are determined by the quench threshold of the superconducting magnets as well as by the sensitive collider detector components placed a few millimeters from the beam. Minimizing the particle loss at the detectors during stores is important for maximizing detector life and data quality. Perhaps the most important issue regarding losses in the Tevatron is that of protection of personnel and the environment. High level losses that might present such a danger are naturally regulated by the cryogenic magnet system, and the time needed to recover cryogenic conditions following a quench. Insuring that personnel and the environment were protected still required a significant dedicated effort.

II. RELEVANT BACKGROUND AND OPERATING PARAMETERS FOR THE TEVATRON

The Tevatron collider operates with 36 bunches of Protons colliding with 36 bunches of Antiprotons at two interaction points (CDF and D0). Proton intensities at the beginning of a store are typically 2.8 e11 per bunch. The Antiproton Intensities range from 3 e10 to 8 e10 per bunch depending on the available supply of Antiprotons in the Recycler Ring. Protons and Antiprotons circulate in opposite directions in the same beam pipe. They are kept separate by electrostatic separators around the azimuth and are brought onto a common closed orbit at the two interaction points.

The injection energy of the Tevatron is 150 GeV. After loading both Protons and Antiprotons, the beam is accelerated and then the Protons and Antiprotons are aligned in time to cross at the interaction points with an RF operation known as collision point cogging. At this point the beams are still separated transversely using electrostatic separators. The lattice is then changed to obtain the desired lattice functions at the interaction points ($\beta^* = 28$ cm). Only then are the beams brought into collisions transversely using the electrostatic separators. Collimators are then brought into position to minimize the halo background rates before the experiments begin taking data.

To understand the use of the beam loss monitor (BLM) system in the Tevatron, it is important to be familiar with the historical use of the accelerator as a fixed target machine. In the 1980s and part of the 1990s, the Tevatron was used to deliver beams to several fixed target experiments. Up to 2.5 e13 Protons were accelerated to 800 GeV and resonantly extracted. This cycle repeated every 57 seconds. These were the operating conditions in place when the BLM system was commissioned and fully utilized.

II. PERSONNEL AND ENVIRONMENTAL PROTECTION

The first 6 months of 1991 the Fermilab accelerators were completely devoted to radiation shielding studies. Beam was run in each accelerator for the purpose of measuring how much radiation could be produced outside the enclosure under the worst of conditions. Earth shielding was increased in areas that were found to be lacking. Cable penetrations were filled with radiation

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* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

absorbing material, and interlocked radiation detectors were added in areas needed to ensure exposures in occupied areas could not increase above acceptable levels.

III. QUENCH PREVENTION AND EQUIPMENT PROTECTION

III.A.1. Understanding Beam Loss Protection in the Early Tevatron Operation

When the Tevatron was first operated, it was unknown how robust it would be in the presence of beam loss. The idea of doing resonant extraction at energies near the quench threshold of the magnets was daunting. It was unclear how the magnet system would hold up to quenches induced by beam loss. Even if the magnet system was able to handle many quenches, the recovery of the cryogenic systems after a quench was a significant source of down time. The BLM system installed was meant to allow the Tevatron to abort beam before losses could induce a quench.

The integrity of the Tevatron magnet system could only be realized with experience. But the impact of a quench on operations was clear. Cryogenic recovery after a high field quench took at least an hour, so a single quench per day cost 5% of the operational hours available. For this reason, the BLM system was designed to respond quickly to any increase in losses. The rise time of the loss monitors was on the order of 1 or 2 μsec. The chambers decay with a time constant of 60 msec. The BLM processors operated with a 2 msec interrupt rate. This system allowed for very fast response to an increasing beam loss condition. If a beam abort was triggered under a condition that would not necessarily result in a quench, the cost was only the remaining portion of the 57 second Tevatron cycle.

Figure 1 below shows measurements made on how much energy is required to quench a Tevatron dipole as a function of its excitation current. These measurements were made by Helen Edwards and Nikolai Mokhov. The energy required to quench the magnet is strongly dependent on how near the dipole is to its maximum current. As a whole, the Tevatron operating energy is 3% below the quench limit, so more robust dipoles need to be installed in areas where beam loss is common. Also, loss monitor abort thresholds would ideally be individually set based on which magnets they are near.

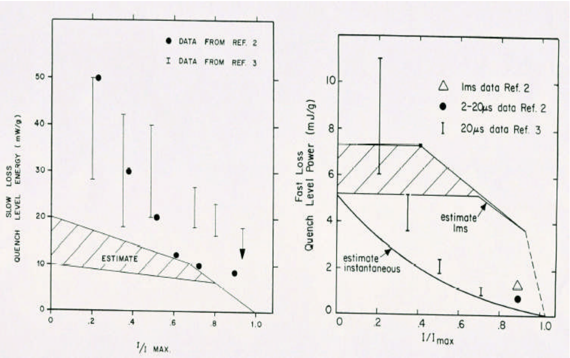

Fig. 1. Measurements made on beam loss levels by Helen Edwards.

III.A.2. Changing Requirements with Colliding Beams Operations

Operation of the Tevatron as a collider brought on a change in philosophy about the condition required to abort the beam. The original Tevatron BLM system had some limitations that made it less than ideal for use in the collider. The loss monitors had a rise time of about 1 μsec, but a decay time constant of 60 msec. This allowed the BLM system to respond quickly, but did not lend itself to a very accurate measurement of integrated losses of short duration. Also, the loss monitors had abort thresholds that were common for an entire chassis (1/24th of the Tevatron). Frequently the system would experience hardware failures, get corrupted settings, or have undiagnosed problems that would result in unintentional aborts.

In the early collider days, 24 hours was a typical time required to accumulate enough Antiprotons to begin a Physics run. The time required to recover the cryogenics after a quench was about 2 hours. Also, by the time the collider was operating, the magnet system had shown itself to be able to withstand beam loss induced quenches. A beam abort could cause the collider operation to be off for up to 24 hours while Antiprotons were produced for the next store. The quench recovery time was small on this scale, so it was decided to eliminate all unnecessary beam aborts when Antiprotons were in the Tevatron. Before the loading of Antiprotons, the abort capabilities of the BLM system were disabled.

III.A.3. Beam Loss Incident to Change the Strategy

On December 5, 2003, an incident occurred that caused the policy of not including loss monitors in the beam abort system to be reconsidered. On that day, a detector that can be inserted directly into the beam pipe failed, and was driven though the beam. The damage done by the beam during this failure was substantial. More than ¼ of the Tevatron magnets quenched during this incident. A correction element spool piece had ceramic feed-throughs that failed under the pressure of the quench. Three cryogenic correction elements failed internally. Two collimator components had holes bored in their collimating surface, and one beam pipe bellows developed a vacuum leak. The detailed examination of this quench led to the realization that there was a category of fast quench that was previously not understood.

The Tevatron magnet system has an active quench current bypass circuit. Once a quench is detected by the Quench Protection Monitor (QPM), which operates at 60 Hz, a bypass SCR is triggered so that current can be shunted around the quenching cell. The bypass SCR self triggers if the voltage across it is above 80 Volts. During this particular quench, the low mass detector moved into the beam very quickly spraying losses along the length of five dipoles in a single quench protection cell. The resistive voltage of the quench built up very fast to more than the 80 volts needed to trigger the SCR. This happened at the start of the QPM’s 16 msec cycle. Current immediately began being shunted around the five main dipoles at a rate of about 500 amps per second. This caused the beam that remained in the accelerator to be wildly mis-steered. The errant beam moved directly on to the Proton collimator target. N. Mokhov estimates that in about 50 machine revolutions, a hole was burned through the 5 mm thick piece of tungsten material. The beam continued on to the next closest aperture which was the 1.5 m long collimator at E11. The beam then cut a groove in this stainless steel collimator until the beam was fully extinguished. The QPM in the area of the original failed detector then pulled the abort, several msecs after all of the beam was dumped in the collimator, at its next interrupt period.

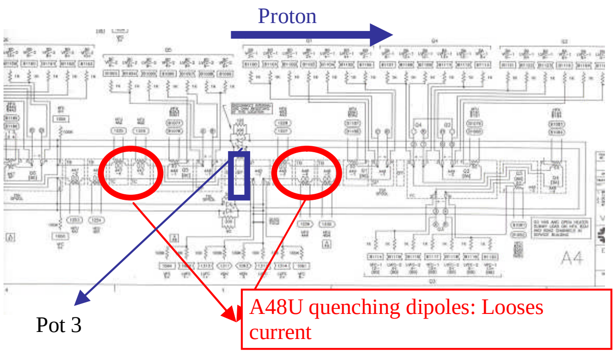

Fig 2. Schematic of Tevatron main magnet bus and quench bypass circuit.

Once this phenomenon of a very fast quench was discovered, previous incidents were re-analyzed and were found to have similar features. Most of these incidents involved separator sparks where the loss increased during a single revolution of beam. This type of incident could be identified by losses that grew very fast (a single 2msec update of the BLM system) followed by a multi-house quench. It was clear from incidents such as these that the Tevatron needed a way to abort the beam faster under these conditions where the quench develops very fast.

It was decided that the Tevatron should develop a new and modern BLM system to better protect the Tevatron. Developing this system would take some time, and in the mean time, the EE support department was able to provide some help on a shorter time scale. The QPMs had been upgraded in 1990s to a system with a higher bandwidth processor. Even though these new processors continued to operate with a 60 Hz interrupt rate, there was the new capability of over sampling the signals at a rate of 5760 Hz. Analysis of this data showed that in the case of a very fast quench, large cell voltages could be detected in a couple of msec. Functionality was added to the QPM to allow it to abort the beam when these fast voltage signals were detected even though the normal quench protection calculations were still done at a 60 Hz rate. This improvement has been in place since July of 2004 to help protect the Tevatron from catastrophic events until the new BLM system can be commissioned.

III.A.4 The New Beam Loss Monitor System

The new BLM system is in the process of being commissioned. One of the improvements of the new system is multiple state dependent abort thresholds for each channel. States that can be recognized by the BLM system to change abort levels include whether there are Antiprotons in the machine, if the Tevatron is at high or low energy, or if collimators are being moved into the beam. Loss monitor multiplicity can also be used in the beam abort decision. Another added capability is that each loss monitor has three different channels with different integration times. Each of these channels can have their own abort threshold. This allows the BLM to abort at a level that is appropriate for the loss rate detected.

One (out of 30) BLM chassis was replaced with the upgraded version in May of 2007. Its abort capabilities were left disabled as its data collection function was examined. A second installation was upgraded in July 2007 and its abort functionality was set up to mimic the old system exactly. Minor issues are still being resolved with these systems, but the entire system should be functional by the end of 2007.

IV. BACKGROUND REDUCTION AT COLLIDER DETECTORS

IV.A.1. Two Stage Collimation System to Reduce Background Rates at the Collider Detectors

The Tevatron has implemented a two stage collimation system for both Protons and Antiprotons to reduce the background rates at the detectors. In a two stage system, halo particles first interact on a thin primary collimator, or target. The particles scatter off of the target and then impact the secondary collimator at larger amplitudes. This increases the efficiency of the collimator as well as reduces the beam heating in the collimator. Figure 3 shows how the secondary collimators are placed at the proper phase downstream of the primary to efficiently intercept the particles scattered off the target.

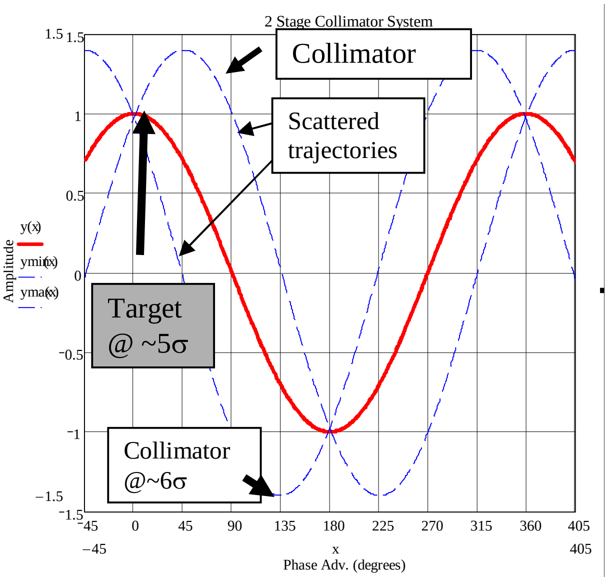

Figure 3 Two stage collimator design showing proper phase relation between target and downstream secondary collimators.

It is important that the target and secondary collimators are placed in suitable locations in the lattice for the system to work efficiently. Collimators must be aligned parallel to the beam and the primary and secondary must both be at the proper distance form the beam in terms of transverse beam sigma. It is possible that under changing beam conditions, a primary particle can strike a collimator before the target causing a shower that actually increases rates at the detector. In the Tevatron this happened as off momentum particles that were not within an RF bucket spiraled into a collimator located at a high dispersion area. This collimator had to be moved farther from the beam with respect to the target to minimize the halo rates at CDF.

The design of the present collimator system originally called for two complete sets of collimators for each beam. A set of collimators consist of a target and two 1.5 meter secondary collimators. Each target and collimator is L-shaped having a vertical collimating surface, and a horizontal collimating surface. The perpendicular surfaces are controlled separately, so they are conceptually separate devices. This means there are six separately controlled collimating surfaces for each set. Some of the collimators were eventually moved and used for purposes other than background rate reduction. Only one complete set is used for each beam. This still leaves 12 collimating surfaces to be moved into positions that change with each store. Each collimating surface is used to scrape a single particle type in a single plane. The orientation of the collimator is dependent on the separated helical orbits.

The collimation system in place is effective in almost eliminating background rates at CDF. Very early in stores, the backgrounds are about where there loss monitor pedestal values are set. In fact, the loss rates often read a negative value. The D0 detector background rates are somewhat higher. Generally, the D0 monitors detect background losses at a rate of about 1 Hz per billion particles in the accelerator. It is believed that beam gas collisions near the D0 detectors are responsible for this baseline loss rate.

IV.A.2. Controlling the Two Stage Collimation System

The collider experiments at the Tevatron do not begin taking Physics data until the collimators are fully in place and stable at optimum positions. All 12 collimating surfaces are inserted to a position that may change with changing beam conditions. Errors of only a few mils may significantly reduce the performance of the system For this reason, it is important to have an efficient and automated process to bring the collimators into their optimum positions.

There are three distinct components to the control system that are needed to control the collimator system. The first is the local microprocessor at each collimator that is able to use signals such as loss monitors, and beam intensity monitors to position the collimators under a variety of feedback conditions. The second major component of the control system is a central process that coordinates these local microprocessors that are installed around the Tevatron. The other critical component of the collimator controls is the set application programs used to set up the feedback loops, and trigger the collimator processes.

When the collider fill process begins, all collimators are moved away from the beam to allow for the injection process. When the Tevatron beams are brought into collisions, the collimators are all put into a state where they immediately move to a predetermined position close to the beam. Once all of the collimators are in these “near” positions, individual collimators begin moving closer to the beam until the local loss monitors detect a rise in losses. At this point the collimators are at the edge of the beam. Next, the targets move in even closer until a pre-defined percentage of the beam is scraped away. Once this beam removal is successfully accomplished, all collimators move back away from the beam by the appropriate amount to establish the two stage collimation. This method of controlling the collimators has been successful in reliably moving the collimators into the proper position in about 10 minutes.

IV.A.3. Protection from abort kicker pre-fires.

After initial operation of the collider in Run II, it became evident that the CDF experiment required extra protection from unsynchronized beam abort. Occasionally one of the Tevatron abort kickers would spontaneously fire asynchronous with the abort gap in the beam. During this type of incident, several Proton bunches would miss the abort dump, but would be kicked hard enough to produce large radiation doses in the CDF detector. Two collimators were moved from their original positions in the accelerator to locations that would protect CDF from these unpredictable incidents.

V. FEED FORWARD TUNING TO MAINTAIN COLLIDER PERFORMANCE

Maintaining collider performance at a peak level involves minimizing the losses during the fill process as well as maximizing the lifetimes once a Physics run begins. This process requires constant adjustments by Physicists that need to be able to retrieve relevant data. Since the collider fill process occurs on average once a day at irregular hours, it is important to be able to retrieve and analyze data from collider fills on demand. Many of the instruments in the field (such as Beam Position Monitors, Beam Loss Monitors, Flying Wires, etc.) store their data until it is overwritten the next fill cycle. But it is often necessary to compare data from earlier stores, so a more permanent data storage system is required. The key tool for this type of analysis is known as “Shot Data Acquisition” (SDA).

There are many steps involved with preparing the collider for a Physics run. Each accelerator at Fermilab plays a part in delivering either Protons or Antiprotons to the collider detectors. Each of the 36 bunches must be as bright as possible to maximize the luminosity. Discovering which steps are not up to performance standards requires easy access to all relevant data during the process.

Figure 4 is an example of a plot that is automatically generated that shows one aspect of recent performance compared to previous stores. Here the Proton acceleration inefficiency is plotted against the injected Antiproton intensity. The slope shows the effects of the long range beam-beam forces of the Antiprotons on the more intense Proton beam. The points marked as recent stores indicate how well those stores performed compared to expected values.

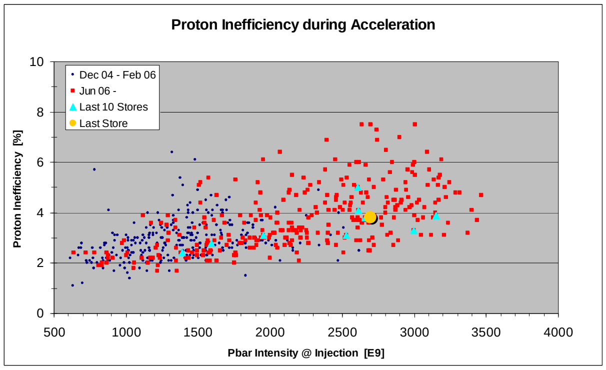

Figure 4. Plot of Proton acceleration inefficiency vs Antiproton intensity with recent store emphasized.

Once an area where substandard performance is identified, further analysis can be done on a more detailed basis. Figure 5 shows a plot of the horizontal tune tracker and a loss monitor near one of the electrostatic separators during the low beta squeeze for two different stores. This shows that while the loss in the earlier store half way through the squeeze might be due to a tune excursion, the loss later in the squeeze is probably not tune related.

Figure 5. Plot of horizontal tune tracker and a beam loss monitor during the low beta squeeze for two different stores.

VI. CONCLUSIONS

Controlling losses in the Tevatron collider involves the protection of personnel and the environment as well as preventing adverse operation of the superconducting magnet systems and the collider detectors. Unexpected beam loss conditions must be managed to prevent accelerator and detector component damage. Luminosity delivered to the experiments also depends on individuals continually optimizing accelerator parameters to minimize losses.

The Tevatron Beam Loss Monitor system and Quench Protection system have both been upgraded to keep up with the needs of minimizing losses and preventing damage from unavoidable loss. A sophisticated collimation system has been implemented to minimize the background rates at the collider detectors. Even with these systems in place, continuous monitoring and optimization of accelerator performance is needed to keep Tevatron losses at the lowest levels possible.

ACKNOWLEDGMENTS

The author would like to acknowledge the many individuals who have provided knowledge, insight and years of effort maximizing the performance of the Tevatron. Special acknowledgements in particular go to Nikolai Mokhov and Dean Still who provided much of the work presented here in the area of quench thresholds, collimation systems and the beam loss monitor upgrade. Dan Wolff is also acknowledged for understanding the details of the fast quench incidents and providing the fast beam abort from the QPMs to protect accelerator components.

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