NuMI Lessons to Learn

Systems Integration WBS 1.1.8
Extraction/Primary Beam WBS 1.1.1

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Systems Integration WBS 1.1.8

- As defined in NuMI Facility TDR (Document covered both civil construction and beam systems)

  Systems Integration: To provide technical and administrative oversight through the project so that performance goals will be met. Also includes beamline cables, beamline control systems and radiation safety system.

  - **Will not discuss cables, standard controls and safety systems here.**

    A lot of very good work was done by Bob Ducar, Peter Lucas and others – all of this worked very well, and as planned.
  - Will discuss some details from the process of understanding technical designs – Are they efficient? Do they work as needed? Do they function together between systems?
    - Here only some concerns are covered – not all the things working well
- It should be noted that Systems Integration was a rather late addition to the project structure.

Some Early Design Concerns
Not from reviews – just basic "sanity checks"

- NuMI facility design (June '97 CDR) – A comprehensive NuMI facility CDR was developed using expertise from both previous FNAL facility construction and TARP (Chicago area Tunnel and Reservoir Plan). Design chosen was a deep cut & fill target hall excavation into upper bedrock, then begin rock mining for decay tunnel.
  - **Concern was that:** Using unit cost estimates from the CDR – this design approach appeared significantly more expensive than either raising the target hall elevation for more conventional construction, or lowering it further to allow mining techniques in the structural rock
  - As NuMI construction issues could be quite different from either previous FNAL beam facilities or TARP tunnels, posed a set of questions to an experienced geotechnical engineer chosen as a consultant – **WELCOME Chris Laughton!!**
  - Example of one question and answer is on the next slide.
  - **Follow-up:** Chris then guided us through a Director's Review re. facility construction and a subsequent NuMI Constructability Workshop getting design feedback from 3 experienced tunneling contractors.. Besides changing to a mined target hall and pretarget tunnel, a significant number of other improvements were made to the underground facility design. Along the way we were fortunate to have Chris join us at Fermilab and as a member of NuMI.

CONSTRUCTION OPTIONS QUESTION to Geotechnical Engineer Consultant (Chris Laughton) and response

Q) Target Hall depth was chosen to locate the enclosure in the bedrock, using a braced excavation construction, with rock mining beginning for the decay tunnel. Two other variations could be to:

a) locate the target hall at an elevation closer to grade and mine the decay tunnel through the till / dolomite interface

b) locate the target hall a few meters deeper, away from the till interface, and mine the construction for the pretarget and target halls. Access would be through the upstream access shaft.

Do either of these alternatives seem potentially a better choice considering both relative cost and construction efficiency?

A) Given the good condition of the rock/till contact in the area, as surmised from core, option b) appears to be both technically feasible and the most cost effective option. The less mining through the till the better - you can reduce water inflow potential, eliminate the requirement to excavate and temporarily support the soil and provide backfill.

A rule of thumb in vertical layout would be to establish a minimum of 0.5 span of "good rock" above the tunnel (Scott suggested 1 span - which would certainly be preferable) possibly supplemented by some cement grouting above the contact;

Before a tunnel option is adopted for the Target Hall it behooves the geotechnical engineers to characterize the quality and topography of the overlying rock surface in detail - this characterization will dictate the decision as to the viability of tunneling.

Note that the general commentary on regional conditions in the CDR does not appear to be applicable to the NuMI site.

Some Beam System Early Design Concerns from the NuMI Facility TDR (Oct. 1998)

This was the design for the project baseline review

- Decay pipe system
  - **Concern was that:** The question of need for active decay pipe cooling had not been seriously addressed. If needed this installation should be part of the civil construction package.
  - **Follow-up**: As discussed in earlier presentations, the need for this cooling was then established. Installation was added to the underground facility contract, but at a significant cost penalty, as this contract was already awarded.
- Target chase shielding thickness
  - **Concern was that**: The shield design (based on detailed calcs using the MARS program, now adopted as the Lab standard) projected shield thicknesses which matched those built for typical TeV FT experiments such as KTeV – but NuMI beam power would be ~ x100 higher.
  - **Follow-up:** Benchmark checks for the MARS program had not included thick steel shields, and a major flaw existing with calc of low energy neutrons thru steel. MARS was then updated [MARS14]. A much thicker - and more expensive - target chase shield built for NuMI, which works well.

Beam System early Design Concerns (cont)
Now focus on extraction/primary beam

- Beam extraction form Main Injector
  - **Concern was that:** The resonant fast extraction planned for NuMI had fundamental beam loss of 1-2 %. Simple scaling from TeV FT operation gave residual activation levels of many Rads/hr at septa and Lambertson magnets. Also very sensitive RF stations in between. Existing design did not address any of this.
- NuMI primary transport – it was known that besides being by far the highest beam power line at Fermilab, there would be serious beam loss constraints due to environmental ground water protection needs. Keep fractional beam loss at $< 10^{-5}$.
  - Existing beam optics had beta values to 750 meters, four times larger than good matches for planned magnet apertures.
  - No plan existed for controlling/preventing accidental beam loss
  - Extracted beam spray from septa losses not addressed
  - Plan for reuse of decommissioned FT beam-line instrumentation, which was poorly matched for NuMI beam power.
  - Beam vacuum system plan, based on existing FT, was not viable.

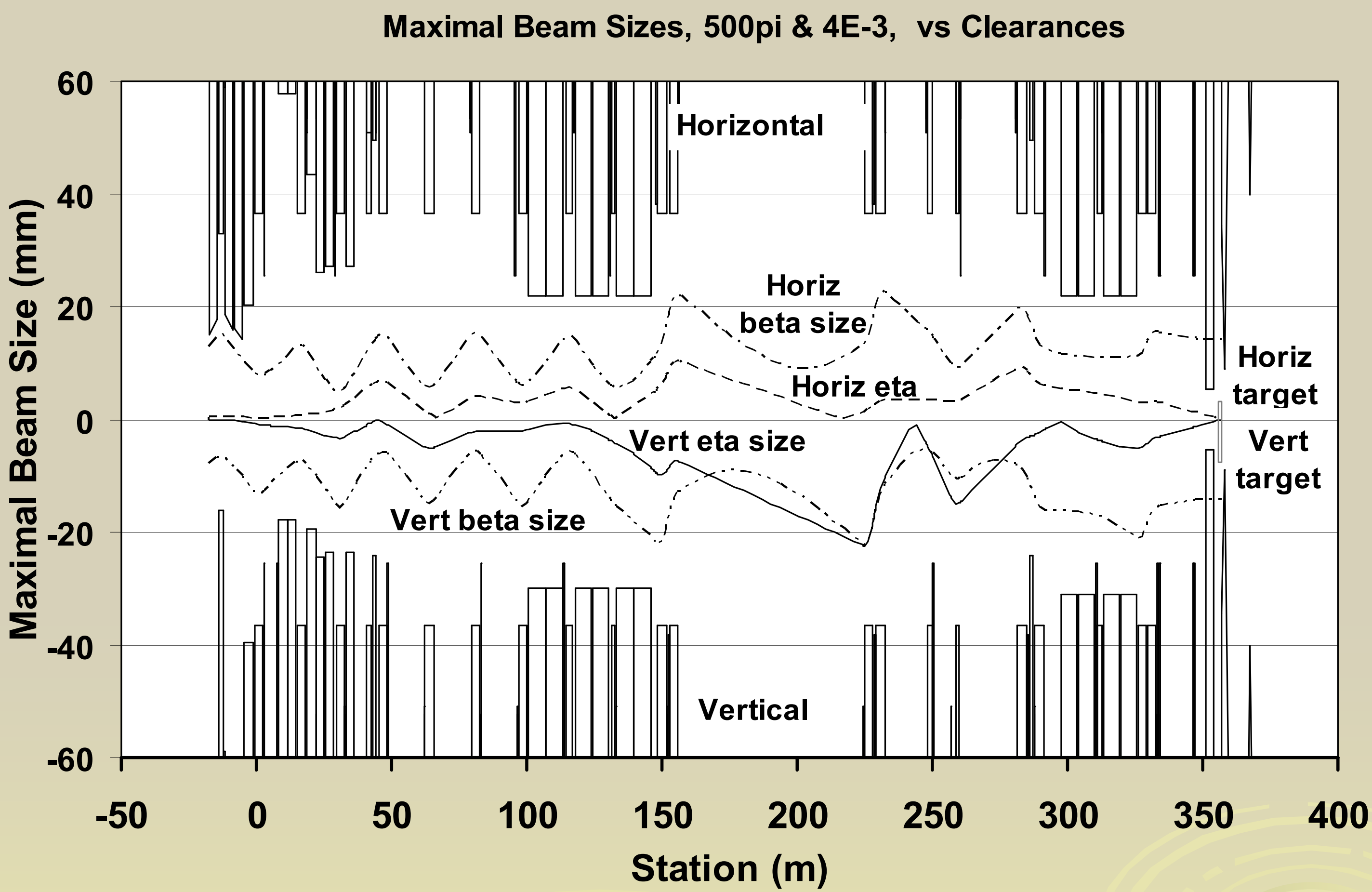
Steps Toward Current Extraction Design

- Quantitative calculations of resonant extraction beam loss. Provided confirmation of scaling projections for ~ 20R/hr residual activations
  - Work by Nikolai Mokhov, Craig Moore, Peter Lucas
- Presentations of resonant extraction design problems, and needed solution of kicker extraction
  - Strong support from Dixon B, NuMI project head
  - Request to MINOS colleagues for this change – produces x100 higher rates in Near Detector. Requires major change in near detector electronics (new electronics based on high rate Collider design)
- Kicker design for MI-60 established based on MI-52 extraction for Pbar. This still would have significant extraction beam loss ~ 10^{-4} although ~ 2 orders of magnitude improvement
- Iterate this design using extra kicker magnet and separate Lambertson power supplies to gain x10 in extraction aperture clearance.
- This is a "keeper", but all of this required from 1999 to early 2002 to accomplish

Primary Transport Beam Optics

- Original optics design was constrained by a plan to pass primary beam thru the glacial till region in an evacuated transport pipe, having a 400 ft. no optics drift region (carrier pipe)
  - Many of the MR and TeV fixed target beam lines used similar type optics, having long carrier pipes to 500 ft. between enclosures to save $$
  - The problem for NuMI – this drift region was too long for our low energy (120 GeV), standard magnet apertures, and very intense beam needing low loss transport.
  - NuMI facility construction provided the possibility for a solution, with 200 ft of this drift region being a relatively small cross-section mined tunnel (other 200 ft length, was a 6 ft. diameter concrete tube)
    - **But an early project decision that there would be no magnets in this narrow mined tunnel**.
- The process to establish that the design optics was not viable, and that fundamental optics redesign was needed – including quads in "rock portion of the carrier tunnel" –was long and challenging.
  - Extensive modeling, demonstrating that 'band-aid' solutions were not viable, reviews, reviews and reviews.
  - At the time in 2002 when consensus reached that major optics redesign was essential, several magnets for the old design were already installed.

Revised Beam Optics
Maximal Beam Envelope vs. Apertures



500 pi envelope shown – matching MI dynamic aperture

Other Primary Beam Systems

- **Added a comprehensive beam permit system:**
  - Uses hardware adapted from TeV fast abort system. More than 250 inputs
  - **Built by Bob Ducar. It works very well – from initial start-up!**
- 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
- **Then and only then, we enable extraction for each beam pulse**

Other Primary Systems (cont)

- **Magnets (dipoles and quads)**
  - Refurbished existing magnets (from fixed target lines and Main Ring). Work by TD
  - New correctors were built – MI design, with external cooling added
  - Almost all of this worked very well – saved many $$$
    - Some vacuum flanges had to be redone for better squareness.
- **Beam vacuum system**
  - Built a system using distributed ion pumps (~ maintenance free)
  - Can not accept the beam loss produced by an isolation window. Hence need "machine quality vacuum" ~ 10^{-8} to 10^{-9} torr. Have a Be exit window at the end inside target pile shield.
  - An improvement from frequent practice – we used only metal seals instead of O-rings. Better vacuum and far better long term robustness.

Other Primary Systems (cont)

- **Beam Instrumentation.** We built all new NuMI primary beam instrumentation, for better performance and added robustness. Some details:
  - Beam loss monitors (BLM's) – Most recent standard AD design units, very comprehensive geometric coverage, and standardized placement on magnets. Log amp electronics providing 6 decades of dynamic range
  - Toroids – For intensity measurement, standard AD design, consistent accuracy to < 1%.
  - Beam position monitors (BPM's) – THE monitors used for beam control. Digital receiver technology electronics designed for Recycler storage ring. Individual measurement for each 1.6 μ sec beam batch with measurement accuracy ~ 20 μm
  - Profile monitors – The one set of instrumentation where problems exist.. University built very thin 5 μm Ti foils. A pre-target monitor which can be left in the beam works very well. Mechanical drive systems to move In/Out of the beam generate x10 too much beam loss for the nine beam transport units. Colleagues worked very hard to build these, but a far better choice would have been using existing Fermilab design mechanical units

Other Primary Systems (cont)

- **Collimation system**
  - A primary transport beam tail collimation system was part of the original design plan, and also frequently recommended by reviewers. This was not at all a viable solution for the original optics design, where there would have been massive beam loss. Also, any functional 120 GeV collimation (and essential shield) system would be extremely difficult to build and use. By far a better choice is to clean up beam tails at 8 GeV, and take advantage of the clean nature of the machine accelerator process to higher energies.
  - Our solution here was to make all apertures for the NuMI primary transport, including extraction channel, larger than the 500 pi dynamic aperture of the MI. Then we have a very nice $150 million collimation system which already exists, otherwise known as the Main Injector

Primary Beam Control

- **The most compelling feature for high power proton beams such as NuMI is that they can damage most materials very quickly – a few seconds or even one cycle of mis-steered beam**
- **Adjacent photo shows the result of a single wayward 450 GeV SPS beam pulse of 3.4 e13 protons (CERN TT40 line Oct.'04) Magnet vacuum chamber destroyed. Views are from inside beam tube**
- Now we need millions of pulses!
- Our solution is the combination of the comprehensive beam permit system plus a fully automated beam position control – Autotune (first developed in 1987 for the TeV Switchyard)

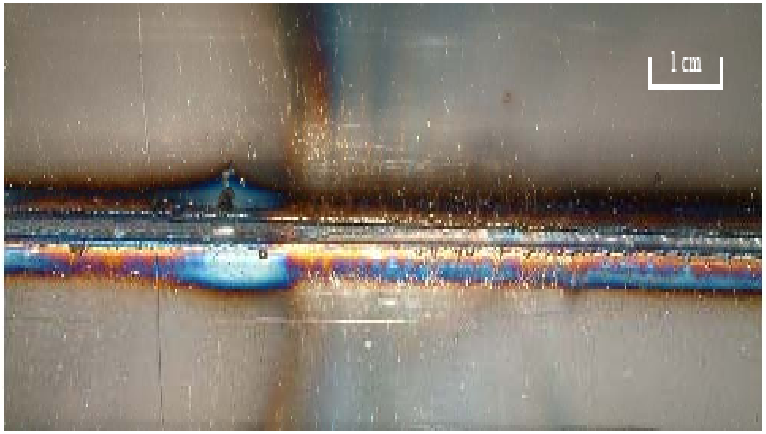


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

Figure 5. Damage observed on the inside of the vacuum chamber, on the side opposite to the beam impact. Molten material has been projected across the chamber and has condensed in droplets on the other wall.

How well does all of this work?

- **Beam Commissioning**:
  - We used a staged approach for beam commissioning of NuMI beam to be able to understand any beam problems as early as possible, while readiness work was still needed for some target hall systems.
  - December 3-4 2004.

Limited to 150 very low intensity pulses of <3 $x10^{11}$ ppp with target out.

Established extraction and beam centered on hadron absorber 1 km downstream in 10 pulses. Established low loss beam transport and instrumentation checkout. Used beam permit system for all extractions. Used Autotune for initial corrector turn-on. Total of 44 beam pulses.

  - January 21-23 2005.

Target in – first neutrino beam. Ran at 2.6 $x10^{12}$ ppp. First neutrino events seen in MINOS near detector. Official completion of NuMI project goals.

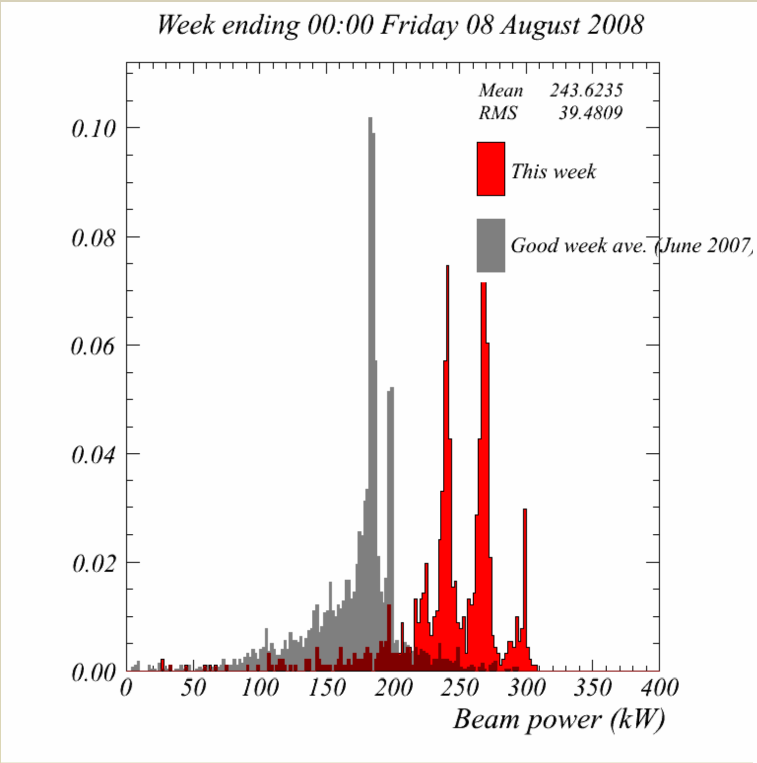
  - February 18-22 2005.

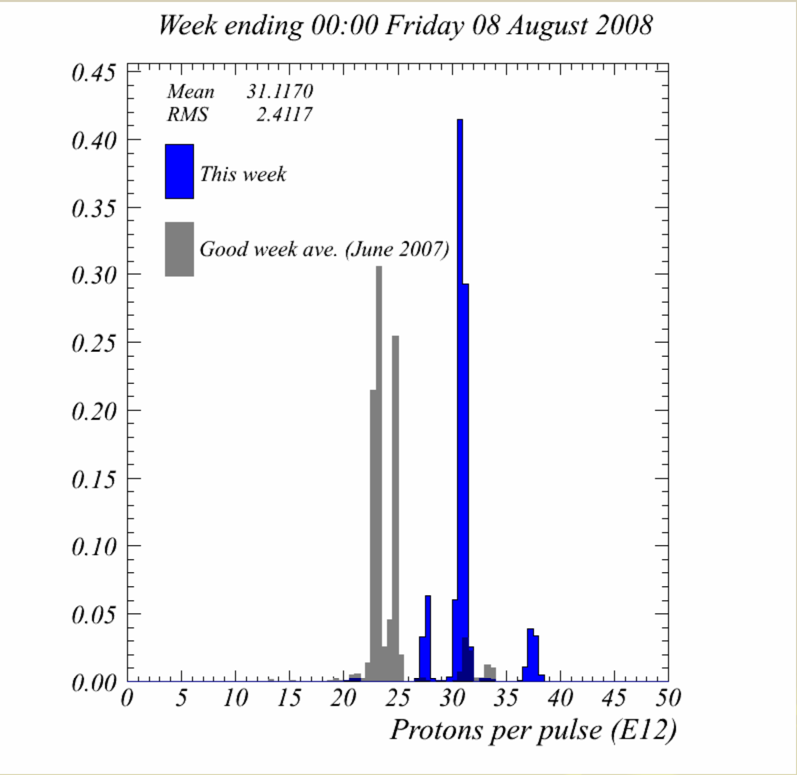
First multi-batch high intensity beam at 2.5 $x10^{13}$ ppp. Very clean beam.

- **Overall – Could not have gone better!**
  - Some important keys – very comprehensive pre-beam checkouts
  - Real time participation of all experts – ran one 12 hour shift daily

Weekly Beam Parameters

intensity & beam power

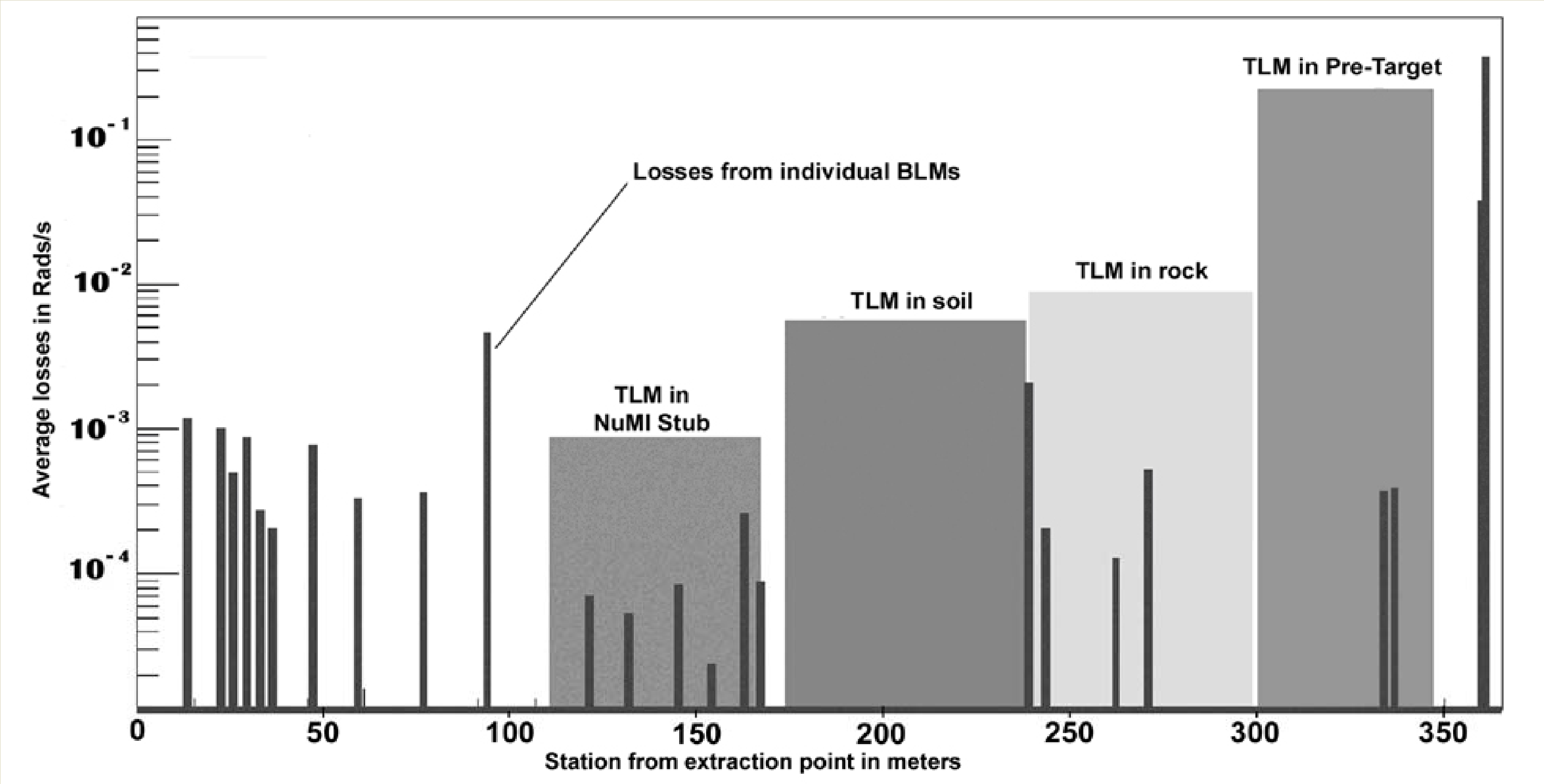




<243.6 kW>

<3.11 e13 ppp>

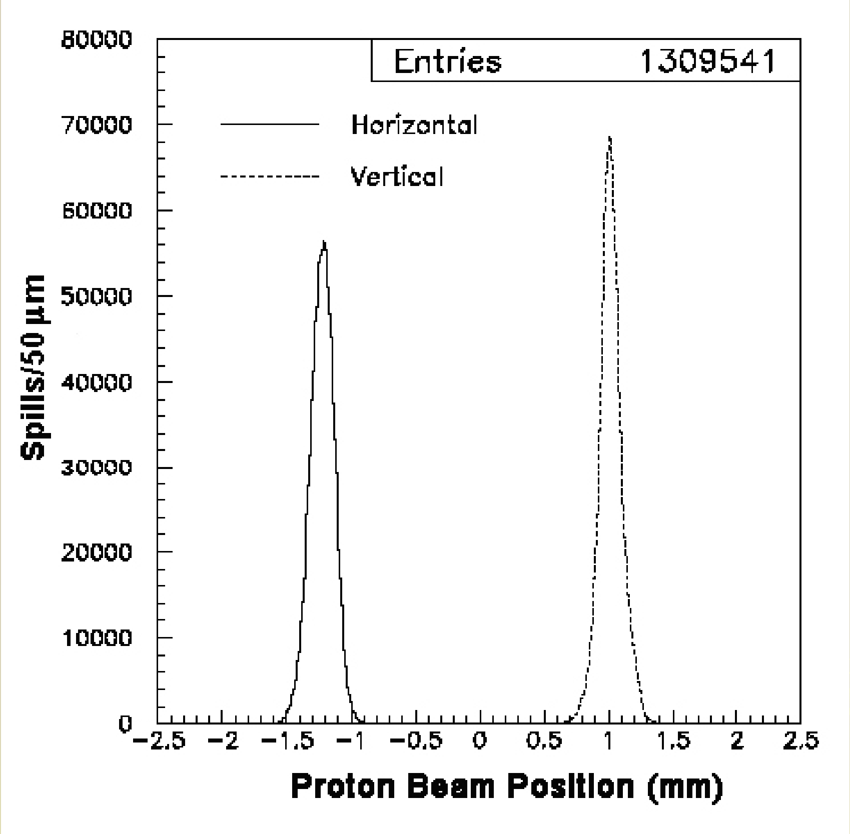
NuMI Primary Beam Performance (cont)
Beam Loss Control



Beam loss per pulse averaging all pulses for one month. Calibration of BLM's provided by most downstream profile monitor in the beam – giving 10^{-5} of beam lost. Other BLM's reading ~ 10^{-7} of beam loss !

NuMI Primary Beam Performance (cont) Targeted Beam Position Control

- Beam position seen by target BPM's for 1.3 million consecutive beam pulses.
- Beam is centered on target, with center at (x,y)=(-1.2,+1.0mm).
  - For each plane rms variation is ~ 90 µm. (spec is 250 µm)
  - Autotune is activated for beam position offset of 125 µm
- **No manual NuMI beam tuning is done during operation – either by MCR operators or NuMI staff.**



NuMI Primary Beam Performance (cont)

- **Accidental Beam Loss Control**
  - During our first 3 years of operation, a total of 5 beam pulses out of more than 24 million total have had primary beam transport loss sufficient to see by comparing upstream and downstream intensity monitors. All 5 were from MI RF trips just prior to extraction.
    - The permit system now prevents extraction of this type of pulse.
  - Our greatest beam mis-steering concern is if a large angle beam pulse were to sneak between the pre-target baffle and the target.
    - We trip the permit for any beam pulse off center by 1.5 mm at the target, precluding a 2nd such high intensity pulse. Work is ongoing to have more robustness against a 1st pulse.

- **Uptime Availability**
  - Over the first 3 years of operation primary beam uptime availability has been about 98%, with a couple of magnet water leaks giving the most downtime.
    - TD has designed and tested a more robust manifold for our EPB dipoles, replacing fragile ceramic isolators with PEEK. We look to install in Apr. 09

NuMI Primary Beam Performance Summary

- **To date performance of the NuMI proton beam extraction, primary transport, and targeting control has been at a world class level.**
- **Also, the techniques developed are well suited for application at much higher beam powers.**
- **We look to continue this, with added emphasis on robustness of control for every beam pulse.**

Some Lessons to Learn
Cannot yet say “lessons learned”

- **The greatest concern** – we came very close to building a NuMI primary beam line which could not have worked, even at 1/10th of design beam power
  - Impact of this for MINOS would have been extremely difficult. With a majority of the NuMI primary transport in the Main Injector/Recycler interlock region, it would have required at least a couple of years to fix.
  - From Review Chairman summary at the Director’s Review April 2002, where there was finally consensus for the need of major design changes

“The fact that an inadequate design could survive for so many years is, frankly, upsetting. The current NUMI team should be commended for rectifying this very serious problem”.

Lessons to Learn (cont)

- **Two major problems seemed to exist with our primary beam efforts for NuMI, and possibly extend beyond this**
  - **Project management was with good administrative managers and large dependence on the review process to find significant technical issues**
  - **There was not good understanding either within the project or higher of where substantial previous experience existed for our most challenging external primary beams**
- **While our reviews are essential, many times they do not go into enough depth to really find many more subtle but major problems. For any challenging technical project, it is essential to have broad based lead technical experience at a decision making level**
- **One problem for the primary beam may have been that this is something we do all the time, with many people having some experience. NuMI was one of the 3 most challenging such beams we have ever built. On this scale the important design and build experience is not at all wide spread.**