NUMI PROTON BEAM DIAGNOSTICS AND CONTROL: ACHIEVING 2 MEGAWATT CAPABILITY

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Abstract

The NuMI proton beam at Fermilab currently delivers 120 GeV protons to the neutrino production target with design beam power capability to 400 kW. Upgrade capability to 700 kW is being prepared, with planning toward delivering 2.3 MW beam provided by the Project X accelerator upgrade plan. We report on the system of beam diagnostics and control used in operation of the NuMI beam. Also considered are the steps to provide a robust system for transport and targeting beam of 2 MW and beyond.

NUMI DIAGNOSTICS AND CONTROL

More detailed description of the NuMI 120 GeV proton beam, operations constraints and operating experience to date are given in references [1] and [2]. Here we provide specifics of the beam diagnostics and control utilized for this intense beam. Current NuMI beam intensity is from 3.0 to 3.7 $x10^{13}$ protons per pulse dependent on cycle sharing with other uses, and a cycle repetition time of 2.2 seconds. The kicker extracted beam pulse is of 9.6 µsec duration.

Beam Diagnostics and Control Requirements

Some significant requirements for NuMI proton beam operation include:

- Targeting precision < 0.25mm to minimize physics backgrounds
- Maintaining fractional beam loss to less than ~ 10^{-5} of the operational intensity beam, to maintain environmental ground water protection. This is required on a pulse by pulse basis.
- Rigorous control of off normal beam trajectories, which could very quickly produce component damage. A single bad spill could lead to extended down time; we need many millions of beam spills.
- Seamless beam control to enable maximizing NuMI pulses during shared operation with the Tevatron Collider physics program. Typically, NuMI receives 75 to 80% of the 120 GeV Main Injector (MI) accelerator output.

Beam Instrumentation Hardware

Beam instrumentation for the NuMI proton beam-line was selected to provide the precision monitoring needed on a continuous basis, robustness for use with automated beam control, compatibility with the intense beam, and large dynamic range beam loss sensitivity.. Shown in Figure 1 is the most downstream beam position instrumentation. station.

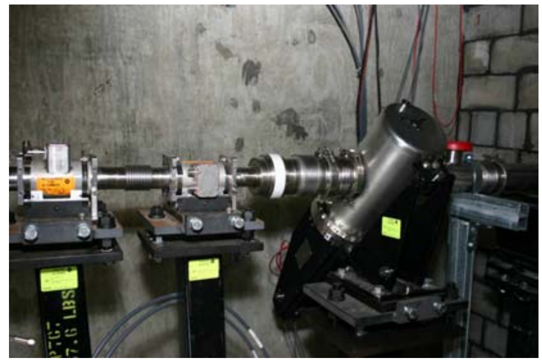

Figure 1: Pre-target beam instrumentation station, showing horizontal and vertical BPM's and SEM profile monitor.

Along the 350 meter length NuMI proton beam transport line we have:

- 2 beam toroids
- 24 split plane beam position monitors (BPM's)
- 10 thin-foil SEM profile monitors (5 µm Ti foils)
- 54 beam loss monitors., including sealed units on each magnet (BLM's) plus four extended length "total" loss monitors (TLM's).

The toroid intensity monitors, one each at the upstream and downstream end of the beam transport, are regularly calibrated and monitored on a pulse by pulse basis with a reproducible measurement accuracy of within 1%. For large beam loss situations, they also can provide some measurement of the amount of beam lost. During NuMI operation, 5 pulses of 24 million total have had beam loss at a level large enough to see toroid differences.

BPM's are the monitors used for measuring targeting precision and as inputs for beam position control. Electronics utilizes digital receiver technology, designed for the Recycler Pbar storage ring in the Main Injector tunnel. For each beam pulse we obtain an individual position (and intensity) measurement for each 1.6 µsec beam batch, with a train of 6 batches in the NuMI beam spill. The beam is bunched with 53 MHz RF structure. Tests of BPM vs. profile monitor position reproducibility give measurement accuracy of order 20 µm.

Of the 10 thin-foil SEM profile monitors, only the monitor immediately before the target station shield wall can be left in the beam, due to the beam loss generated. The monitors are designed for minimal foil material thickness, with foil strip material of $5x10^{-6}$ to 1 $x10^{-5}$ interaction lengths, dependent on the foil strip spacing. This monitor has had good longevity in the beam of size 1.1 mm rms, with sensitivity degradation of about 25%

for exposure to $3x10^{20}$ protons on target. This degradation occurred relatively quickly, with stable sensitivity after the first $5x10^{19}$ protons.

The sealed Ar gas unit BLM's have displayed good response linearity in bench tests over a dynamic range of almost 6 decades, from a few $x10^{-3}$ to 10^3 Rads/sec. A log amp readout is used to provide this dynamic range.

For NuMI, we look toward maintaining the best low end beam loss sensitivity. even with the very intense beam. This is due to the requirement for maintaining less than 10^{-5} fractional beam loss for the NuMI proton line transport. Loss monitor calibrations using the thin foil profile monitor SEM grids as calibration targets have demonstrated that peak BLM readings of 0.5 Rads/sec are obtained for fractional beam loss of $1.0x10^{-5}$ with $3x10^{13}$ protons. As example, see the most downstream BLM readings in Figure 3. These beam loss readings are also consistent with detailed calculation using the MARS program. BLM readout saturation at 1000 Rads/sec occurs for beam loss of ~ 2% at nominal intensity. But we then have sensitivity to fractional loss values of 10^{-7}.

Beam Permit System

For NuMI we have built a comprehensive beam permit system (BPS) which is required to give a permit to enable the extraction kicker prior to each NuMI beam pulse. This system uses dedicated hardware, based on that designed for the Tevatron superconducting accelerator fast abort system.

A total of more than 250 inputs are provided to the NuMI BPS. A final status check is made in the millisecond prior to NuMI extraction for:

- Beam position and angle in extraction channel
- Excessive residual MI beam in NuMI kicker gap after earlier extraction for Pbar targeting
- Extraction kicker status
- NuMI power supplies ramped to proper flattop values
- Target station and absorber beam readiness

Also verified to be within limits are:

- All beam loss monitors readings from the previous extraction
- Previous pulse position and trajectory at targeting

With the very high power NuMI beam, the beam permit system is our most important operational tool. The BPS has been used for all NuMI beam operation, including for initial beam commissioning..

Extracted beam lost due to permit system trips has consistently been considerably less than 1%. A summary of this data is provided in [2], with an average of 10 BPS trips per day resulting in a few minutes total of downtime. The average number of beam pulses per day is ~ 35 thousand.

Autotune Beam Position Control

A fully automated beam position control (Autotune) is used to maintain beam positions along the NuMI proton beam transport and for targeting. This type of control [3] has been used in Fermilab external beams over a 20 year period, has been very robust, and is most useful for intense beams where precise beam loss or position control is needed for each beam pulse. With Autotune, large dipole strings are maintained at fixed currents, which are verified for each beam pulse. BPM's then provide beam positions, which are kept within tolerance using corrector dipole adjustments . Typically, an assignment is made of one BPM to each corrector, the response of the beam for each corrector change is well determined, and the tuning algorithm is the inversion of a set of linear equations for responses of each pair of devices. "Sanity check" safeguards are utilized to insure that proper data is used for each position correction, and that corrector currents remain within allowed limits. Current versions of this application are written in Java using a client-server [4].

OPERATIONS EXPERIENCE

The NuMI 120 GeV extraction and proton transport has functioned extremely well since initial beam commissioning and for the first three years of operation[2]. System uptime availability has been 98-99%.. Beam targeting precision within 100µm rms is consistently maintained, as shown in Figure 2 for a sample of 1.3 million consecutive beam pulses. In each plane the beam position rms variation is ~ 90 µm. For targeting BPM's, Autotune is activated for beam position offset of 125µm.

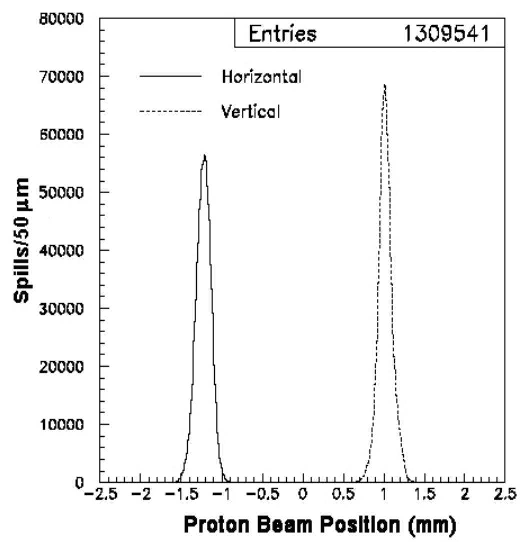

Figure 2: Histogram of proton beam position as seen by target BPM's for both horizontal and vertical planes. Beam is centered on the target, which is located at (x,y)=(-1.2,+1.0mm).

The targeted beam aim point of (-1.2,+1.0mm) was determined by a series of beam based alignment measurements [5], and includes both installation errors and some deformation of the target hall cavern, after shielding was loaded.

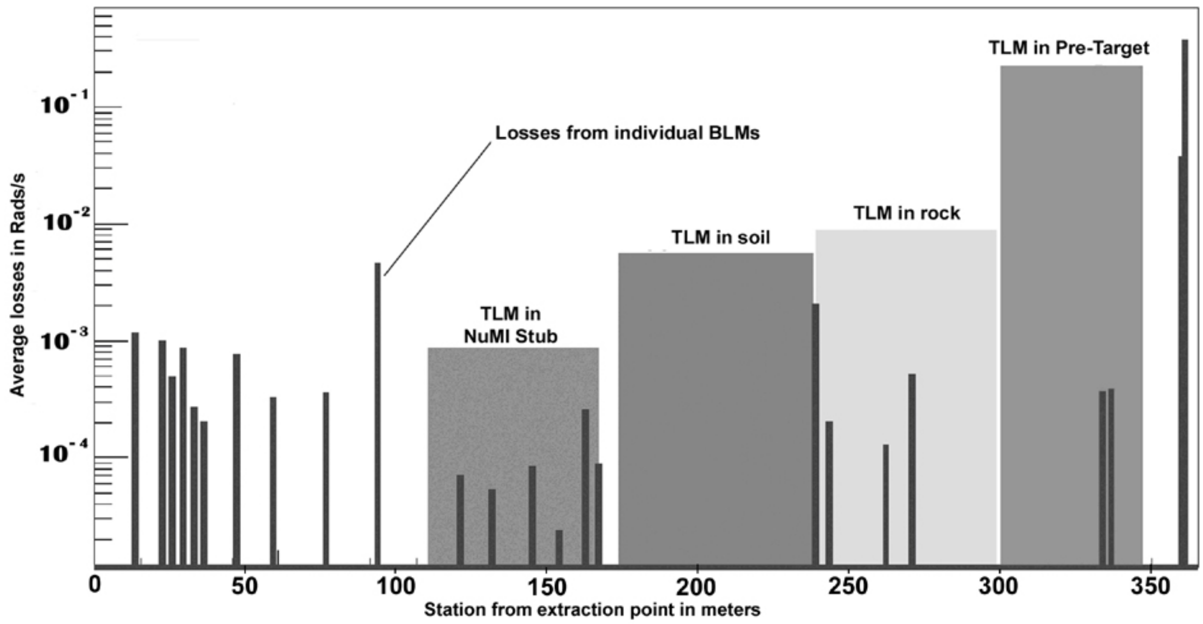

Figure 3. Beam loss along the NuMI proton line averaging for all beam extractions over a one month period. The beam loss scale can be obtained by the reading of the most downstream BLM which sees beam loss from the target profile monitor. This monitor scatters 10^{-5} of the beam passing through it.

NuMI extraction channel and primary transport average per pulse beam loss is shown in Figure 3 for all beam extractions over a one month period (January 2006). The relatively very large loss seen at the downstream end is due to the effect of a profile monitor scattering 10^{-5} of the incident beam. As can be seen other individual BLM's see beam loss at a maximum level ~ 10^{-7} of the beam. This provides a good safety margin below the maximum 10^{-5} fractional beam loss permitted for critical regions of the proton transport line.

UPGRADES FOR 2 MEGAWATT BEAMS

As we look toward significant increases in proton beam power, an assessment is made of how the current NuMI beam diagnostics and control would be applicable at much higher beam power. Additionally, we evaluate upgrades which would be needed for these beams.

The fundamental approach currently used for NuMI should be readily appropriate for higher power beams. Key is to do the same types of beam control as presently done, but ever more carefully as beam power increases:

- The most important protection remains with a comprehensive and well tested beam interlock or permit system. No beam should be extracted until all parameters are at specifications within tight tolerances.
- Robust design for beam optics and aperture clearance. Beam loss should be very low in normal conditions. For abnormal conditions extraction should be inhibited.
- A robust automated beam position control system can reliably maintain beam targeting to high precision. As currently for the NuMI Autotune application, its first mission should be to "do no harm".
- Precision monitoring of instrumentation stability during high intensity operation. Inaccurate BPM readings can occur from many possible problems, and are potentially dangerous. But BPM's are our mainstay continuously active beam position monitors.

NuMI Specific Upgrades

Within this scope several specific improvements are being planned beyond present NuMI capabilities. An example of needed improvement for higher beam powers is to rigorously preclude beam pulses off center at the target by < 0.5 mm, as (solid material) target stresses are significantly increased by such beam. For NuMI, we protect against 2nd beam pulses hitting 1.5 mm off center, but do not yet have rigorous monitoring of BPM stability.

Improvements we are working toward:

- The precision monitoring of power supply ramp levels prior to beam extraction. While current power supply regulation control is ~ 50 ppm, analog signals to the BPS are limited by noise levels to be accurate only to 0.5%. Design has been accomplished to improve power supply monitoring with the permit system to 100 ppm.

- Improved monitoring of corrector current limits, for added robustness with the Autotune beam position control.
- Lower mass profile monitor SEM grids which give fractional beam loss of ~ $2x10^{-6}$ when inserted into the beam path, and rapid drive systems to position the monitors without additional beam loss.
- Comprehensive and regular monitoring of BPM and BLM function, using profile monitors as targets.
- Updating precision calibration of the BPM's to be done during beam operation.
- Evaluation of alternative design "no mass" beam profile monitors such as ion profile monitors (IPM), which could give precision measurements for very high intensity single pass beams.
- An intensity control sequencer to step up to high intensity operation after downtimes. This could mitigate high intensity drift effects as systems return to operating temperatures.

The current usage of diagnostics and beam control as done for NuMI is readily adaptable to much higher beam powers. But we need to be continuously careful as this is done.

ACKNOWLEDGMENTS

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