Beam Induced Backgrounds: CDF Experience

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Abstract

We summarize the experiences of the Collider Detector at Fermilab (CDF) experiment in the presence of backgrounds originating from the counter circulating beams in the Fermilab Tevatron. These backgrounds are measured and their sources identified. Finally, we outline the strategies employed to reduce the effects of these backgrounds on the experiment.

EFFECTS OF ACCELERATOR BACKGROUNDS AT CDF

Since the beginning of the Tevatron run II, CDF has experienced a number of operational issues related to accelerator induced backgrounds. Among these issues are: chronic radiation damage to detectors, which we define as damage induced by long term exposure to radiation, single event effects (SEE) in electronics and signals in detectors which mimic expected physics signatures. Each of these issues will be addressed in turn in the following paragraphs.

Chronic radiation damage, particularly to the innermost silicon detectors is expected at CDF. While the damage mechanisms are well known, the lifetime of detectors typically can only be estimated from either from simulations with large uncertainties (typically 50% to 100% uncertainty) or from projections of measured damage profiles. In these lifetime estimate, one of the largest uncertainties involves details of the radiation environment near the detectors. Measurements of the observed radiation damage to the CDF silicon detector have been reported elsewhere [1] and are beyond the scope of this paper. However, the observed radiation damage is as expected from projections based on radiation field measurements summarized in the following sections [2].

In addition to chronic radiation damage, sensitive electronics may exhibit a change of state (bit flip, transistor state change, etc.) due to the passage of a single particle. These phenomena, collectively, are known as single event effects (SEE) in the literature. How these processes affect the operation of a complex detector range from reasonably benign such as single bit errors in the data, through annoying occurrences where electronics in the readout chain freezes and needs to be reset, to catastrophic where the electronics fails completely and must be replaced. As part of the run II upgrades, much of the CDF detector infrastructure and readout electronics is now located on the detector. Figure 1 shows a photograph of the face of the CDF detector showing locations of sensitive electronics.

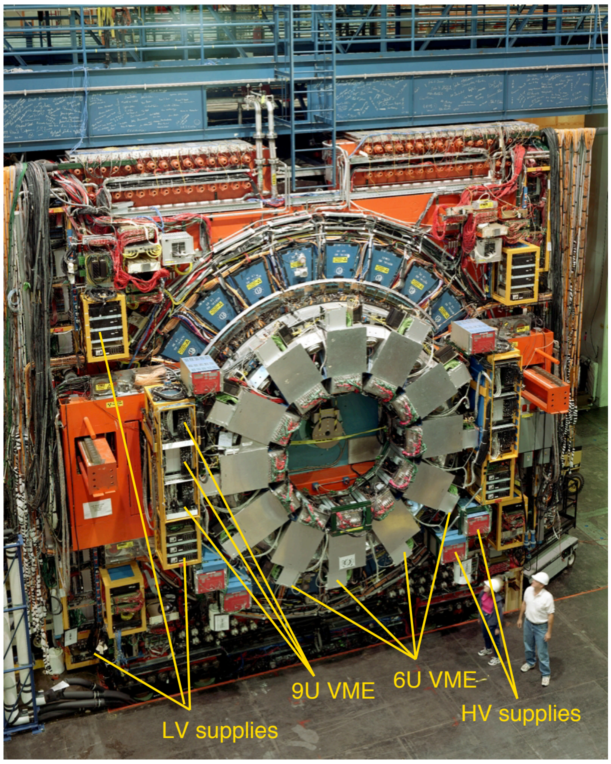

Figure 1: Photograph of the CDF detector. Some of the electronics found to be sensitive to radiation are indicated. For reference, protons are incident into the page.

Since 2001, CDF has observed multiple types of SEE in sensitive electronics. Single event burnout (SEB), a catastrophic failure of a power MOSFET was observed in high power (5kW) low voltage, switching power supplies during commissioning phase of the experiment. Subsequently, single event upsets (SEU) and single event latch-up (SEL) were observed in commercial high voltage, switching power supplies and in custom detector readout electronics.

Typical SEB rates in these power supplies were approximately three failures per week. Epidemiology of the failures indicated more on the incoming proton side with nearly all failures occurring in locations where the power supply had an uninterrupted (line-of-site) view of the final focus quadrupole triplet. The SEU and SEL events are in regions where the electronics have a line-of-site view of the final focus magnets or near the beam line, in regions where radiation is expected to be more intense. Additional details regarding the above SEE may be found in references [3, 4].

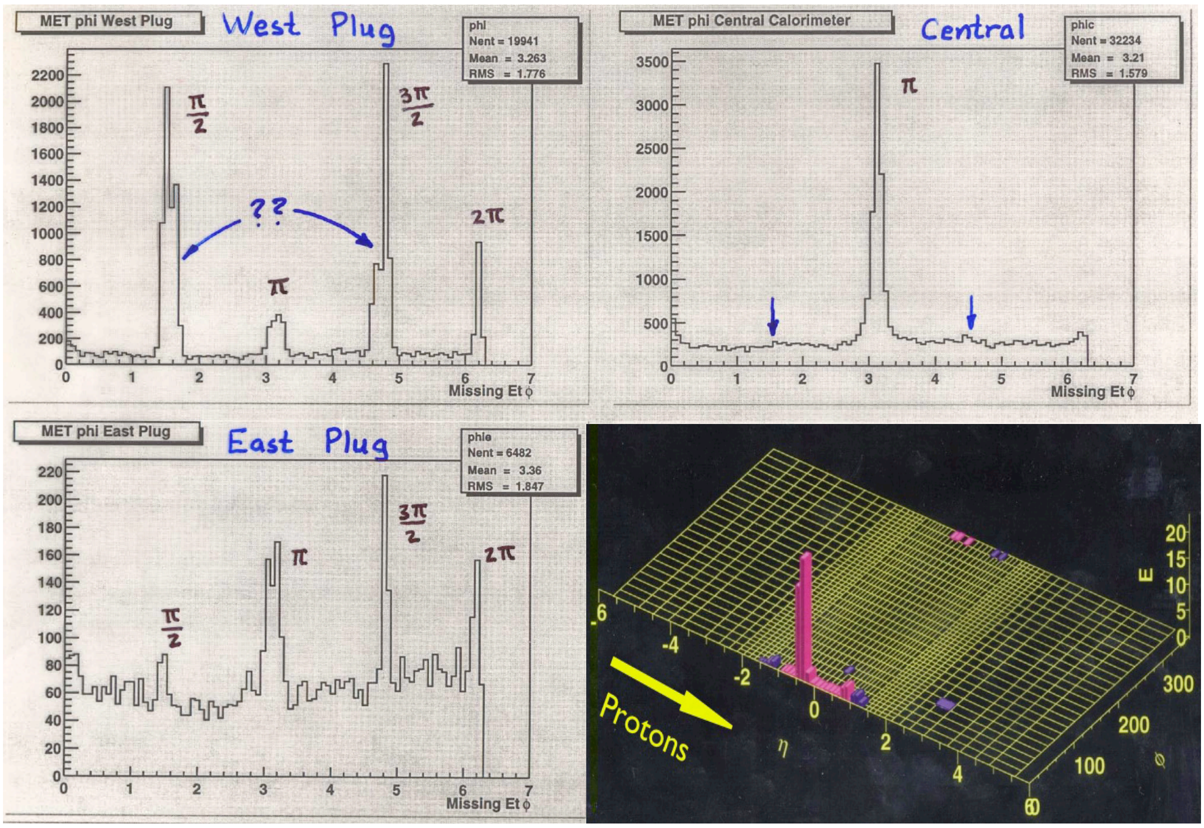

Figure 2: Missing transverse energy (MET)ϕ distributions for events with at least 25 GeV of MET by detector region. Distributions are shown for the forward calorimeters on the incoming proton (upper left) and incoming antiproton (lower left) and central calorimeter (upper right). The direction $\phi = 0$ corresponds to the plane of the accelerator pointing radially outward from the center of the accelerator, the z axis is defined by the proton direction. In the lower right is an event display showing energy deposits in the electromagnetic calorimeters (pink or light color) and hadronic calorimeters (blue or dark color) as a function of $\eta = -\log\left(\tan\frac{\theta}{2}\right)$ and ϕ for a beam halo muon.

In addition to the operational issues outlined in the above paragraphs, beam related particles are observed to produce signals in the CDF calorimeters which mimic certain kinds of physics signals requiring energy imbalance in the detector (missing transverse energy or MET). Because MET is "missing" or unbalanced energy, the energy deposited in the calorimeter is opposite the direction of MET. Figure 2 shows the ϕ distribution of the MET for triggers with MET larger than 25 GeV in the two forward calorimeters and the central calorimeters. Peaks in the MET distributions occur at multiples of $\pi/2$ in the calorimeters.

The sources of the peaking background in the MET ϕ distributions are different for the central and forward (plug) calorimeters. In the central calorimeters, the source was tracked down to beam particles outside the core of the beam hitting an aperture restriction, the CDF Roman pots, approximately 60 m upstream (on the incoming proton side) and producing muons. The relative size of the peaks at $\pi/2$ and $3\pi/2$ between the two forward calorimeters is approximately the same ratio as the incoming proton and antiproton beam currents (losses). The peaks are consistent with beam losses hitting the far forward (miniplug) calorimeters. The resulting secondaries then pass through a 5 cm crack in the shielding surrounding the miniplug calorimeters and shower in the plug calorimeters. Detailed information about these backgrounds is found in ref [5, 6].

BEAM LOSSES AND HALO

All the effects outlined above have been traced to particles lost from one or both beams. Identifying sources of those losses and the subsequent radiation requires detailed knowledge of both the accelerator and the experiment. While a detailed discussion of the Tevatron and CDF are beyond scope of this paper, Relevant components or geometry are discussed when appropriate. Table 1 summarizes some of the basic accelerator parameters for the Tevatron collider which are relevant for subsequent discussions.

Accelerator performance and quantifying the beam losses mentioned earlier is accomplished by making measurements near the CDF detector. Luminosity is measured at CDF using a gaseous Cherenkov counter system located on the CDF detector. Measurements of beam losses and beam halo are made using sets gated scintillation counters

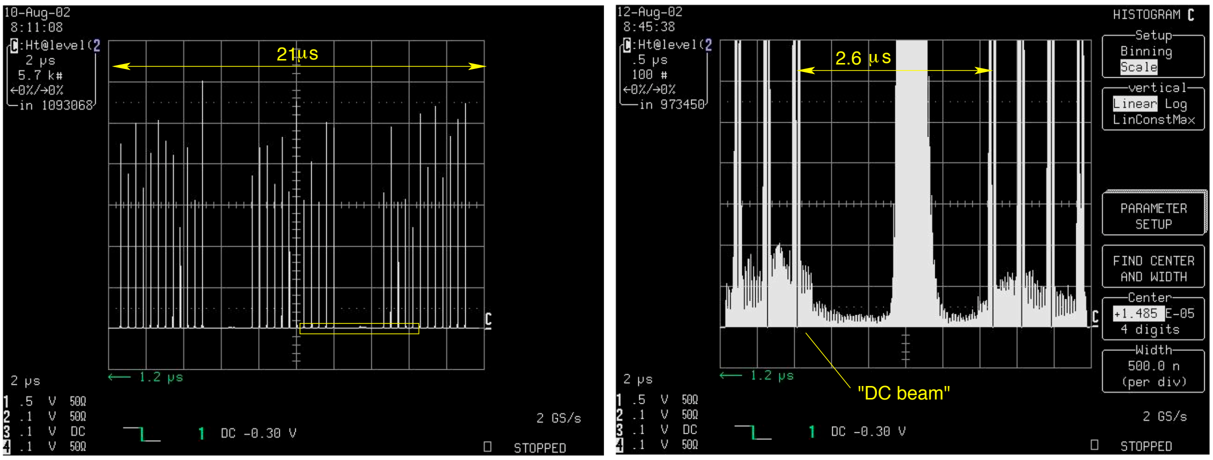

Figure 3: Distribution of beam losses as a function of time during a revolution. The left figure expands the vertical and horizontal scales to view the abort gap. The comb-like structures is due to the accelerator RF.

Table 1: Summary of Tevatron accelerator parameters.

Parameter	Value	Units
interaction regions	2	
beam energy	980	GeV
# bunches[1]	36	
bunch length	1-2	ns
bunch spacing	396	ns
abort gap[2]	2.6	μs
protons/bunch	30×10^{10}	particles
pbars/bunch	8×10^{10}	particles
luminosity	2.8×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
RF frequency	53	MHz

[1] 3 trains of 12 bunches
[2] 3 abort gaps

to provide some discrimination between protons and antiprotons. Details of the luminosity, beam loss and beam halo systems may be found elsewhere [7, 8, 9]. For the loss and halo measurements, discriminated counter signals are in coincidence with the time beam particles pass the plane of the counter on their way into CDF. Beam losses are measured using coincidences with a bunch signal and measured within a few centimeters of the beam. Halo is measured using the same technique, but with larger counters approximately a half meter from the beam. All these monitors provide real time feedback on beam conditions at CDF to the accelerator control room. While the beam loss and halo counters typically measure rates integrated over one second, because the counter signals are extremely fast, one may use these devices to understand beam structure. An example of such a measurement is shown in Figure 3. The same Figure also shows losses measured in the abort gaps and between bunches: "DC beam" or un-captured beam."

BACKGROUND RADIATION

To understand radiation effects in various CDF instruments, a number of measurements were made of the spatial distribution of ionizing radiation and low energy neutrons using thermoluminescent dosimeters(TLDs). Details of the individual measurements taken inside the CDF tracking volume are reported elsewhere [10, 11, 12, 13, 14]. Similar measurements were made external to the CDF detector in the collision hall [15].

In the CDF tracking volume measurements were made under differing beam conditions. The left side of Figure 4 shows the ionizing radiation measurements for three periods under differing beam conditions. In the Figure, protons are incident from the left and antiprotons are incident from the right. Assuming that the measurements represent a linear superpositon of contributions from beam losses and proton-antiproton collisions, we can separate out the effects from the two sources. The right side of Figure 4 shows the spatial distribution of ionizing radiation in the CDF tracking volume due to collisions and proton losses. From these data the radiation dose inside the CDF tracking volume may be estimated for any combination of integrated luminosity and integrated proton losses and is publically available [16].

Multiple measurements of the radiation field external to the CDF detector do not include periods which were dominated by beam losses. Consequently, a separation of components from losses and collisions was not made. However, measurements were made for different configurations of the collision hall. Results of these measurements are presented later in this paper.

In addition to TLD measurements, a series of experiments using telescopes of scintillation counters were also performed to isolate sources of charged particles. Details of those measurements are described elsewhere [17, 18]. From the counter experiments, we learn that the final focus triplet forms a line source of charged particles. These parti-

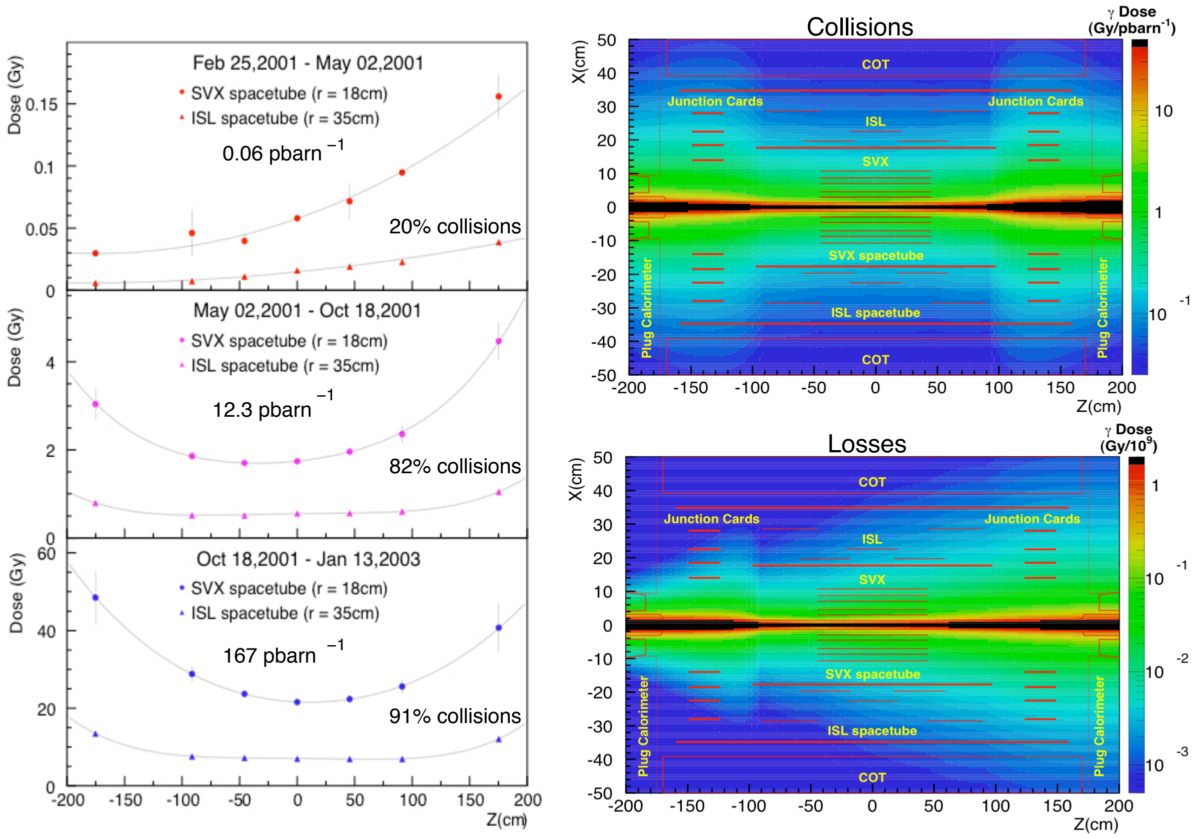

Figure 4: Ionizing radiation field in the CDF tracking volume. The left figures represent separate measurements using thermal luminescent dosimeters for three exposure periods. The right plots show the radiation field maps for collisions(upper right) and losses (lower right) based on the measurements. In all plots, protons are incident from the left, antiprotons from the right.

cles originating from beam protons and antiprotons hitting the walls of the vacuum pipe inside the quadrupole magnets.

BACKGROUND REDUCTION

The previous sections summarize the effects of accelerator induced backgrounds at CDF. The effects of these backgrounds are addressed in a collaborative effort between CDF and accelerator personnel. This effort has resulted in a number of steps taken to minimize the imact of beam induced backgrounds including:

- Reduction of beam losses at CDF by improving the beam quality in the Tevatron.
- Installation of additional shielding at CDF to reduce backgrounds.
- Modification of operating conditions to eliminate catastrophic failures.
- Modification of operational procedures to reduce the amount of down time for resetting electronics.
- Development of analysis selection criteria to remove beam background events.

The following paragraphs will briefly describe each of the steps noted above.

Reduction in beam losses near CDF represent the single largest improvement to accelerator backgrounds. Early studies found that vacuum in warm sections of the Tevatron was higher than expected [19, 20, 21]. Improvements to the vacuum quality,commissioning of a multiple stage collimation system [22] and routine re-alignment of magnets have all contributed to a reduction of beam losses at CDF [23]. Typical proton losses in 2004 were 2–15 kHz. By 2008, proton losses have been reduced to the range of 0.05–15 kHz[3]. An improvement of nearly two orders of magnitude.

In addition to reducing particles lost from the accelerator, additional shielding was added surrounding part of the final focus quadrupole magnets. The effectiveness of this shielding was subsequently evaluated using TLDs as described previously. Figure 5 shows the ratio of radiation dose rates before/after installation of the shielding on the incoming proton side of the CDF collision hall. The reduction near sensitive electronics is observed to be approximatley 25%, consistent with reduction of solid angle sub-

[3] Loss rates for a typical store start out at the higher value, but quickly reduce to a steady state value near the lower value after approximately 2 hours.

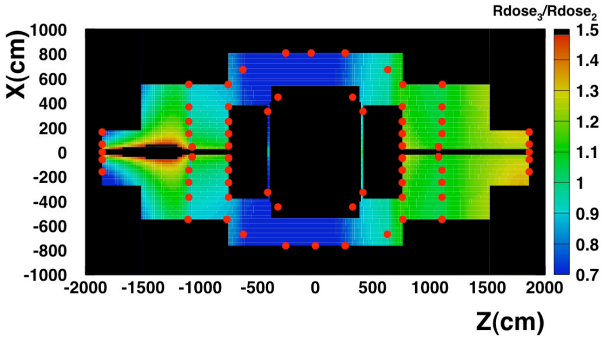

Figure 5: Ratio of ionizing radiation dose rates before/after installation of shielding surrounding the incoming proton focusing quadrupole magnets. Protons are incident from the left. The red spots indicate locations of TLDs used in the measurements. Sensitive electronics are located in the "central corners" of the collision hall. near $z = \pm 700$ cm.

tented by the quadrupole magnets at the electronics. Details of the shielding and evaluation may be found in references [15, 18].

The catestrophic SEB events observed earlier have been eliminated by changing the operating point of the sensitive MOSFET. However, despite the overall reduction in beam losses, SEU and SEL events continue to occur in CDF. These effects were responsible for 16% of the non-accelerator related downtime for CDF. Operating efficiency was improved by modifying recovery procedures from these faults. Additional details of the effects and recovery procedures are given in references [3, 4].

Physics backgrounds were reduced by as much as 40% in some triggers by the reducing beam losses by approximately a factor of 10. However, analysis selection using calorimeter timing and event topology has further reduced these backgrounds to negligible levels and has resulted in several physics results [24, 25].

SUMMARY

The Tevatron beam has been shown to be an important source of backgrounds for CDF. Particles escaping the beam contribute to degradation in detector performance due to radiation damage, compromise detector reliability from SEE and contribute to backgrounds to physics processes. Many sources of these backgrounds have been identified. Improved the quality of the Tevatron beam, added shielding around background sources, improved operational procedures and event selection have all contributed to reduction of the above effects.. Close collaboration between experiment and accelerator physicists was instrumental in this effort.

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`http://ncdf67.fnal.gov/~tesarek/radiation`