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NuMI primary beam monitoring

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Abstract

The position and intensity of the Fermilab Main Injector 128 GeV proton beam being delivered to NuMI have been monitored since the start of beam delivery in 2005. The results of this monitoring, and the monitoring of the performance of the instrumentation are discussed. Upgrades to and tests of improved SEM (multiwire Secondary Emission Monitors) are also discussed.

Keywords; NuMI; Beam; BPM; SEM; Toroid:

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1. Introduction

The NuMI (Neutrinos at the Main Injector) beam line was developed to deliver 120 GeV protons from the Fermilab Main Injector to an underground neutrino target system. The beam line is shown in figure 1. This beam line, originally developed to deliver beam to the Minos experiment, is currently delivering beam to Minos and Minerva, and will be used to transport beam to the NoVA experiment. As can be seen in figure 1, the beam line is about 370 m long, including 20 bending magnets, 21 quadrupole magnets and a number of trim magnets, ultimately impinging on the target 30 m below the surface. The beam line is well instrumented with loss monitors, BPMs (beam position monitors) and SEMs (Secondary Emission Monitors). Up to 4×10^{13} protons per 2 microsecond spill is extracted every 2.2 sec. Beam losses are required to be very small to minimize activation in beam-line components and to prevent losses in or near the aquifer. The extensive monitoring of the beam losses shows that the losses are typically less than a few parts per million.

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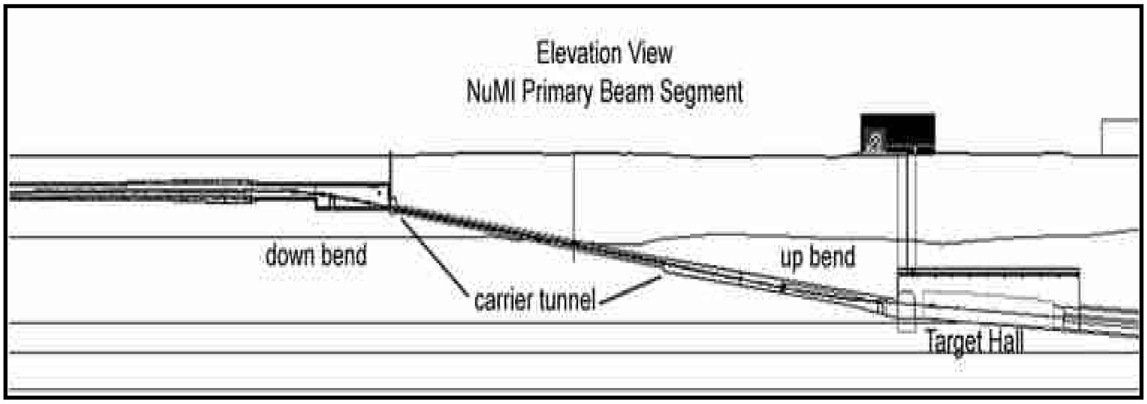

Figure 1 Elevation view of the NuMI beam line

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The Minos experiment has been running since 2005. The history of beam operation is shown in figure 2. The intensity has improved over the duration of operation. Gaps in beam delivery are for scheduled shut-downs for maintenance and improvements, and for repairs to the NuMI target.

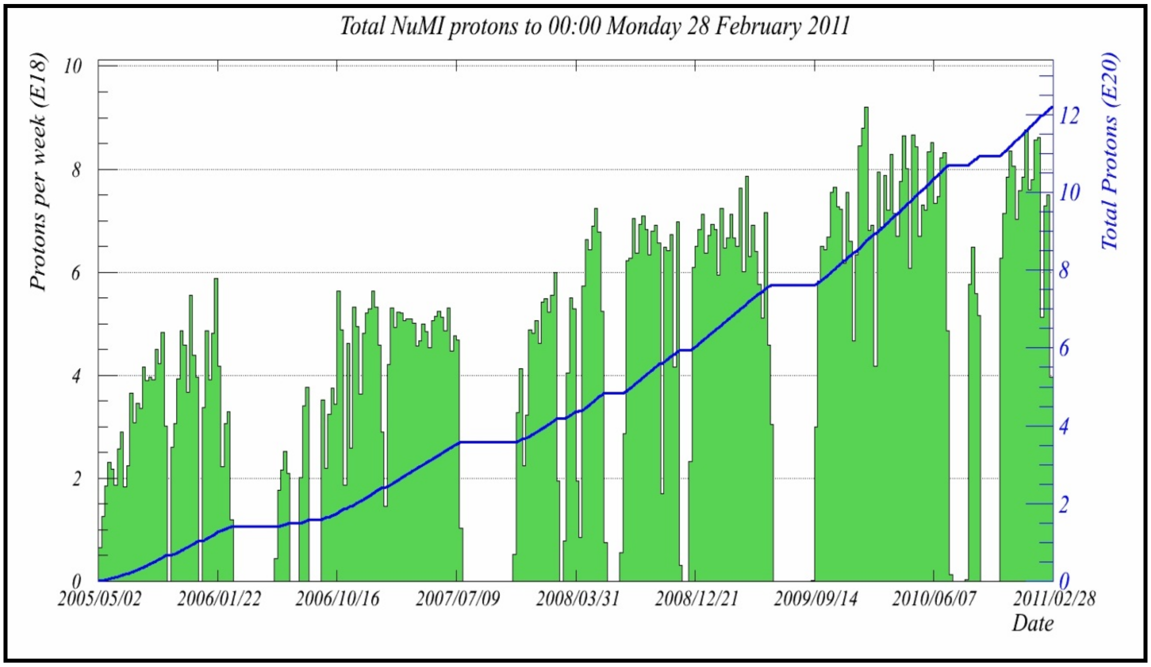

Figure 2 History of NuMI beam operation

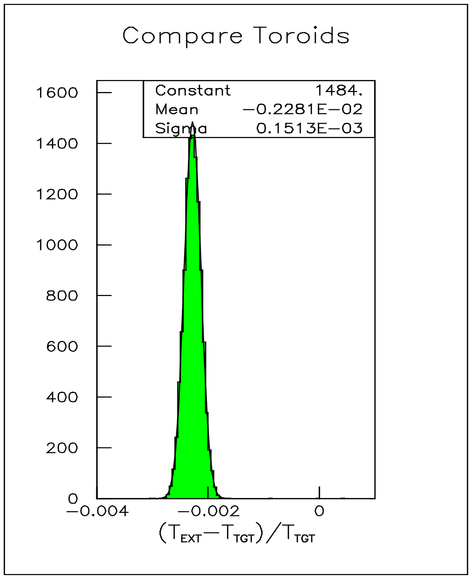

Figure 3 NuMI Toroid difference divided by TRGTTD –horiz. vs number of samples – vert.

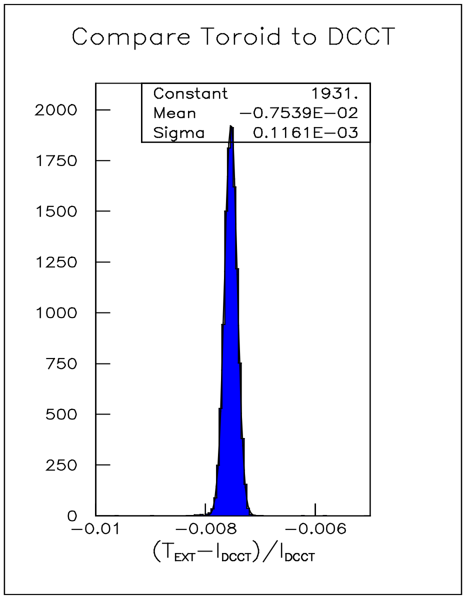

Figure 4 TRTGTD/DCCT – horiz. vs. number of samples – vert.

2. Intensity Monitoring

The intensity in the NuMI beam line is monitored using two toroids[1]: one (TR101D) located in the beam line immediatel y after the beam is extracted from the MI (Main Injector) and a second (TRTGTD) just upstream of the neutrino production target. The TRTGTD is used as the primary intensity monitor for the NuMI beam line. The difference between the two toroids divided by TRTGTD is monitored to assure the stability of the beam-line toroids. The amount of beam in the MI is monitored using a direct coupled transformer (DCCT)[2]. When only the NuMI beam-line is receiving beam, the ratio of the NuMI toroid to the DCCT provides a second independent monitor of the stability of the intensity monitoring. In each case, the ratios should be equal to 1 to high accuracy as the extraction efficiency and the transport efficiencies are very close to 1. Extensive monitoring of the losses from extraction to the end of the beam line confirms that the losses are indeed very small. Figure 3 shows the short term precision of the NuMI toroid ratios. The short term (~ 1 hour) resolution is $1.5x10^{-4}$, corresponding to a noise level of 0.66 milivolts. The resolution is 0.0033/I, where I is the beam intensity in units of 10^{12}. Over a full day, this broadens by about 2×10^{-4}. Figure 4 shows a similar comparison for TR101D/DCCT. Table 1 below shows a small sampling of calibrations over the years of running. The systematic errors (instrument calibrations, component precision) are less than 1% and the measurements are clearly stable to about 0.5%

Table 1 Beam intensity monitoring stability

Date	TR101/ DCCT	TRTGTD/ TR101D
Feb 12, 2008	.996	.998
Dec 5, 2009	.997	.995
Sept 20, 2009	.993	.997
Nov 9, 2009	.992	.998
Apr 11, 2011	.992	.999

3. Multiwire SEMs

Secondary Emission Monitor wire chambers (SEMs)[3] are located at several stations along the NuMI beam line. The SEMs are particularly useful as they can be used to monitor both the position and size of the beam. Most of the SEMs are out of the beam (to minimize beam loss) during normal operation. Three of the SEMs are in the beam all of the time. In figure 5, each bin corresponds to one wire. The wire spacing is 0.5 mm in the Target SEM

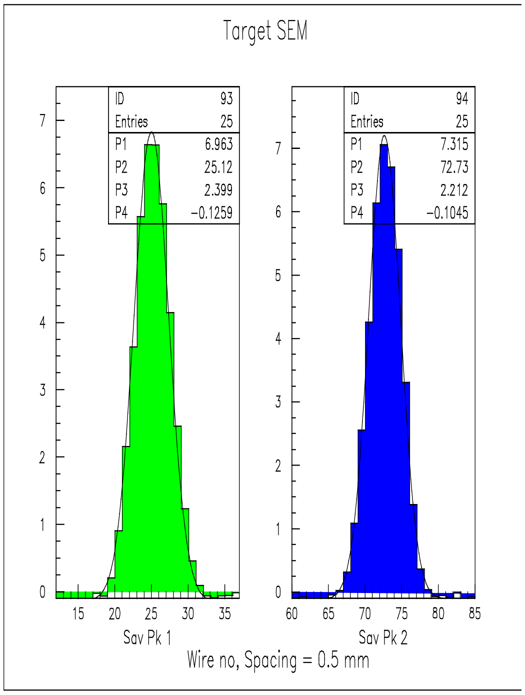

Figure 5 Target SEM signal fit to Gaussian plus a constant background – 1 Vertical, 2 - Horizontal

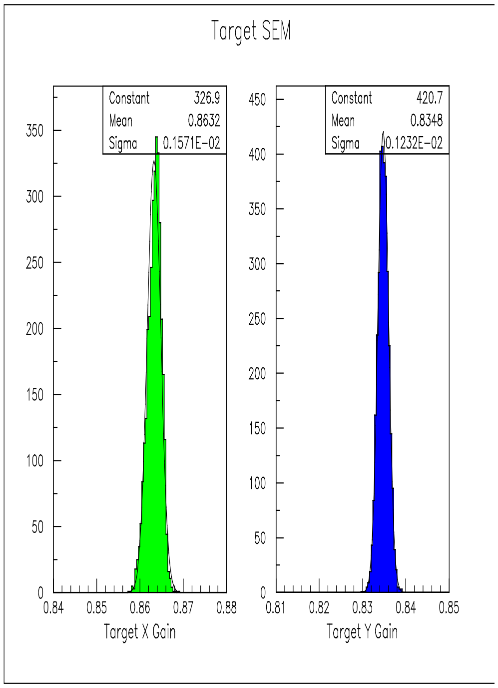

Figure 6 Gain of the target SEM for horizontal and vertical planes – horiz. vs number of samples - vert

- The target SEM: used to monitor the beam position and size at the target. It is monitored during running and is required in the off-line data analysis in the experiment. This chamber is constructed using 2 micron thick bu 25 micron wide Ti foils as electrodes

- MW101 SEM: This SEM was constructed using 40 micron Ti wires. It is monitored to compare the aging (gain as a function of integrated beam exposure) of wire electrodes versus the foil electrodes of the target SEM.

- MW118C SEM: The electrodes in this SEM are 33 micron carbon filaments [4]. It was placed in the beam to evaluate the gain and stability of a carbon filament chamber. In addition to being in the beam constantly, this chamber was cycled in and out of the beam 125,000 cycles to demonstrate the mechanical stability of the carbon filaments.

Data is collected spill by spill, placed in a histogram and fit to a Gaussian plus a flat background – the results of the fits are shown on figure 5. Figure 5 shows the data from one spill from the target SEM. The gain is defined as the area of the Gaussian divided by the intensity (in units of 10^{12} protons). The gain is then monitored over time as a monitor of the stability of the device. Histograms of the gain of the target SEM as measured over a two hour period are shown in figure 6.

The target SEM has a larger gain than the 118C and 101 SEMs – a typical gain in horizontal and vertical for these SEMs is about 0.1. It is the stability of the gain as a function of beam exposure that is of interest. The gains for the Target and 118C are shown in figures 7 and 8. For the target SEM there is an initial rapid decrease in gain, followed by a slow decrease in the gain. This target SEM was in the beam from June 6, 2006 until the date of the last data shown May 15, 2011. The total beam exposure is 12 x 10^{20} protons. The fits shown are linear fits over the region represented by the lines. There is no fundamental reason the gain should decrease linearly. The apparent noise in the gain is due to small movements of the beam – if, for example, the beam moves to an area that has not been exposed to as much beam, the gain is higher.

The 118C SEM (using carbon filaments) gain shown in figure 8 shows a much less dramatic initial gain decrease. The fit to the data in this case is taken as a quadratic – again there is no fundamental reason to assume a quadratic dependence – it is simply a heuristic observation. Note also that the decrease in gain is much more rapid. We note that the carbon filament chamber has been exposed to very high beam intensities – to 40 x 10^{12} protons per pulse! SEM 118C was in the beam from Nov 1, 2010 to May 16, 2011 for a total exposure of 1.4x10^{20} protons.

One of the reasons for using C as opposed to Ti signal wires in the SEM is to reduce beam losses and reduce residual radiation from beam devices. A simulation of the two materials using G4beamline [5] was carried out to study losses. The simulation did not show a large difference in the expected beam losses for the two devices.

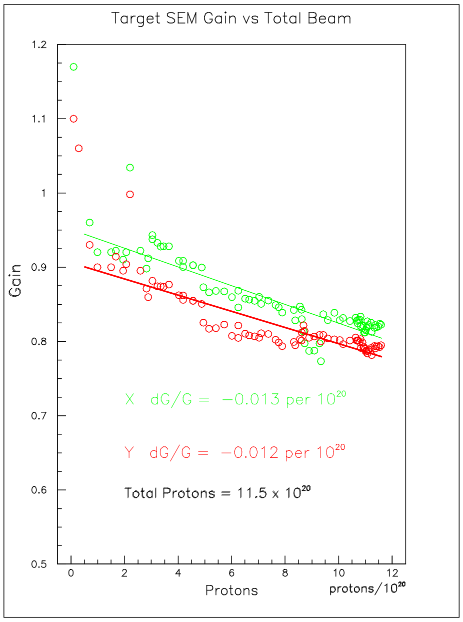

Figure 7 Target SEM gain vs. beam exposure

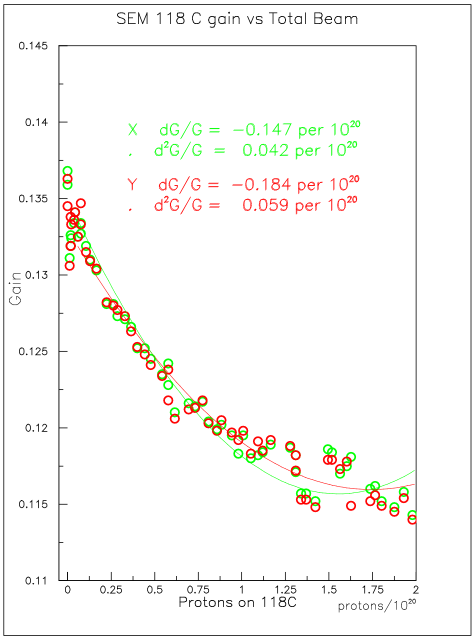

Figure 8 MW118C gain vs. beam exposure

Because the beam sizes are different at different SEMs, it is necessary to correct for beam size to determine the relative number of protons on a wire in each device. If the beam is smaller, the local intensity is higher. Table 2 shows these corrections. dG/G for the 118C SEM shown in table 2 is for a linear fit to a shorter beam exposure. The gain vs. beam exposure for 101 SEM is not shown. After corrections, the aging of the two Ti devices are quite comparable, where the C device ages much faster.

Table 2 SEM gain corrections to compensate for beam size at the detector

Device	Wire Dia	Beam Size σ_x x σ_y	Obs dG/G	Normalized dG/G

Target SEM	25 x 5 μ	1.8 x 1.1	1.8	3.6
101 SEM	.40 μ	0.68 x 0.86	5	2.9
118C SEM	33 μ	1.08 x 1.18	11	14

4. BPMs and BPM – SEM comparison

BPMs (Beam Position Monitors) – cylindrical electrodes around the beam sensitive to the beam position – are located at 26 places along the beam line. The BPMs are very rapid response devices, so that each beam batch can be monitored individually. The BPMs are the sensors in a closed loop system along with trim magnets to control the beam position through the full length of the proton beam onto the target. They therefore play a critical role in the operation of the NuMI beam line. The signals from the two electrodes in the BPM may be summed to measure the beam intensity. The resolution of the BPMs being used as an intensity monitor is about 3×10^{-3} compared to the toroids. Intensity monitoring using the BPMs does not play a role in the NuMI beam line operation.

At a number of locations, there are SEMs located adjacent to the BPMs. At these locations, it is possible to compare the positions as measured using the two devices. This comparison makes it possible to check the relative position calibrations and resolutions. It was observed that the positions as measured using the BPMs and SEMs did not always agree. In this discussion, it is assumed that it is the BPM position that is in error, and a correction is applied as needed. The position calibrations are carried out using data where there is a change in beam position. Corrections are applied to the BPM position scaling to force the change in positions as observed using the BPMs and SEMs agree. The factors needed are noted on figures 9 and 10. The units on the plots are mm, so the position resolution when comparing the BPM and SEM is of order 5 microns.

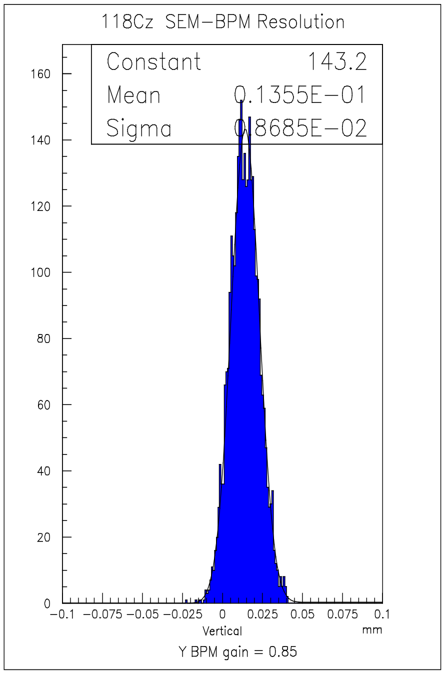

Figure 9 118C – BPM resolution

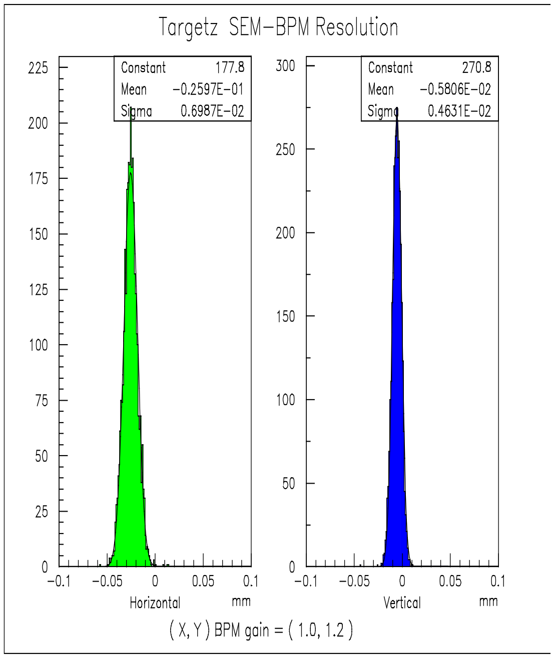

Figure 10 Target SEM – BPM resolution, horizontal (green) and vertical (blue)

6. Conclusions

We have shown that the NuMI beam position has been monitored and controlled with high accuracy. The intensity has been monitored using redundant instrumentation to of order 1%. The monitoring of the NuMI beam continues.

Acknowledgements

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