BEAM-INDUCED DAMAGE TO THE TEVATRON COMPONENTS AND WHAT HAS BEEN DONE ABOUT IT*

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Abstract

A beam-induced damage to the Tevatron collimators happened in December 2003 was induced by a failure in the CDF Roman Pot detector positioning during the collider run. Possible scenarios of this failure resulted in an excessive halo generation and superconducting magnet quench have been studied via realistic simulations using the STRUCT and MARS14 codes. It is shown that the interaction of a misbehaved proton beam with the collimators result in a rapid local heating and a possible damage. A detailed consideration is given to the ablation process for the collimator material taking place in high vacuum. It is shown that ablation of tungsten (primary collimator) and stainless steel (secondary collimator) jaws results in creation of a groove in the jaw surface as was observed after the December's accident. The actions undertaken to avoid such an accident in future are described in detail.

INTRODUCTION

There are 24 cryogenic refrigerator houses for the Fermilab Tevatron ring. One house cryogenically keeps about 40 magnets at superconducting temperatures. On December 5, 2003, the Tevatron suffered a 16 house quench during the end of a proton-antiproton colliding beam store followed by the damage of 2 collimators used for halo reduction at the CDF and DØ interaction points (Fig. 1). In addition, a cryogenic spool piece that houses correction elements was also damaged as a result of helium evaporation and pressure rise during the quench, requiring 10 days of Tevatron downtime for repairs.

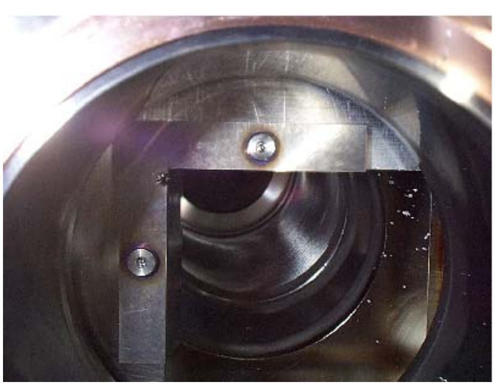

Figure 1: Damage to D49 5-mm thick tungsten primary collimator.

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The initial reason of the large quench was found to be caused by a CDF Roman Pot reinserting itself back into the beam after it had been issued retract commands. The Roman Pot motion control hardware has since then been found to be faulty. This event prompted an investigation in order to describe the sequence of events to understand the damage imposed on the collimator devices [1, 2].

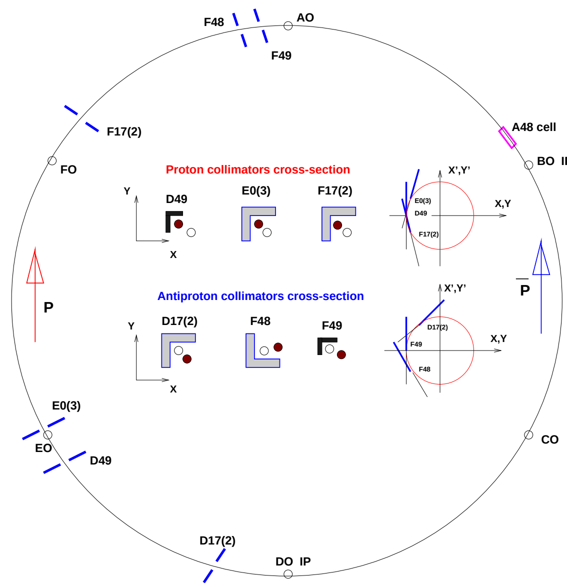

Figure 2: Tevatron Run II beam collimation system.

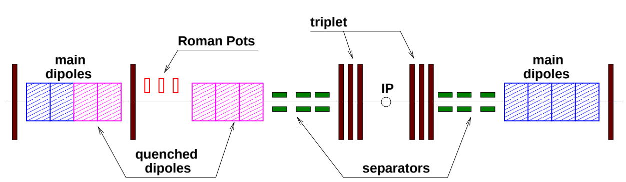

Figure 3: Schematics of the BØ interaction region with its Roman Pots and quenching cell A48.

BEAM DYNAMICS AT MAGNET CELL QUENCH

Fig. 2 shows the layout of the Tevatron and its Run II beam collimation system [3]. Normally, the beam scraping is done by the primary collimators at $5\sigma_{x,y}$ and secondary ones at $7\sigma_{x,y}$ at the beginning of accelerator cycle flat top after beams are brought to collisions. After the scraping is done, all collimators are retracted back from the beam by 1 mm, which is approximately equal to $2\sigma_{x,y}$. After collimators retracting the primary halo builds up to $7\sigma_{x,y}$ and secondary halo to $9\sigma_{x,y}$ during about 70 seconds.

The analysis of accident has shown that the Roman Pot moving fast towards the beam stopped at 5 mm from the beam pipe center. The Roman Pot vessel was at $\sim 6\sigma_x$ from the beam center, producing a tremendous spray of secondaries in the downstream magnets. This caused quench of the A48 superconducting magnet cell (Fig. 3). The magnet current degradation at the quench was equal to about 500 A/s effecting a degradation rate of magnetic field in five dipole magnets of $\Delta B/B_o$ = 2.39×10^{-6} per turn. As was shown using the STRUCT code [4], the circulating beam moves towards the D49 collimator jaw with a rate of ∼0.005 mm per turn, and reaches the jaw surface by its 3σ-amplitude particles in approximately 300 turns after the quench start.

Particle hits at the collimators and a hits time distribution are shown in Fig. 4. The entire beam is lost during about 400 turns (8.4 msec) starting from the turn number 400, mostly on the D49 primary collimator and EØ3 and F17(2) secondary collimators.

The creation of a groove in the vertical jaw of the primary collimator (Fig. 1) was simulated by shifting out the jaw with a rate of 0.003 mm per turn starting from the turn number 550.

ENERGY DEPOSITION IN COLLIMATORS

Using the beam loss distributions calculated in the previous section, detailed energy deposition modeling was performed with the MARS14 Monte Carlo code [5] for the D49 tungsten primary collimators. Fig. 5 shows two-dimensional contours of energy deposition density in a 0.5-mm layer of the collimator vertical jaw. One sees that energy deposition is noticeably larger at the downstream end of a 5-mm plate, because of an intense cascade development for a 980-GeV proton beam over 1.5 radiation length thickness. One can expect that a semi-conical groove is drilled in the vertical jaw, that is confirmed in next Section. The hole diameter at the downstream end is about 2.5-3 mm.

Calculations performed for the 1.5-m long L-shaped secondary collimators E03 and F17(2) have shown (Fig. 6) that a 250-mm long and 3-mm wide slot is created in the stainless steel collimator vertical jaws.

ABLATION OF THE TUNGSTEN COLLIMATOR

The interaction of intense proton pulses with the collimator can result in rapid local heating and ablation of primary collimator tungsten or secondary collimator stainless steel from the surface.

Following a standard approach in surface physics [6, 7], we define the desorption rate, or the number of atoms leaving the unit surface of the solid tungsten in unit time, as

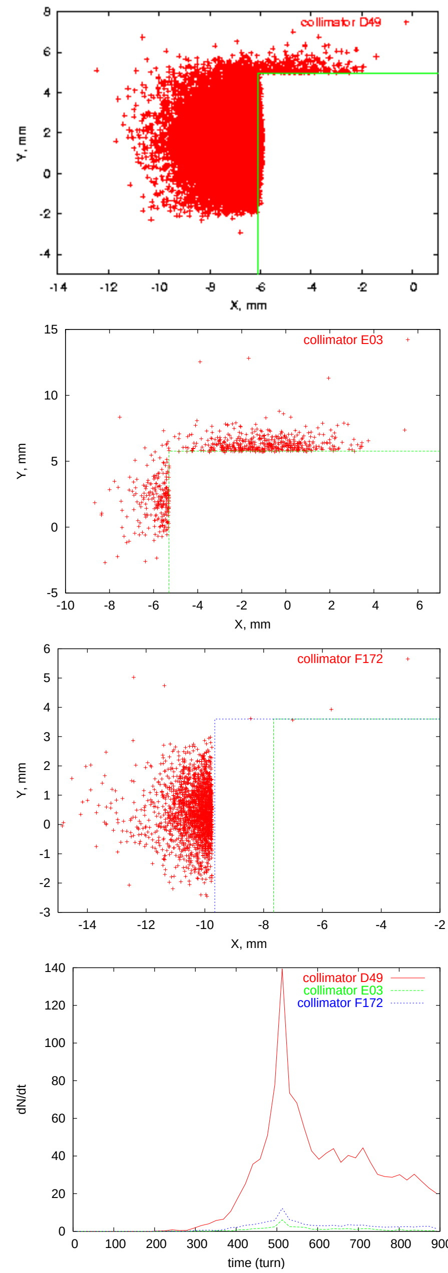

Figure 4: Particle hits at A48 cell quench in the collimators D49, E03 and F17(2), and hits time distribution.

$$dN = N_0 \nu e^{-E_D/kT}, \quad (1)$$

where N_0 is the number of atoms on the unit surface, $\nu = 10^{13}\,\mathrm{sec}^{-1}$, and E_D is the surface energy per tungsten atom which is equal to the heat of vaporization per atom, k is the Boltzmann constant, and T is the absolute temperature. The tungsten heat of vaporization is $Q_v = 824\,\mathrm{kJ/mol} = 1.3683 \cdot 10^{22}\,\mathrm{J/atom}$ and $N_0 = \sqrt{2}/a^2$, where a is the lattice constant; for tungsten $a = 3.16$ Å.

The equation for the evolution of temperature in the collimator plate is

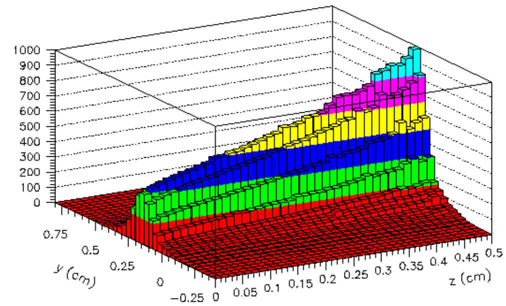

Figure 5: Energy deposition (J/g) isocontours in the D49 tungsten vertical jaw.

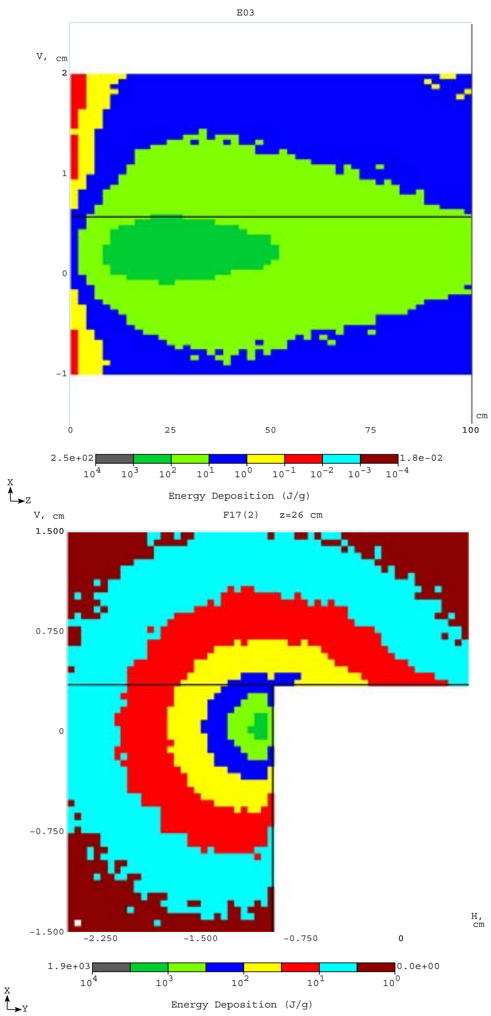

Figure 6: Energy deposition isocontours along the vertical jaw of E03 (top) and at shower maximum across the F17(2) (bottom) collimators.

$$\frac{dT}{dt} = \frac{1}{C_p}\frac{dE_{\text{ext}}}{dt} + \kappa\nabla T, \tag{2}$$

where C_p is the specific heat at constant pressure, κ is the heat conductivity, and E_{ext} is the external energy deposited by the proton beam and calculated numerically using the MARS14 code.

Therefore, solving (2) and using (1), the normal displacement due to ablation of a surface element during time dt can be calculated as

$$dl = \frac{m_0 N_0 \nu dt}{\rho} e^{-Q_v/kT}, \tag{3}$$

where the tungsten density $\rho = 19.35\,\text{g/cm}^3$, and the atomic mass $m_0 = 183.85\,\text{au} = 3.053 \cdot 10^{-22}\text{g}$.

Numerical simulation results are given in Fig. 7. It shows the time evolution of the front and back surfaces of the collimator plate. We observe that the ablation of the back surface is much faster at early time due to cascade development in a 5 mm thick tungsten plate. At later time, the ablation rates at two surfaces are approximately equal.

Note that the numerical results presented here give the fast time limit estimate of the ablation process. This is due to the fact that some processes which may slightly slow down the ablation were neglected. These include the reduction of the internal energy of the collimator plate due to the kinetic and internal energy of the ablated material as the kinetic energy of the ablated material is unknown. The pressure of the ablated gaseous material was also neglected which may contribute during late stages of the ablation.

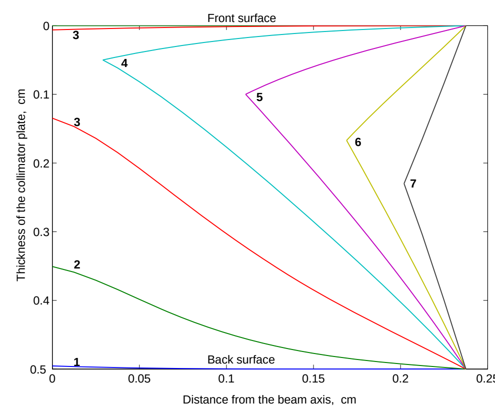

Figure 7: Evolution of the front and back surfaces of the collimator plate at $t = 0.4_{[1]} - 1.6_{[7]}\ ms$ with Δt=0.2 ms.

WHAT HAS BEEN DONE

This section describes the actions undertaken to avoid such an accident in future.

Roman Pots

The Roman Pots were locked out pending investigation. A problem was found with brake system used to prevent movement of the pots – the brakes were not applied as long as pulses are being generated even if a limit switch was depressed. The motor was working against a 700-lb vacuum load. There were no physical stops to prevent the pot from getting too close to the beam.

The controllers have been fixed. This involved rewiring the brake circuits and inhibiting the drive pulses when a limit switch was detected. The drivers have been changed to provide more current to optical isolators. Hard stops have been installed. Note the Tokyo pots are mechanically different than the "Roman" pots. The system was being reviewed prior to being allowed to return to service.

AC Power in Kicker Room

The first step was to reconfigure the AC Power distribution so the kicker and the CAMAC Abort controls are on a separate feed from the sub-station. In the prior distribution, anything that tripped the main circuit breaker would turn off the kickers and CAMAC Abort rack. It now requires a failure of the sub-station. Uninterruptible Power Systems have been designed and installed for the CAMAC Abort rack.

Timing Generator

The CAMAC Abort system will now generate an abort pulse, phase locked to the abort gap, if the accelerator timing system clock is lost. With the UPS system in place, if the site power is lost, an abort will occur properly timed by the CAMAC phase locked loop. Given the time constant of the machine this has been demonstrated to safely abort the beam.

Multi-house Quench

The beam blow up scenario has been well documented by several members of the Tevatron Department. The Quench Protection System samples at a 60 Hz rate. The loss occurred extremely quickly compared to more "normal" quenches. The loss occurred immediately after a QPS (Quench Protection System) sample, so no abort would be generated until many milliseconds later. The Teatron beam loss monitors (BLM) are masked off during a store to prevent accidental aborts from the losses. This was the philosophy adopted many years ago when collider operation began. The BLM's are masked off globally at the abort concentrator modules (C200 series). This mask takes all BLM protection away in each house that has the mask set (currently set in every house). The sampling rate has now been increased to 1 kHz in order to protect against the fast loss.

One of the biggest changes that was made was the implantation of a new fast detection buffer inside the Quench Protection Montior system (QPM) that samples quench data at 5khz and determines a quench and pull the abort in 2msec instead of the 16 msec before the change. The Tevatron relies heavily on this now.

BLM System

The BLM system is the original 1983 system built to protect the cryogenic magnets during fixed target operation. In the early Tevatron days it was okay for the abort system to fire during fixed target operation. The downtime amounted to a few minutes. With collider operation, it was determined that it was better to run without the BLM's due to the long antiproton stacking time. Original system has Z-80 based Multibus processor. The original designer of the system was helping with the new system. The system is already installed in the Tevatron.

Vacuum System Failures

Some stores were lost due to a failure of a vacuum gauge that controls a gate valve in the Tevatron beamline. It was thought the valves pulled the abort when the "Out" limit switch deactivates. This left a great deal of head scratching to try and determine how a mechanical valve could beat the abort loop. The actual path was more convoluted. The "Out" switch removes the permit from the Beam Safety Valve. The BSV coming off the "Out" limit generates the abort command. It was determined that this takes 200 ms for the abort to be generated by this route. A new chassis that monitor the voltages going to the valves has been designed, built and installed. If the voltage is removed, this new chassis generates an abort command in approximately 7 ms. It was verified this does beat the valve. Twenty four crates have been installed during the shutdown.

Controls

The beam abort loop is comprised of a loop of C200 family modules (one in each sector) that provide a permit (antifire) signal for the kickers. Each upstream module is input into the next downstream module. The C200 series was designed when the machine was being used for fixed target operation. The internal timer was found to be insufficient for the long cycle times of the Tevatron. The timer had to have a pre-scaler to prevent the roll over of the counter. This has led to a lack of resolution of the timer. It was difficult at times to determine what event happened first. After one of site power glitches, it was discovered that the C200 masks could return in an arbitrary state rather than in the designed "all un-masked" state. Modifications have been made to ensure the startup state for the masks. The timer circuitry was also modified.

Correctors

The records on corrector repairs do not include information on lost stores. An express analysis of the e-logs for two years preceding the beam accident looking for anything pertaining to "corrector", revealed two events since of lost stores, and one event of corrector trips without losing stores. It seemed the Tevatron is OK with the correctors.

CONCLUSIONS

Analysis and simulations performed show that we have a good understanding of the entire picture of the December 2003 beam accident, both on dynamics and material damage sides. Calculated parameters of the hole and groove created in the collimators are very similar to those observed after the accident. To eliminate a possibility for such an accident in future, The substantial work has been performed by peeling back and questioning each system and its interaction with the Tevatron. The beam handling philosophy was examined and changed. A new BLM system has been designed to operate with multiple types of loss detection (average loss, fast and slow losses) and with independent abort thresholds. The system has also the capability to have different loss abort limits for different Tevatron states such as acceleration, injection and collisions. New kicker AC and UPS systems, vacuum interfaces and controls have also been implemented. All these systems were documented at every level and captured in the Accelerator Division data base.

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