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Radiation in the CØ Assembly Hall due to Muons from Accidental Beam Loss in the Tevatron*

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Abstract

A set of calculations performed with the MARS15 code indicates a maximum radiation dose due to muons in the CØ Assembly Building (CØ AB) for a person standing on a ladder in the orbit plane of the Tevatron of 10 mrem and a maximum dose for a person standing on a CØ AB floor < 1 mrem per loss of 2.5×10^{13} protons of 1 TeV energy in the Tevatron.

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1 Introduction

The desire to begin long term occupancy during Tevatron Collider operations of the CØ Assembly Building (CØ AB), specifically the below grade Assembly Hall and Mezzanine areas, has led to a revisiting of the question – with the realistic calculations performed with the MARS15 code [1, 2] – of the maximum expected radiation dose to workers due to muons, generated by losing the proton or antiproton beams in the Tevatron. The muons penetrate the accelerator components, soil and concrete to reach the CØ AB [3](Fig. 1). In the figure, the transverse reference lines and distance from the Tevatron beam for the MARS geometry are indicated. To avoid clutter, the surface floors at 744'-4" and 746'-4" elevations are not shown. It would be desirable to allow Radiation Workers unlimited occupancy in all areas of this building [4].

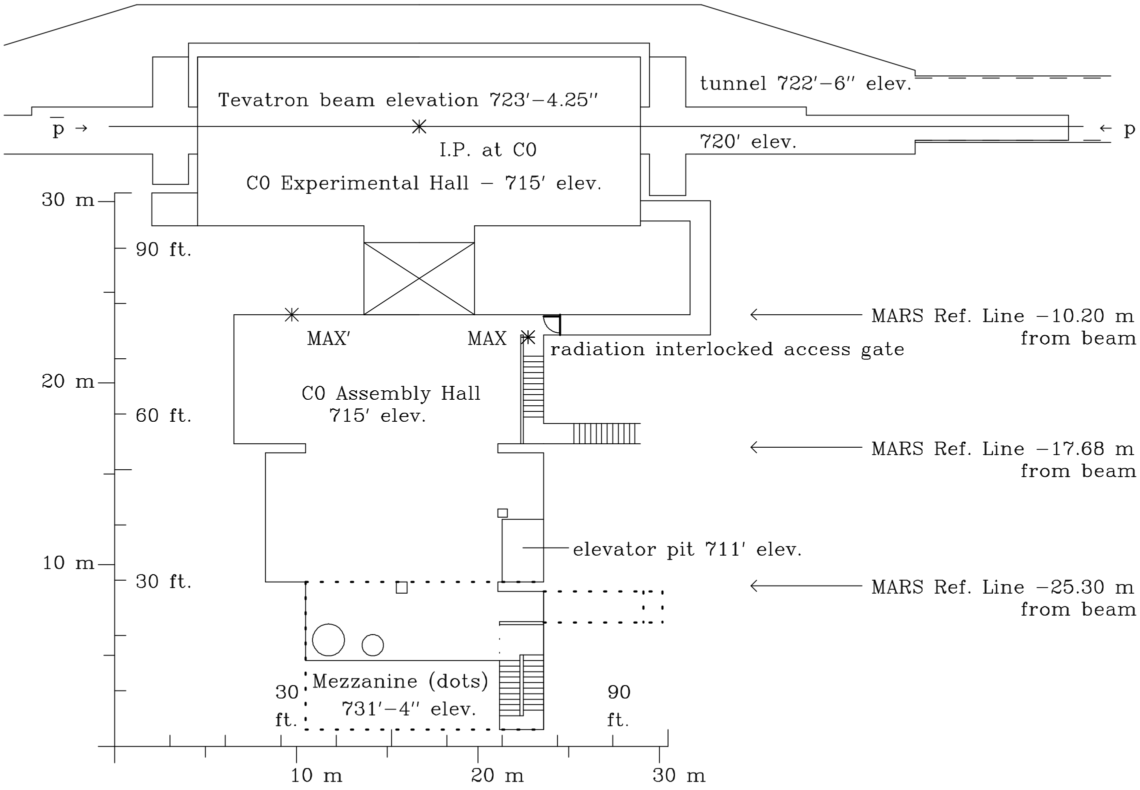

Figure 1: Layout of CØ Assembly Hall with Mezzanine indicated [3]. The position of maximum dose for beam loss at 138 meters from the CØ station is denoted the star at MAX. The star at MAX' denotes the center of the muon plume generated at the same loss point for a simulation ignoring the magnetic field. The significance of the beam loss location is explained in the text.

As part of the planning for the construction of this building, the calculation [5] for accidental muon exposures in the CDF Assembly Hall at BØ were scaled to the particular geometry of the CØ AB. This calculation assumed that the Tevatron geometry was a perfect circle, that the circulating proton beam struck accelerator components with no empty decay path for pions to decay into muons, and that the entire distance from the point-like Tevatron beam loss to the CDF Assembly Hall was treated as soil, averaging over the higher density accelerator components and the empty distance between the Tevatron components and the outer wall of the tunnel. Since the deepest penetrating muons are those of the highest energy, the beam loss was assumed to occur at 1 TeV. The 1-TeV protons were modeled as emerging tangentially from the Tevatron and striking a soil shield of 151 meters thickness, corresponding to the distance of a person's closest approach to the Tevatron for the CDF Assembly Hall. The maximum number of muons per cm^2 per proton (or dose) and their tightly collimated transverse distribution (3-mrad half-angle for half-maximum dosage, or ±0.5 meter) in the CDF Assembly Hall were calculated using a muon version of CASIM [6].

Besides being a very simplified geometric representation, this calculation fails to account for the magnetic fields of the Tevatron magnets which are traversed by the particles, both secondary hadrons and prompt and decay muons, which fans out the muon distribution within the (horizontal) orbit plane of the Tevatron, dramatically decreasing the maximum dose rate for a given accidental beam loss.

Subsequently, other models and calculations have been performed for a variety of muon radiation dosages for simple soil equivalent shields, with varying lengths of pion decay channels, but without magnetic fields [7, 8, 9, 10, 11]. Even after correcting for customary density of wet Fermilab soil (ρ = 2.24 g/cm^3), the muon dose at a typical 150-m soil shield calculated using [7] was approximately a factor of 3 larger than that calculated using [8]. Reference [12] used MUSIM [8] along with a model (not described) to account for the magnetic dispersion of the Tevatron dipoles. This study quoted a reduction factor, due to the magnetic fields, of up to 50 in the muon dose.

Results of detailed MARS15 calculations are presented here to evaluate realistic radiation environment in CØ AB at beam accident in the Tevatron. With apologies, mixed units are used in this document. The radiation physics simulation uses meters, whereas building elevations are quoted in feet and inches above mean sea level, as is customary in the construction industry.

2 MARS15 Modeling

The MARS15 [1, 2] simulation code is used in this study. The current Tevatron lattice [13], layout, 3-D geometry, materials and magnetic fields for all the elements (dipole, quadrupole, and corrector/trim magnets), the tunnel and the CØ AB [3] geometries, including concrete and soil have been built into the MARS model (Figs. 2-3). The utility Mezzanine, and the area under it, is not included in this model.

The reduced soil shielding due to the 9.1-m long corridor of the access labyrinth is explicitly modeled, leading to increased value at point of the peak dose. The soil between the tunnel and the CØ AB is assumed to be of the standard wet Fermilab density of ρ = 2.24 g/cm^3. The detailed magnetic fields of the superconducting dipole and quadrupole magnets at excitation for 1 TeV were modeled as shown in Figs. 4-5, including the magnetic field in the cold mass coil package, vacuum spaces, and steel flux return [14]. MARS simulates the production, tracking, bending, scattering, and interaction of hadron and electromagnetic shower particles, including prompt muons, and those from decays of pions and kaons. The particle cutoff energy in these studies is 1 MeV. The dose calculated within the CØ AB also includes that due to neutrons, electrons, and photons produced by the muons as they exit the concrete walls of the building. The cutoff energy described above underestimates the actual dose by a few percent.

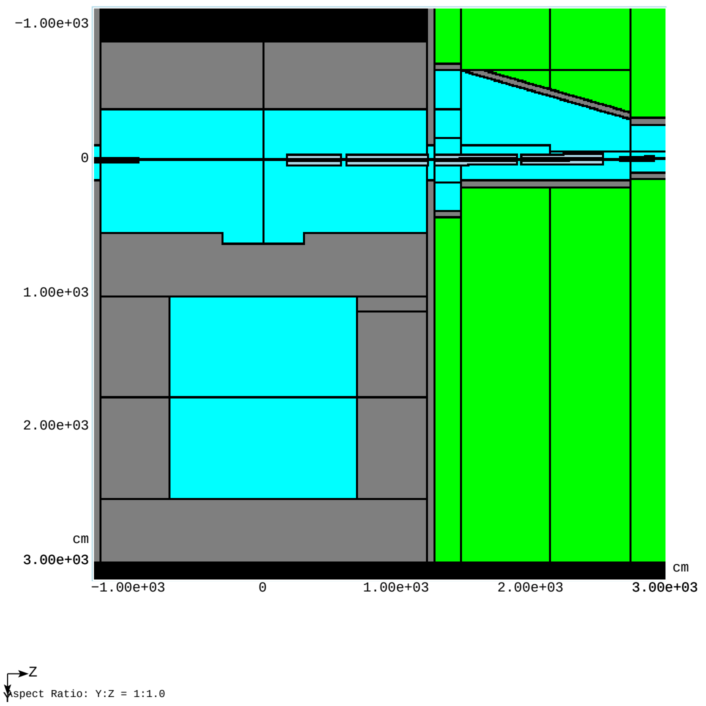

Figure 2: The MARS model of the C0 AB at the beam elevation. The Experimental Hall, the access labyrinth, and the Assembly hall air is shown in blue. Grey represents concrete and green - soil. The reference lines at 10.2 m, 17.68 m, and 25.3 m shown in Fig. 1 are used as transverse reference distances in the MARS plots of the next section.

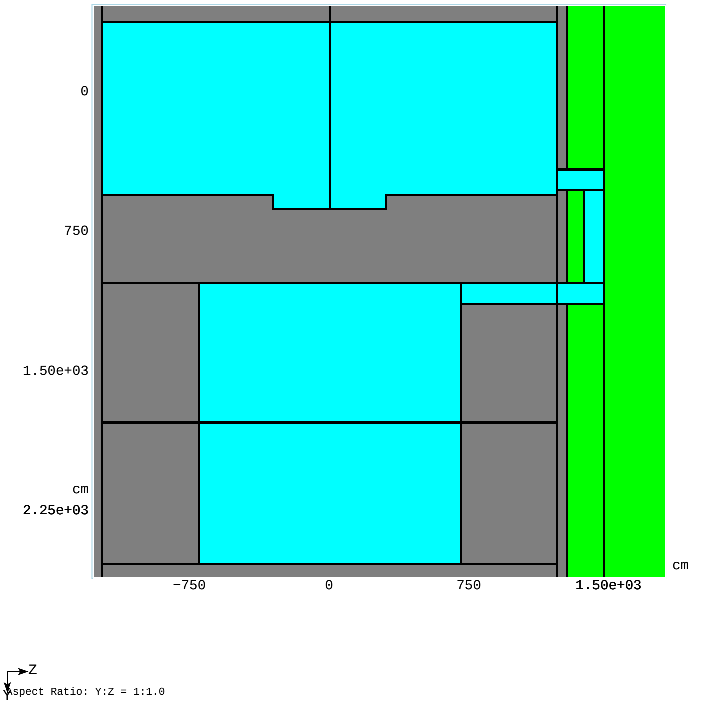

Figure 3: Same as in Fig. 2 for the 715’ elevation of the Assembly Hall floor.

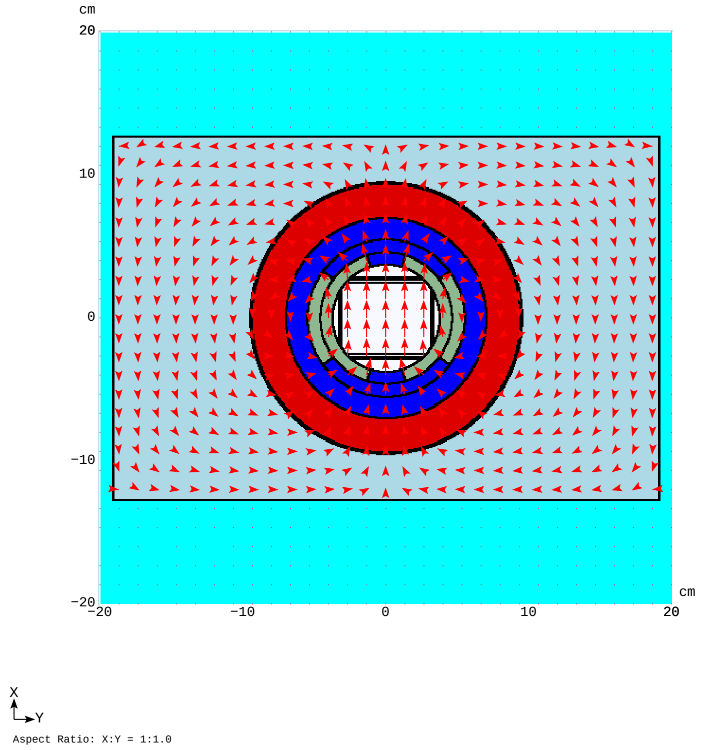

Figure 4: The MARS model of the Tevatron superconducting dipole.

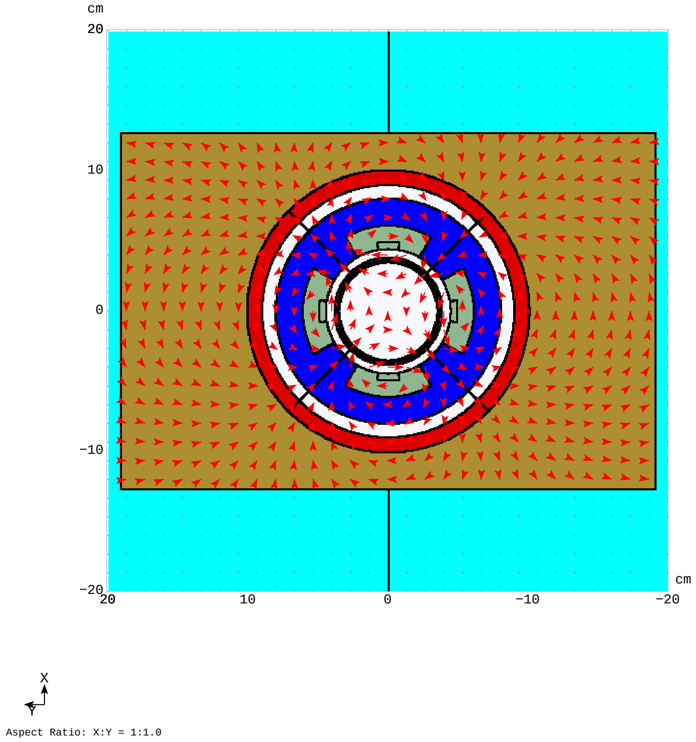

Figure 5: The MARS model of the Tevatron superconducting quadrupole.

The beam of 2.5×10^{13} protons of 1 TeV energy is assumed to have transverse dimensions characterized by $\sigma_x = \sigma_y = 1$ mm (typical of beam size within the FODO half-cells) and was assumed to strike the beam pipe (that side towards the center of the Tevatron) at an angle of 0.3 mrad (toward the center of the Tevatron, typical of the maximum bend of the Tevatron trim/corrector dipole magnets). This produces a primary loss region along the beam of $\sigma_z \approx 3$ meters.

In general, the positively charged muons tend to be channeled, following the curvature of the Tevatron elements and tunnel, while the negatively charged muons emerge quasi-tangentially to the Tevatron ring in an elliptical cone (Fig. 6). Both charge components are tightly collimated in the vertical orbit plane of the Tevatron, with a somewhat more dispersed horizontal component. There is no muon radiation issue at the surface level of CØ AB (746'-6" elevation = 7.0 m above the orbit plane of Tevatron), or the sunken computer floor (744'-6" = 6.4 m above), or the sunken elevator pit (711' = 3.5 m below). The floors of the mechanical utility Mezzanine (731' = 2.3 m above) and the Assembly Hall (715' = 2.55 m below) require more discussion. There is a steep fall-off in muon dose as one moves vertically away from the orbit plane of the Tevatron. For this assessment, we will describe the maximum dose in the CØ AB close to the orbit plane of the Tevatron, assuming a person can be standing on a ladder or the staircase near position MAX (the staircase is only used as a secondary emergency escape route, and thus may be considered minimally occupied). We also describe an average dose, integrated over the cross sectional area of an average person's trunk (0.6 m vertical x 0.3 m horizontal), which is comparable to the characteristic fall-off distance of the muon dose from its maximum value.

Scanning possible loss points between B44 (183 meters from CØ) and B46 (124 meters from CØ) indicates that losing the proton beam at 138 meters [15] from station CØ , within the B45 half-cell of the Tevatron, produces the absolute maximum dose at position MAX in Fig. 1. These B45 dipoles are downstream of a horizontally defocusing quad, which is quite typical for beam losses in the Tevatron. Fig. 6 shows the simulation of 30 protons being lost at that location which produce muons creating the highest dose at point MAX in the CØ Assembly Hall, at an elevation near the orbit plane of the Tevatron. The proton interactions were selected with a likelihood of producing muons capable of reaching the CØ Assembly Hall, therefore every muon track shown in the figure carries a statistical weight of about 10^{-4}.

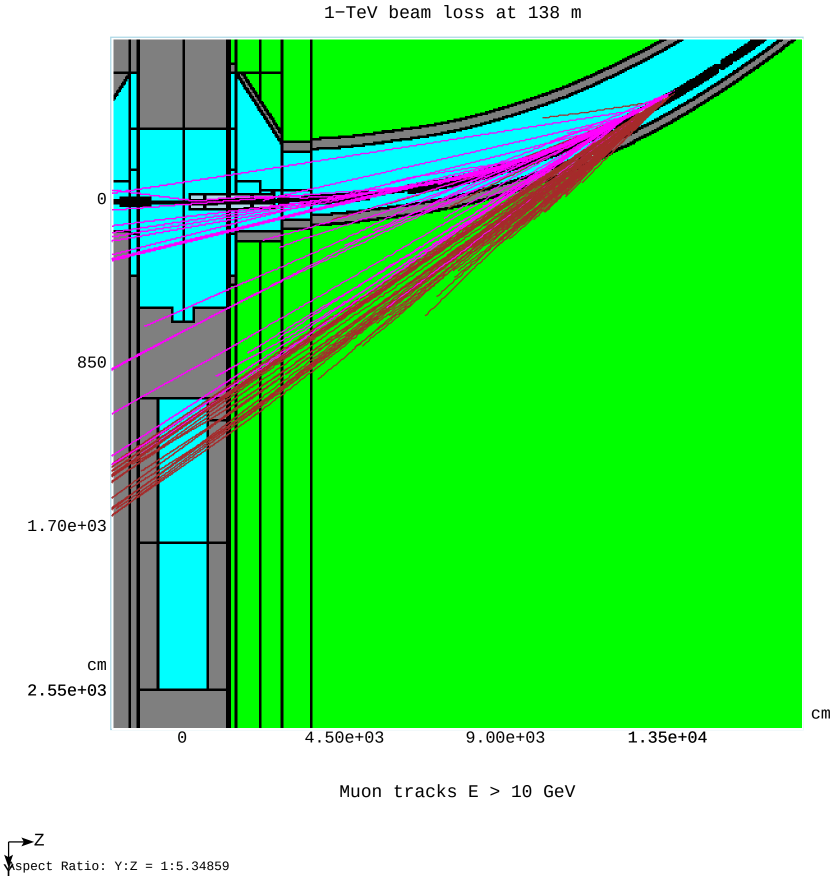

Figure 6: Positive (magenta) and negative (brown) muon tracks above 10 GeV creating the peak dose at point MAX of CØ AB for the 1-TeV proton beam lost at 138 m from CØ. Every track carries a statistical weight of about 10^{-4}. The significance of the beam loss location is explained in the text.

3 Radiation Dose in Assembly Hall

Muon-induced radiation fields in CØ AB are presented in this section for the worst case beam loss accident at 138 meters from station CØ. Two-dimensional dose equivalent distributions calculated are for loss of 2.5×10^{13} protons at 1 TeV as described in previous section. Fig. 7 shows the dose isocontours averaged over v = ±0.5 m above-below the orbit plane of the Tevatron; in this section v is a vertical coordinate. One can see the (mainly) positive muon plume along the Tevatron tunnel, and a second (about 90% negative) muon plume tangential to the tunnel. Fig. 8 zooms in on the radiation fields in the CØ Assembly Hall. Refer to Figs. 1 and 2 for the positions of the MARS geometry reference lines. Notice that the color coding has changed from that of Fig. 7 and that the average is from 0.8 to 1.8 meters below the orbit plane of the Tevatron, as typical for a dose to the head and trunk. Fig. 9 shows the radiation fields in the CØ AB as observed by standing against the upstream wall and looking back toward the loss point. The edge of the figure is at the shield door (10.2 m from the beam) and the right line is at the 25.3 m reference line. The top (0 cm) is in the orbit plane of the Tevatron (723'-4.25" elevation) and the bottom (-255 cm) is the floor of the Assembly Hall (715' elevation). The location of the maximum dose (in the orbit plane of the Tevatron) is depicted as point MAX in Fig. 1.

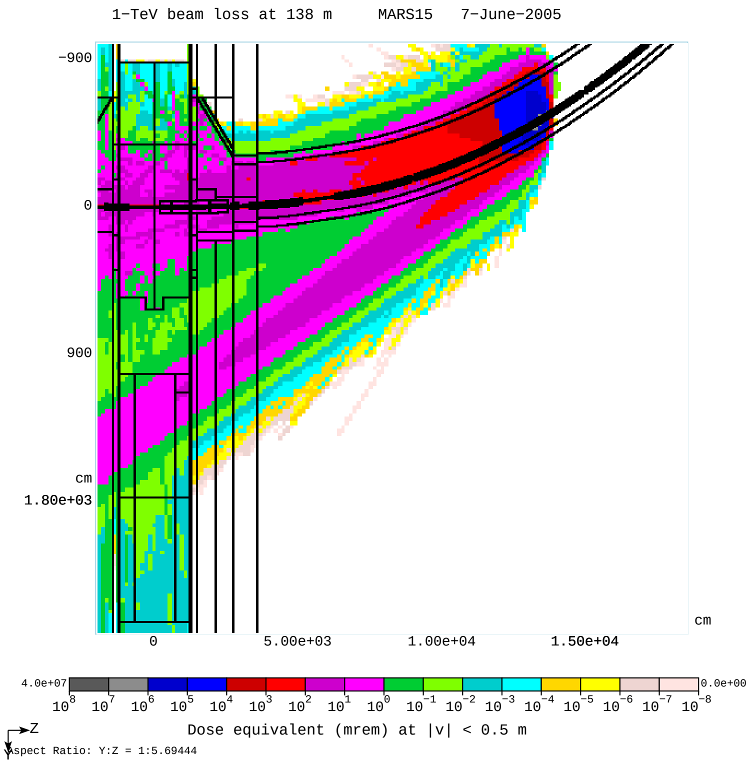

Figure 7: Dose equivalent isocontours (mrem) in the Tevatron orbit plane.

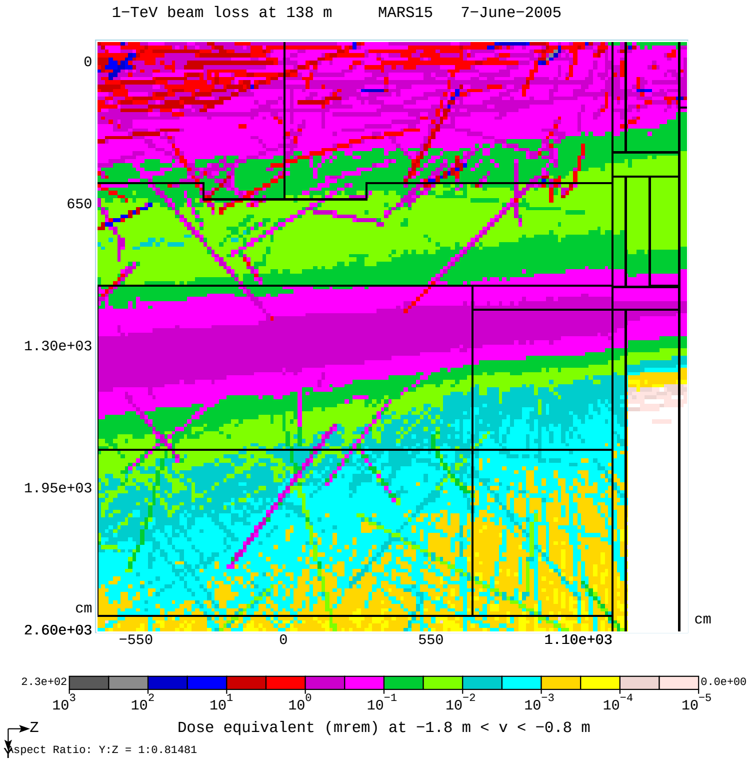

Figure 8: Dose equivalent isocontours (mrem) at 0.8 m to 1.8 m below the Tevatron orbit plane.

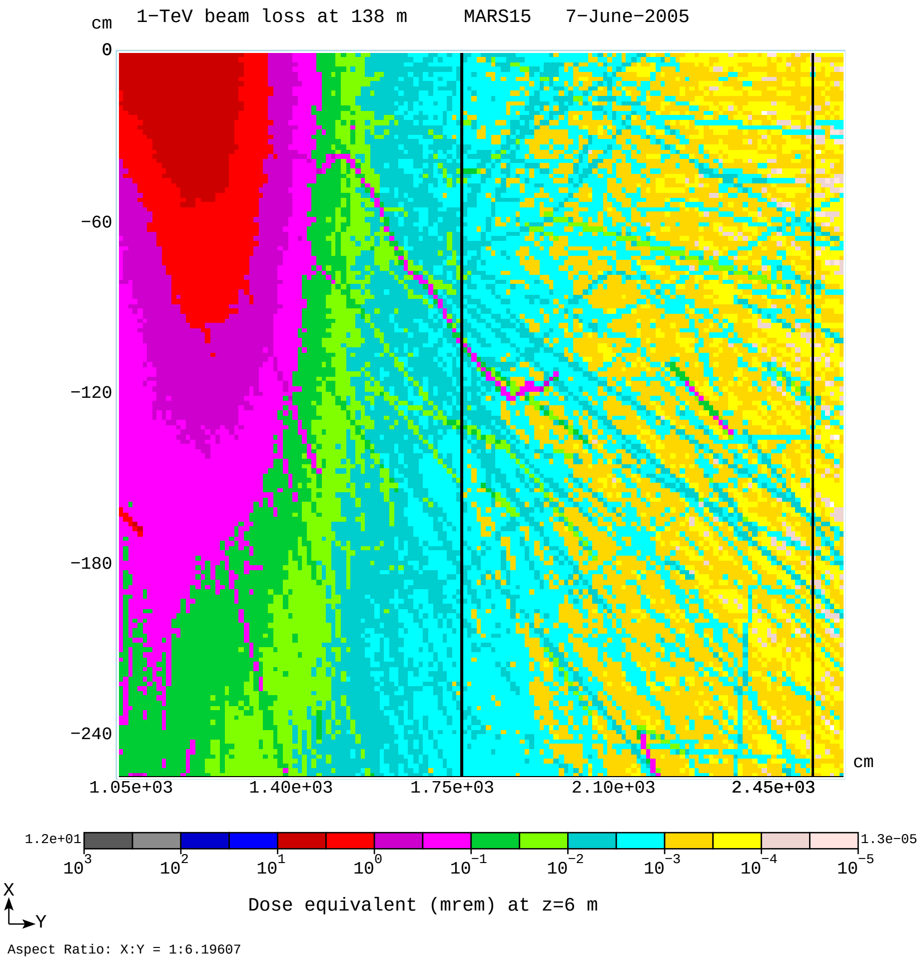

Figure 9: Dose equivalent isocontours (mrem) in the vertical plane facing the labyrinth mouth.

Particle energy spectra at the labyrinth mouth averaged between 10.2 and 13.2 m horizontally and from the CØ AB floor to the orbit plane vertically are presented in Fig. 10. One observes low-energy photons, electrons and neutrons being in a 100:10:1 ratio, respectively. These particles are produced by energetic muons in the preceding concrete walls and soil and their mean energies are 2.6 MeV, 5.4 MeV, and 3.0 MeV, respectively, with the cutoff energy of 1 MeV. The muon mean energy in CØ AB at point MAX is 4.3 GeV, a thousand times higher.

For the considered worst case accidental beam loss scenario of 2.5×10^{13} 1-TeV protons, the hottest point in the CØ Assembly Hall is denoted as MAX in Fig. 1. The maximum dose at this point averaged over a region within 0.3 m of the orbit plane of the Tevatron (-0.3 m $< v <$ $+0.3$ m) is 11 mrem. This corresponds to the radiation dose averaged over the trunk of an average size person [16]. The maximum dose averaged over $0 < v < 0.5$ m, corresponding to Fig. 7, is 8 mrem. The maximum dose averaged over the trunk of an average person just below the orbit plane of the Tevatron (-0.6 m $< v < 0$) is 6 mrem. All three of these cases would be for a person working on a ladder or on a piece of equipment above the floor of the CØ Assembly Hall. Averaged over the trunk of a person standing at any position on the floor of the CØ AB (-1.8 m $< v <$ -0.8 m), the maximum average dose doesn't exceed 1 mrem. According to the Fermilab Radiological Control Manual [17], a maximum accidental dose of $<$ 1 mrem per accident (or per hour) implies that for a possible muon radiation field no precautions or occupancy restrictions would be necessary for the CØ Assembly Hall, the worst case, and thus for the entire CØ AB.

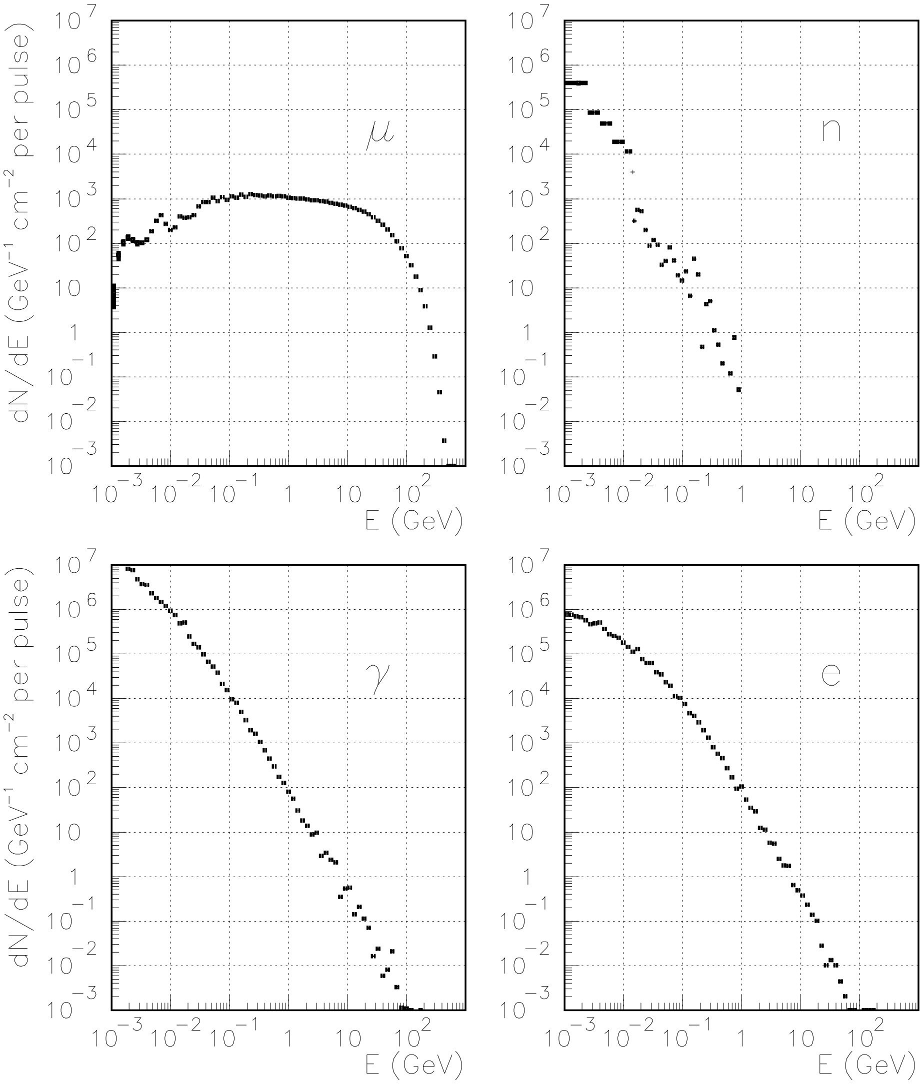

Figure 10: Energy spectra of muons, neutrons, photons and electrons at the labyrinth mouth.

Two special runs were performed with MARS15 with the magnetic field in the Tevatron magnets turned off. For the proton beam loss at 138 m, the axis of the muon plume, now consisting of both positive and negative particles, is shifted towards the C0 station centerline. Therefore, the peak dose in C0 AB for this hypothetical case occurs at the MAX' point at z = -7 m in Fig.1 and is pretty close to the above maximum of 10 mrem and average $<$ 1 mrem values, but with approximately 22 meters of additional soil/concrete shielding, considering the extra path length and discounting the labyrinth corridor. Fig. 11-12 compares dose isocontours for the proton beam loss at 153.5 m (putting the muon plume right down the labyrinth corridor) with and without magnetic field in the Tevatron magnets. In this case, the peak dose in C0 AB is about a factor of 8 higher, comparing the center of the muon plumes in C0 AB, when one hypothetically turns off the field in the magnets. The dose in reality is lower with field on, because the field traps positive muons in the magnets and makes the negative muon flux more diffused.

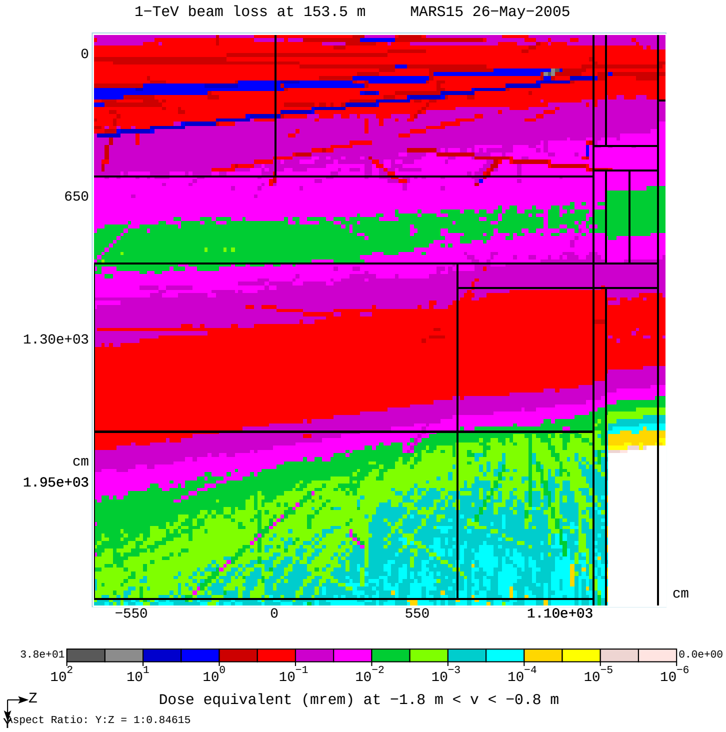

Figure 11: Dose equivalent isocontours (mrem) at 0.8 m to 1.8 m below the Tevatron orbit plane for beam loss at 153.5 m.

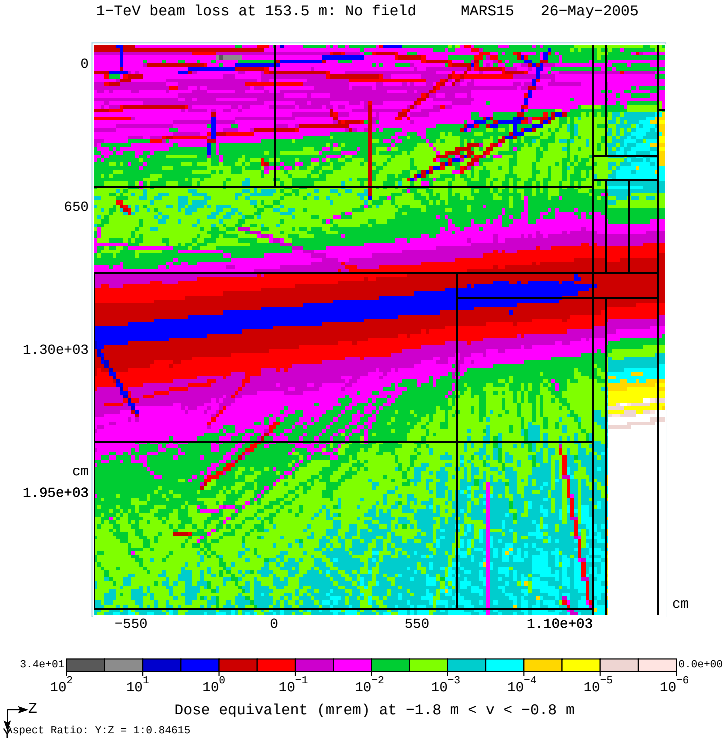

Figure 12: Same as in Fig. 11 but – hypothetically – without magnetic field in Tevatron magnets.

4 Occurrence of Beam Accidents in Tevatron

As few as 10^7 protons at 1 TeV lost in a single Tevatron superconducting magnet are likely to quench that magnet [18, 19]. Conversely, a major localized beam loss would result in a quench in that region. Quench history records [20] are available for the Collider Run II period from May, 2001 to the present. Through June, 2005 there have been 4 beam-induced quenches for the B4 cryo-house, of which 3 were at locations (B42, B48, and B48) for which the resulting muon plume would not have been aimed at the CØ AB. The other quench during beam scraping included B4 (unspecified exact location(s)) and 11 other cryo-houses (total of 12 out of 24 cryo-houses) along with the low-β systems. Such wide-spread quenching indicates wide-spread beam loss around the ring, diluting the loss that could have produced muons in the CØ AB. The radiation monitor in the CØ Assembly Hall did not trip during this quench, but that could mean that the monitor was not directly in the muon plume.

The muon radiation fields for antiproton beam losses in the C14 half-cell are assumed to be mirror symmetric about a line containing the CØ Interaction Point and the centerline of the CØ AB. During this same time period, there were also 4 beam related quenches for the C1 cryo-house. Three of these were not aimed to produce muons in the CØ AB (C11, C1 for proton beam only, and C1 on a proton B48 abort kicker prefire. (Note that this kicker has since been removed from the Tevatron). The remaining C1 beam quench did not have a location further specified, but it occurred at 153 GeV during the ramp with a poorly coalesced antiproton beam. The reduced beam energy and the reduced number of antiprotons (typically 10^{12}) would also reduce the number of possible muons into the CØ AB. Again, the radiation monitor in the CØ Assembly Hall did not trip during this quench.

In order for a person to get average dose close to 1 mrem, the loss point must occur within a few meters of the exact point to aim the tightly collimated muon plume directly at that person. Experience has indicated that over the last four years of Tevatron operations, there have been at most two beam-related quenches that could have occurred at points which had the possibility of aiming a muon plume into the CØ AB. However, due to the distribution of beam losses over much of the Tevatron ring for one, and the lower antiproton intensity for the other, we conclude that the probability of having a beam loss in at a position that would send a muon plume which approaches the maximum dose of 10 mrem to any position or height in the CØ AB has to be less than 0.5 occurrence per year.

5 Acknowledgments

We are thankful to J.D. Cossairt for fruitful discussions and constructive comments.

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[15] The designation of the loss point as 138 m from C0 represents the inner 4 σ_x striking the beam pipe. The centroid of the beam strikes the pipe at 133 m from C0 and the outer 4 σ_x at 129 m. The same specification of distance from C0 is used throughout this report.

[16] Don Cossairt, private communication on June 7, 2005, suggested the use of a cross sectional area of 0.6 m vertical by 0.3 m horizontal as representative of the trunk of an average size person for the calculation of average radiation dosages.

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