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Abstract

The radiation shielding in the Fermilab Main Injector (FMI) complex has been carried out by adopting a number of prescribed stringent guidelines established by a previous safety analysis[1]. Determination of the required amount of radiation shielding at various locations of the FMI has been done using Monte Carlo computations. A three dimensional ray tracing code as well as a code based upon empirical observations have been employed in certain cases.

I. Introduction

The Fermilab accelerator complex consists of a chain of four proton accelerators with a beam energy up to 800GeV for fixed target experiments and up to 2 TeV (center of mass energy) for collider experiments. The Fermilab Main Injector (FMI) which is being built in a separate enclosure, will replace the 150 GeV Main Ring (MR) accelerator which is currently being used as an injector to the Tevatron. FMI has many added advantages over the MR[2]. Having larger admittance both in the transverse and in the longitudinal phase space, the FMI is capable of providing more than 5E12 protons/batch at 120 GeV for the antiproton production target and over 3E13 protons/batch at 150 GeV for the fixed target operations. When such a high energy and high intensity facility is being built, it is necessary that proper care is taken regarding environmental protection as well.

II. Shielding Guidelines

The radiation safety is an important and mandated requirement for all Fermilab facilities. In order to meet this responsibility a number of guidelines have been provided in the FERMILAB RADIOLOGICAL CONTROL MANUAL and have been followed for designing the FMI. Many of the stated guidelines in this manual are more stringent than the DOE standards. A list of Fermilab standards which are relevant to the aspects of radiation shielding evaluation at the FMI, are given in Table I.

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Table I. Fermilab standards for radiation shielding evaluations.

Description	Maximum Allowed Dosage
Visitors and public: Whole body	0.05 rem/year (i.e., 0.025 mrem/hr) (Unlimited Occupancy)
Non-radiation workers: Whole body	0.05 rem/year (i.e., 0.025 mrem/hr) (Unlimited Occupancy)
Radiation workers: (direct 'prompt' radiation)	1.5 rem/year ($\leq$300 mrem / quarter)
Ground water activation[a]	20 pCi/ml-year (^{3}H) 0.4 pCi/ml-y (^{22}Na)

[a] These nuclides are of major concern to Fermilab. However care has been taken to meet the requirements of DOE order N0. 5400.5 for other radioactive nuclides causing contamination in the ground water.

Using the guide lines in Table I and the results of Monte Carlo calculations with CASIM[3] for some typical cases, the following shielding criteria have been developed[1]:

1. For unlimited occupancy we need soil equivalent shielding of 7.92 m (26 ft) for 150 GeV beam-lines enclosures, and a soil equivalent shielding of 7.46 m (24.5 ft) forthe 8 GeV beam-lines and the FMI enclosures.
2. 0.305 m (1 ft) of steel[4] is a soil equivalent of 0.88 m (2.89 ft) and 0.305 m of heavy concrete (78% concrete with 22 % steel) is a soil equivalent of 0.46 m.

These are used very often in deciding the shielding thickness for radiation protections.

III. FMI Design, Beam Intensities and Beam-losses

FMI is located underground. The tunnel floor of the FMI is at an elevation of 217.47 m (713.5 ft) which is about 1.82 m lower than the Tevatron tunnel floor. It has a total circumference of 3319.41 m. A geometric layout of the

FMI along with some critical area of interest from the radiation shielding point of view are shown in Fig. 1. For the purpose of injection and extraction of the proton beams, a total of seven beam lines will be built. Some beam lines have varying elevations.

Each region of FMI and its beam-lines that poses potential radiation safety problems has a unique structure, so they have to be treated individually. For instance, the RF gallery near the MI60 straight section is one such area. The proton and the antiproton beams from the FMI will be injected in to the Tevatron near(under) this gallery. The two accelerators are at different elevations. A total of five beam lines originate in the vicinity of this region. The walls in the beam enclosure have a number of utility penetrations and alcoves. At the surface level (at an elevation of 226.31 m) there is the MI60 service building. Evaluating the radiation shielding for a region like this is very difficult task. We will briefly discuss the shielding aspects of this region later.

The beam in the FMI will be accelerated to 120 GeV and 150 GeV depending upon the application. The operating scenarios for the FMI are listed in Table II. The FMI is capable of operating in five different modes. The beam intensities shown in Table II are design goals.

Table II. The beam intensities for different operation scenarios of the FMI and beam loss terms.

FMI Mode of Operation	Proton Beam Intensity and Cycle time
pbar Production	5E12p/1.5sec @120GeV
Fast Resonant Extraction	3E13p/1.9sec @120GeV
Slow Resonant Extraction	3E13p/2.9sec @120GeV
Collider Injection	5E12p/5sec @150GeV
Tevatron Fixed Target	3E13p/30sec @150GeV
Beam-loss Scenario	Source Term
Operation Losses (Annual)	1E19 @8GeV 4.1E18 @120GeV
Accidental Losses	5.7E16 @8GeV 8.5E15 @120GeV

Defining the beam-loss term for an accelerator is a difficult task. Generally they are categorized into, a) normal operational beam-losses and, b) accidental beam losses. A

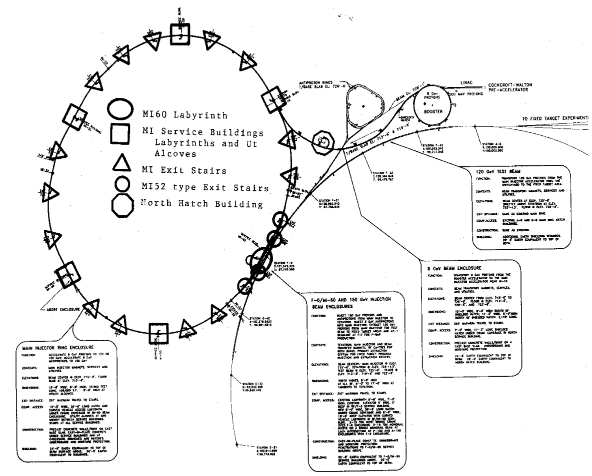

Figure 1: A geometric layout of the FMI. Ellipse : MI60 labyrinth, square:MI Service Buildings, Triangle : MI Exit Stairs, Circle : MI52 type Exit Stairs, Octagon : 8GeV North Hatch Building.

conservative estimate for the FMI has been made based upon our past experience with the Main Ring operation and are listed in Table II. These beam-losses have been used as source terms for shielding evaluations. There is also an estimated annual proton beam abort for the FMI which has been taken into account in designing the FMI beamdump[5].

IV. Shielding Calculations

After establishing the guidelines and beam-loss terms, radiation shielding calculations have been performed. When a high energy particle interacts with a material, a shower of particles mainly consisting of protons, neutrons and pions will be produced. These in turn interact further resulting in cascades of particles with angular distribution peaked in the forward direction. If the beam is lost in an energized magnet, the angular distribution need not be symmetric. The radiation dose at any point will be calculated using the number of stars produced at that location which depends upon the hadron flux, the energy, the angle and the shielding in between. When multi-GeV primary protons are lost in a target, the contributions to the prompt radiation dose in the transverse direction will be dominated by the low energy neutrons, while in the forward direction the muons (which are long-ranged) will dominate. For shielding purposes we have to consider both of them separately.

We have carried out shielding calculations for most of the locations around the FMI using Monte Carlo codes[3] CASIM (for hadrons) and MUSIM (for muons) in cylindrical geometry. The culverts are some of the locations of potential problems around the FMI which do not have cylindrical symmetry. In these cases, we have used a derivative of the code CASIM (called CASPEN [3]) and the required amount of steel under the culverts were determined. There

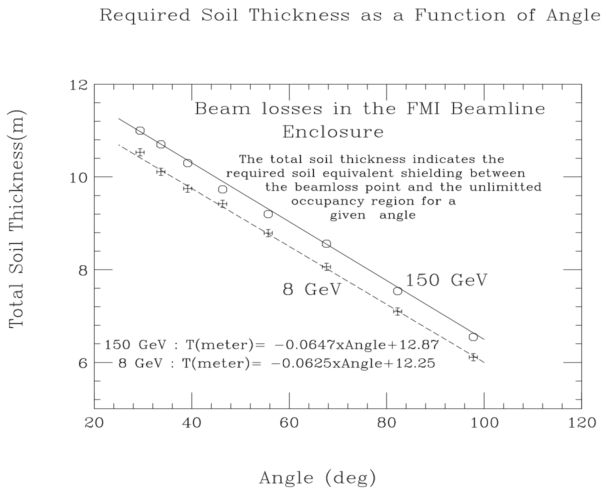

Figure 2: The soil equivalent shielding thickness as a function of angle adopted in the ray tracing computer code.

are a number of locations with very complicated geometry around the FMI. The radiation shielding calculations for such locations using a Monte Carlo code is extremely difficult and time consuming. Therefore we developed a three dimensional ray tracing computer code with Monte Carlo results embedded in it. The CASIM calculation on a typical beam-line enclosure (with soil around) has shown that the shower maximum is occuring at an angle of 68^o for 150 GeV beam loss. This has a total radial soil equivalent shielding of 8.4 m from the loss point to the unlimitted occupancy region. Lower the angle larger will be the radial shielding thickness. The required soil equivalent shielding thickness for unlimitted occupancy as a function of angle is shown in Fig. 2. We have adopted this scheme in our ray tracing code.

For exit stairs and penetrations we used EXIT2A which assumes that two successive legs in an exit stairs are at 90^o to one another. This program was developed by using empirical observations in fixed target experiments[6]

V. Radiation Dose at Some Critical Locations

The estimated radiation doses near the unlimited occupancy regions for some critical locations of the FMI are listed in Table III. For many cases a combination of Monte Carlo calculations and EXIT2A or ray tracing computer programs were used. For example, for MI52 exit stairs the EXIT2A is used in combination with CASPEN because the MI beam-line enclosure is under one of the five legs. The shielding between the beam-line and this leg is only 0.6 m of concrete. Hence, the strength of the radiation source is evaluated using CASPEN and the attenuation terms are determined using EXIT2A. In order to achieve radiation dose $\leq$0.01 mrem/hr for normal operation beam losses we had to vary the lengths of each leg to get an optimum value. This gives a conservative estimate of radiation dose at MI52 exit stairs.

MI60 straight section is another complicated area as mentioned earlier. Here we used the ray tracing program to decide the required amount of shielding as a function of angle. For some locations CASIM calculations have been carried out with rectangular geometry to estimate the leakage due to edge scattering. For the entire straight section we achieved minimum of 7.92 m of soil equivalent shielding.

Table III. Summary of radiation shielding evaluations for FMI.

Description	Max. Dose Rate	
	operational (mrem/hr)	Accidental (mrem/acc.)
MI60 Labyrinths[a]	0.09	1.2
Labyrinths and Utility Alcoves in MI Service Buildings(5)	0.01	0.06
Exit Stairs (14)	0.01	.15
MI52 Exit Stairs (4)	$\leq$0.01	0.05
North Hatch Building	$\leq$0.01	0.43
Penetrations	$\leq$0.01	0.09

[a] Posting a caution sign is required.

VI. Summary

The radiation shielding evaluation has been carried out for FMI using previously set guidelines. The FMI beamloss terms for different scenarios have been mentioned. The shielding evaluations have been carried out using Monte Carlo and a ray tracing computer code. For exit stairs calculations have been done with EXIT2A. For 8GeV beam lines and FMI enclosure we have achieved a minimum of 7.46 m soil equivalent shielding and, for the 120 and 150 GeV beam lines a minimum of 7.92 m soil equivalent shielding have been achieved.

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