NuMI Beam Control Protection Systems

& Experience on Rogue Pulses

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Key NuMI Beam Control Protection Systems

- Accelerator Complex Global Clock System
- Time Line Generator Defining Beam Scenario for Each Cycle
- Comprehensive Beam Permit & Interlock System **
- Failsafe Repeat Beam Loss Protection **
- Extensive Beam Instrumentation & Continuous Monitoring *
- Fully Automated Autotune Precision Beam Position Control *
- Multiple Ongoing Status Checks *

** Developed for NuMI

* Significant Upgrade for NuMI

Controlling Where the Beam Goes

- Global Clock System & Time Line Generator
- Generated clock events define destination for each beam pulse
- Each system beam permits continuously monitored
- On a NuMI cycle, systems not involved stay at rest state (These cannot transmit beam if for example a kicker pre-fires)

Fermilab Main Control Room

Comprehensive Beam Permit & Interlock System

- Developed specifically for NuMI
  - ➢ Quickly became standard for all our intense beams & adopted internationally
- Uses dedicated hardware, based on that originally developed for TeVatron fast abort system
- Permit decision prior to each beam pulse required to enable extraction kicker
- More than 250 inputs for NuMI system
- Final permit decision in last msec before extraction
  - ➢ Checks for kicker status, accelerator beam position & angle, power supplies at proper values, good previous pulse

Our most important hardware NuMI protection system

Failsafe Repeat Beam Loss Protection

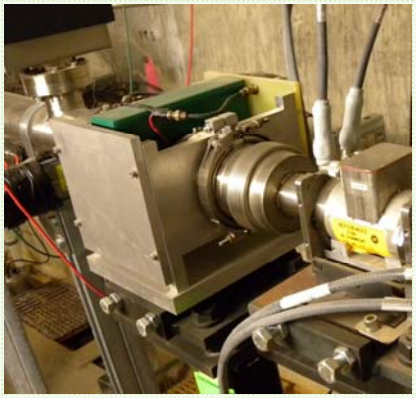
- For all NuMI beam operation we have required a failsafe safety system ion chamber in the tunnel which trips for a fractional beam loss of ~ 10-5 (normal intensity)

A key requirement to NOT radiate the protected groundwater resource transported by the unshielded deep NuMI proton beam tunnel

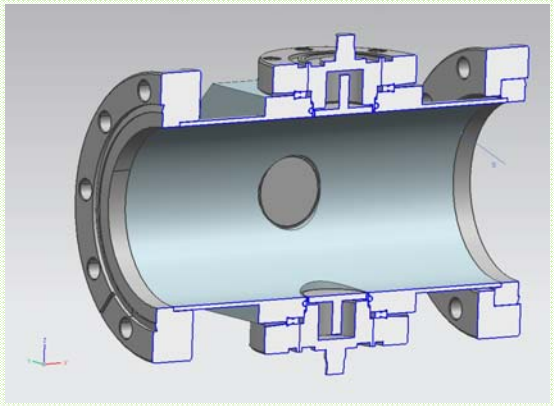
We had to develop a design which works well with this constraint ➔ a strong side benefit is no proton beam residual activation

Extensive Beam Instrumentation

2 Pearson Toroids



24 Beam Position Monitors



52 Beam Loss Monitors &
4 Extended Length TLM's

11 New Design Profile Monitors
~ 3 parts per million beam loss & inserted seamlessly into the most intense beams

Used to calibrate BLM's and regular checks on BPM stability

Autotune Beam Position Control

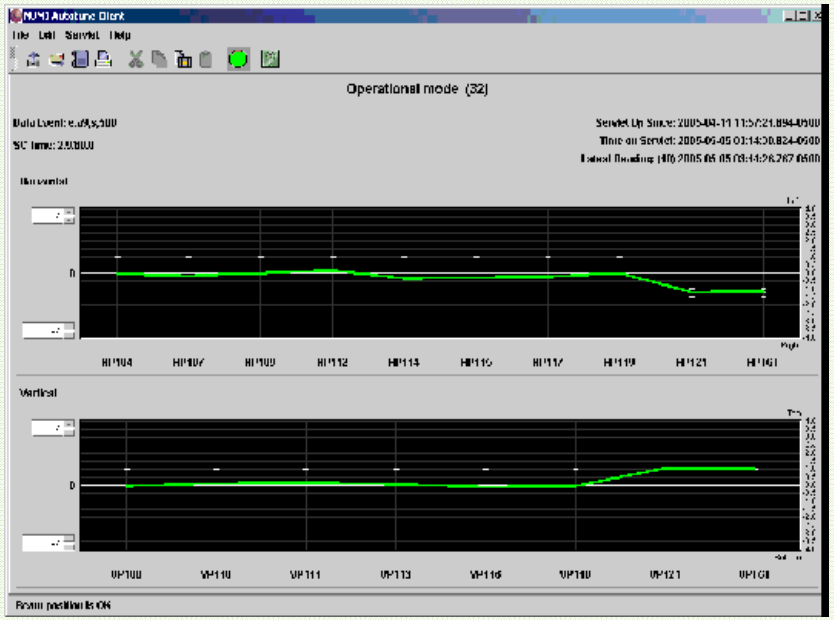
- ALWAYS active except at very low intensity

Automatic adjustment of correctors using BPM positions to maintain primary transport & targeting positions

Commissioned at initial turn on for correctors

Vernier control for targeting. Initiate tuning with Automatic adjustment of correctors when positions > 0.125 mm from nominal at target

Very robust



The Process of NuMI Beam Turn-on

- NuMI initial 400 kW design beam power was a large factor above that for our previous beams. (NOvA era 700 kW and soon higher still)
- From initial commissioning we looked toward a very controlled approach for every step to ensure an efficient beam commissioning and robust operation to follow
- The large majority of these turn-on steps have been both very efficient and successful as have our sustained many years of operation.
  - ➢Will return later to the one preventable exception

Beam Commissioning & Operation

- Very efficient proton beam commissioning late 2004
  - ➢ 10 pulses to establish extraction and transport to beam dump 1 km away (target out)
- Neutrino beam commissioning & 1st high intensity each during one weekend in January & February 2005
  - All this while target hall cooling being completed
- Subsequent transition to 24 hour operation by Main Control Room Operators also very smooth
  - A consistent key has been that the system experts maintained hands on responsibility throughout

Experience with Rogue Pulses

- With NuMI operation to date we have transported and targeted 125 million beam pulses
- For the first 8 years of our intense beam operation we experienced NO large beam loss pulses. (above ~ 1 percent) with a focused beam
  - Some of the most significant challenges have been dealing with Main injector RF glitches very close to extraction and insuring power supply flattop stability .
  - Most MI RF problems are now safely aborted prior to extraction. Larger problems have led to loss of bunch capture with a very spread out beam spray
  - We have also developed high precision digital power supply control which has enabled tightening permit limits

More Recent Experience:
2 Damaging Rogue Pulses

- Feb. 2014 & June 2017
  - In each case focused beam hit and damaged a vacuum seal in NuMi high dispersion region. Each led to ~ 12 hours of beam downtime.
  - Each appeared to be extracted at the wrong momentum– lower by about 0.8%.
  - In later analysis several similar beam pulses were seen, but with only small beam loss.
  - Root cause is NOT understood (probably RF related), but we are implementing what should be a robust solution.
  - We have BPS inputs monitoring Main Injector position and angle at flattop. But this is a straight section with very low dispersion.
  - Solution is new BPS inputs in higher dispersion arc region, where beam position deviation is several mm (We will trip at 1.5 mm)
- With these 2 pulses we were fortunate to not damage a magnet!

By Far: Our Worst NuMI Beam Damage Problem

- The cause – very preventable human error

In early March 2005, final installation for the target chase cooling system was completed slightly ahead of a revised work schedule.

Key people who had led the very successful beam commissioning were not available, but a manager decision to proceed with other physicists was made.

A single bump beam excursion study was done without turning down an already intense beam.

Result – a damaged target water line. **We had no spare target.** A strong effort to use He back pressure to control the water leak limited down time to ~ 2 months.