Radiation Environment Resulting from Main Injector Beam Extraction to the NuMI Beam Line


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Abstract

A 120 GeV Main Injector proton beam will be delivered to the NuMI beam line at Fermilab at the rate of $3.7 \times 10^{20}$ per year. Realistic Monte Carlo simulations have been performed to examine the radiation environment in the beam extraction system and NuMI beam line elements. A complete 3-D model of the 160 meter extraction region has been implemented utilizing the computer code MARS. The model includes a description of the field of the electrostatic septa and POISSON calculated field maps of the Lambertson magnets and the other lattice components in the area. The beam element alignment and the source term have been simulated using the code STRUCT. Results on beam losses in the system, energy deposition in the core elements and residual dose rates on the components are presented.

1 INTRODUCTION

The projected intensity for the NuMI project of $4 \times 10^{13}$ protons extracted at 120 GeV from the Main Injector every 1.867 s [1] can result in a severe radiation environment [2]. To explore this, full-scale Monte Carlo simulations with the STRUCT [3] and MARS [4] codes are performed for the beam loss and showers induced in the Main Injector and NuMI beamline elements.

2 SOURCE TERM AND BEAM LOSS

The Main Injector lattice with all the optics elements in the extraction system region, electrostatic deflector, three modules of the Lambertson magnet, and the NuMI beamline components have been implemented into the simulation codes. The Lambertson magnet modules are rotated with respect to the longitudinal axis by 0.22 rad, 0.098 rad and 0.037 rad, correspondingly, to bend the extracted beam out of the accelerator in both vertical and horizontal planes. All essential details of the accelerator and NuMI beamline elements are taken into account in the simulations. The beamline is aligned with respect to the extracted beam axis to prevent primary proton loss anywhere but at the electrostatic deflector wires. Extracted and circulating beam densities at the entrance to the electrostatic deflector ES are calculated as in [5] for the Main Injector circulating beam emittance of 30° mm-mrad and shown in Fig. 1.

The ES wire distribution and other septum details are assumed as in [6]. Two cases of septum wires are studied, 2 and 4 mil, or 0.0508 and 0.1016 mm, correspondingly. A $10^5$ proton sample in the extracted beam is taken in the calculations. About 2.5% of those hit the 2-mil electrostatic deflector wires, and twice that fraction the 4-mil wires. Some of these protons interact inelastically with the tungsten nuclei generating secondary particles responsible for radiation fields in the immediate vicinity of the ES. The others lose a small fraction of their energy, getting an angular kick due to multiple Coulomb and elastic scattering and electric field, resulting in long-range beam losses both in the machine and the NuMI beamline. Fig. 2 shows the calculated proton flux at the downstream end of the 2-mil...
wire septum. The \( \beta \)-function in the beamline after the ES and calculated heat load to the beam pipe due to high energy protons lost in the studied sections are shown in Fig. 3.

Figure 3: NuMI beamline \( \beta \)-function (top) and beam loss distribution in the accelerator and in the beamline (bottom).

A fine structure of the lost proton distribution along the first 160 m of the beam pipe is given in Fig. 4 for 4-mil wires. One sees that most protons are lost on the septum and immediately downstream resulting in high radiation levels in the first 50 meter region. The second peak is at the Lambertson magnet as expected. In the 2-mil wire case, the particle loss on the pipe in the first 50 meter region is about three times lower, resulting in a more favorable radiation environment. The peak at the Lambertson is about the same. Fig. 5 shows calculated proton beam densities at the Lambertson magnets. The aperture of the quadrupole between the first and second Lambertson magnets is an ellipse of \( R_x \times R_y = 61 \times 27 \) mm\(^2\). To eliminate the extracted proton loss in the quadrupole, the beam orbit needs to be moved at extraction by \( \delta x = 4.5 \) mm and \( \delta y = 11.5 \) mm, using for example the Main Injector beam orbit correctors.

3 PROMPT AND RESIDUAL RADIATION

3.1 Septum Heating

Although a fraction of the beam hitting the 4-mil wires is twice that of the thinner wire case, the peak energy deposition density is about the same in both cases. It peaks at the beam center at about 10 cm from the upstream end and decays exponentially along the septum to negligible values at about 200 cm. Thermal analyses have been performed.
3.2 Equipment Activation

Equipment activation is rather high in the vicinity of the ES and in the Lambertson magnet region. The calculated residual dose rate on the outer surface of the components is presented in Fig. 7 for $t_e=30$ day irradiation and $t_c=1$ day cooling. The rates at the two hot locations are rather high. They go down approximately as $1/r$ with distance from the beamline, and can be re-scaled to other irradiation/cooling conditions via $\log(t_i/t_c)$.

4 CONCLUSION

The results of this study indicate that there will be manageable thermal effects from the desired intensity but the residual radiation levels in the extraction area will be very high. For the case given in Fig. 7 one observes that maintenance issues must be addressed for both the extracted beam line components and the near by components of the Main Injector itself. Longer irradiation times and a desire for access after shorter cooldown periods could lead to a several-fold increase in the dose rates shown in Fig. 7.

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6 REFERENCES


