Some Radiation Protection Challenges: Deep Underground vs. Shallow Beams

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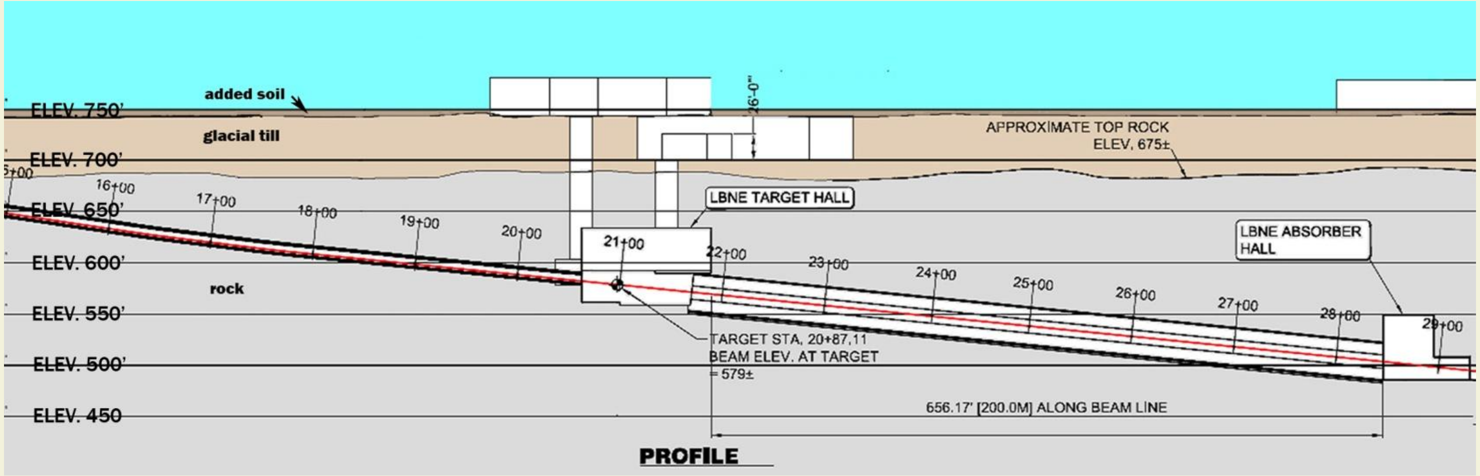
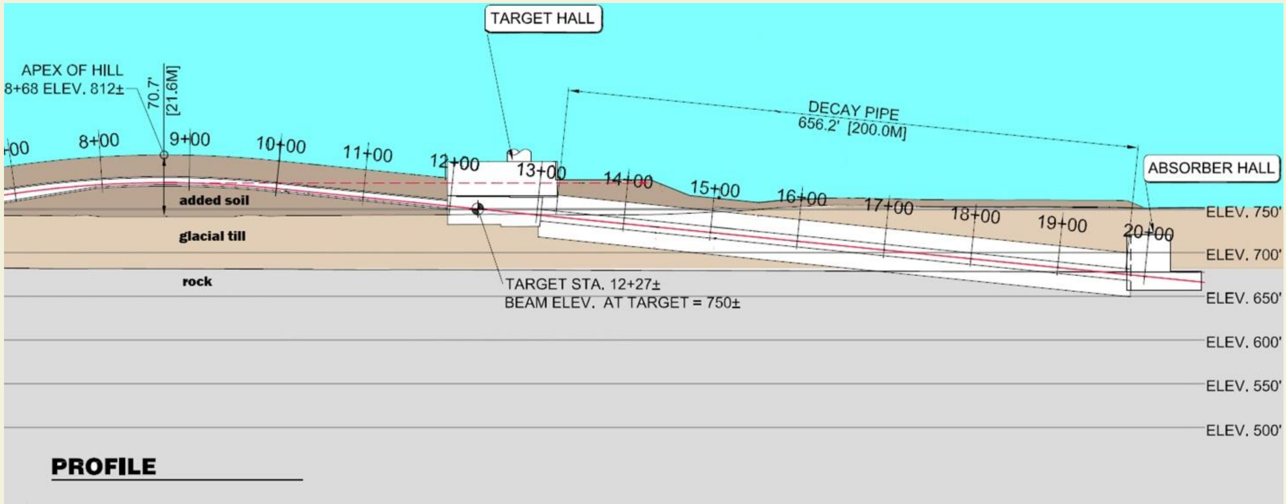
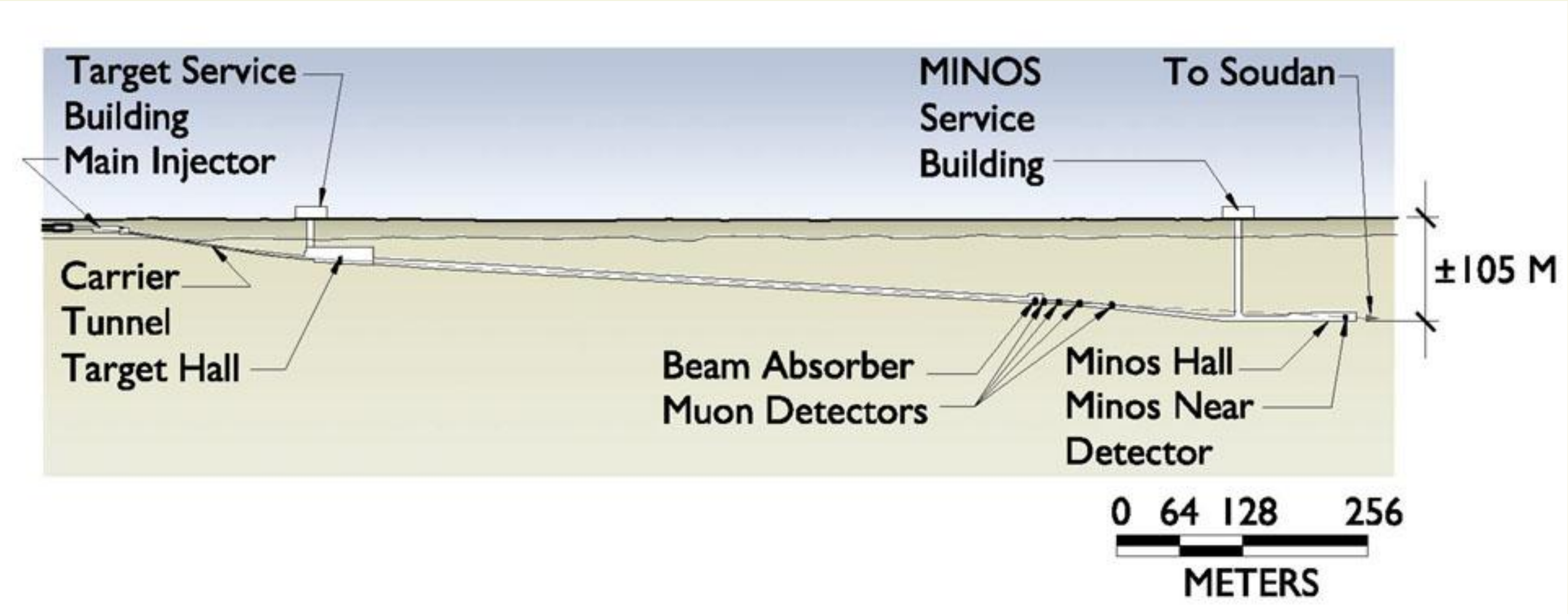




NuMI Beam Profile View

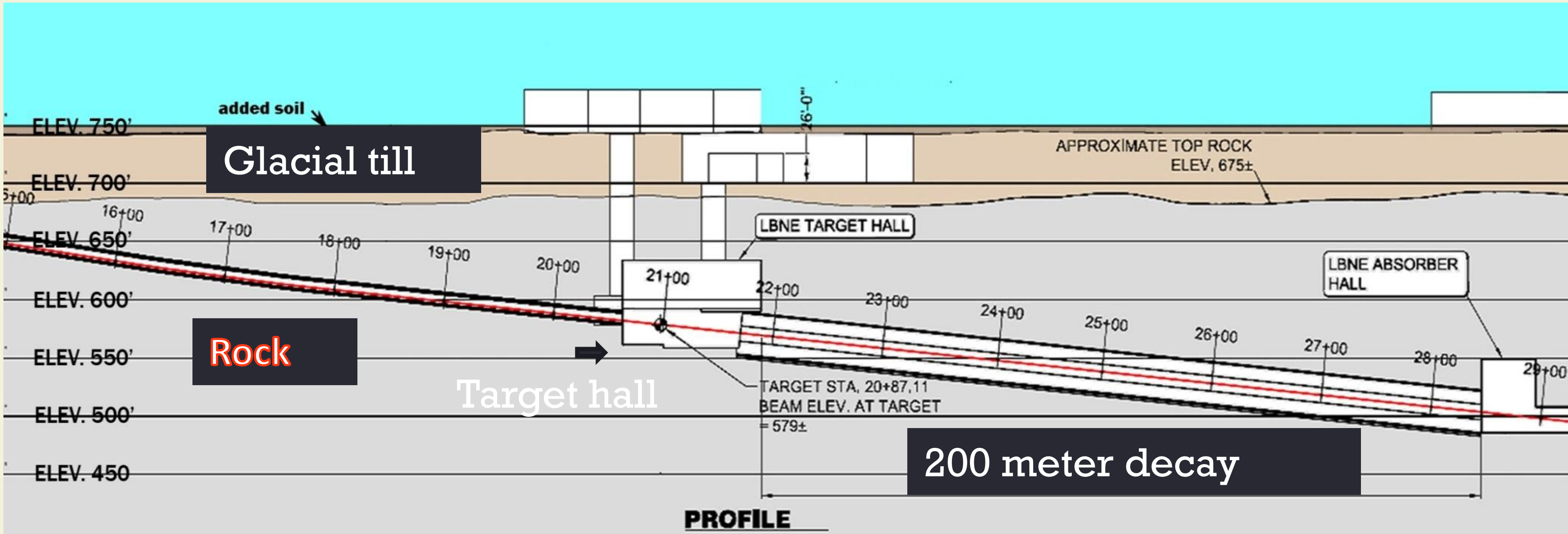


For NuMI we have a deep beam facility mined in underlying rock strata with the design driven by length of the decay pipe (675 meters). Initially we started with a similar design for LBNE.

NuMI Radiation Protection Results

- For most radiation protection goals the NuMI beam design has worked very well. The deep beam facility enabled most shielding requirements to be readily met.
- The most challenging radiation protection efforts have been of two types:
  - Developing techniques for maintenance and replacement of highly activated target hall components.
  - Tritium mitigation.
- Techniques developed for working with highly activated components have been described previously, have proved successful, and differences for either a deep or shallow beam facility are ones of detail only.
- Jim Hylen’s earlier talk has discussed NuMI tritium problems and continuing mitigation efforts.

Profile View for Deep LBNE Beam Facility



Target hall location chosen by reaching sufficient depth to enable structural rock cover above the hall. Maximum primary beam slope angle limited to -150 mr. Bend down at this angle, then bend up to target at -101 mr.

NuMI Style Design

Issues with Deep LBNE Facility Design

- In late 2010, we had received DOE funding agency feedback that, even after significant value engineering efforts, we still needed to make large further cost reductions to be able to go forward with LBNE.
- An underlying concern also was that even with a very expensive facility design we had not yet addressed solutions for the tritiated water problems seen with NuMI.

- At an early stage for NuMI, a small group evaluation of unit costing information obtained from the initial facility Conceptual Design Report showed that a very different NuMI facility design could be significantly more cost effective. This effort then expanded rapidly including efforts by the full project team to develop the NuMI design which we built.
- In late November of 2010, a similar process was begun for LBNE.

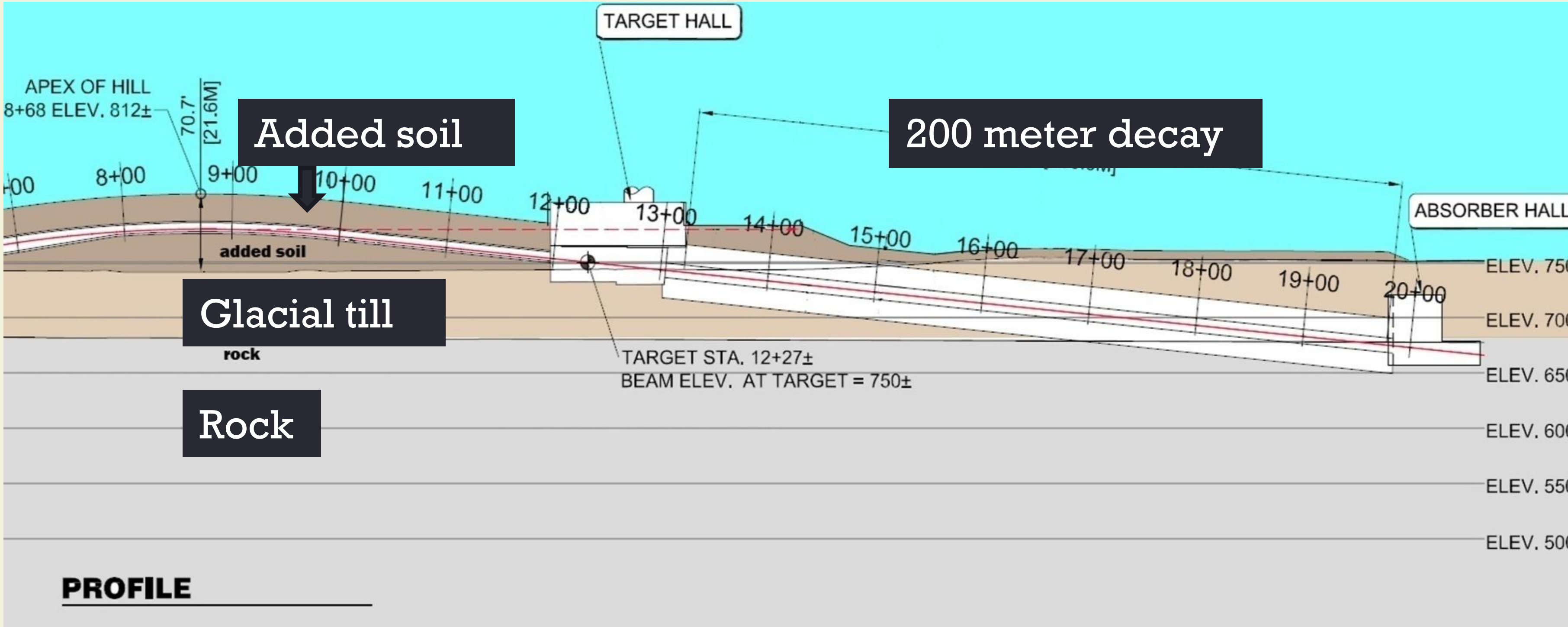
Toward a More Cost Efficient LBNE Facility Design

- During the costing process for an earlier LBNE Project Definition Report, we obtained experts feedback that underground mining costs have risen very significantly since NuMI facility construction.
- Using unit cost details for construction in different elevation regions: glacial till, deep cut rock excavation and mining in structural rock regions, a first pass cost differential effort was done as a function of elevation for the fixed geometry region of the LBNE beam facility – the 101 mrad down-bend region from target to beam absorber.
- As beam elevation is raised, costs are reduced for target hall, decay region and absorber hall. There is then a tradeoff where optimal target hall costing is for location at upper region of the glacial till (normal building construction location). As elevation is raised further, costs rapidly rise for primary beam and target hall facilities.
- An optimal region was chosen for more detailed evaluation with target elevation between 750 ft. and 777 ft., where natural grade elevation is ~ 745 ft. **By comparison, for the deep facility design, target elevation is ~ 50 meters lower**, at 585 ft.

Toward a More Cost Efficient LBNE Facility Design

- A target elevation of 777 ft. enabled the full (200 meter) decay region and absorber hall to be positioned above the rock strata. This has dual advantages of optimizing construction costs for these regions, and also being above the most critical till – rock interface region for ground water protection.
- A target elevation of 750 ft. enabled the possibility of a beam extraction from the Main Injector MI-10 region, with a greatly reduced primary beam transport needed for establishing beam trajectory toward far detector site in South Dakota.
- For a more efficient optimization process, two Shallow Beam designs were carried forward:
  - MI-60 extraction (as for NuMI) with target elevation of 777 ft.
  - MI-10 extraction with target elevation of 750 ft.
- The latter was then chosen for the LBNE beam facility design.
  - **This enabled a net reduction in beam facility cost of ~ 1/3 compared to the optimized deep facility costing.**

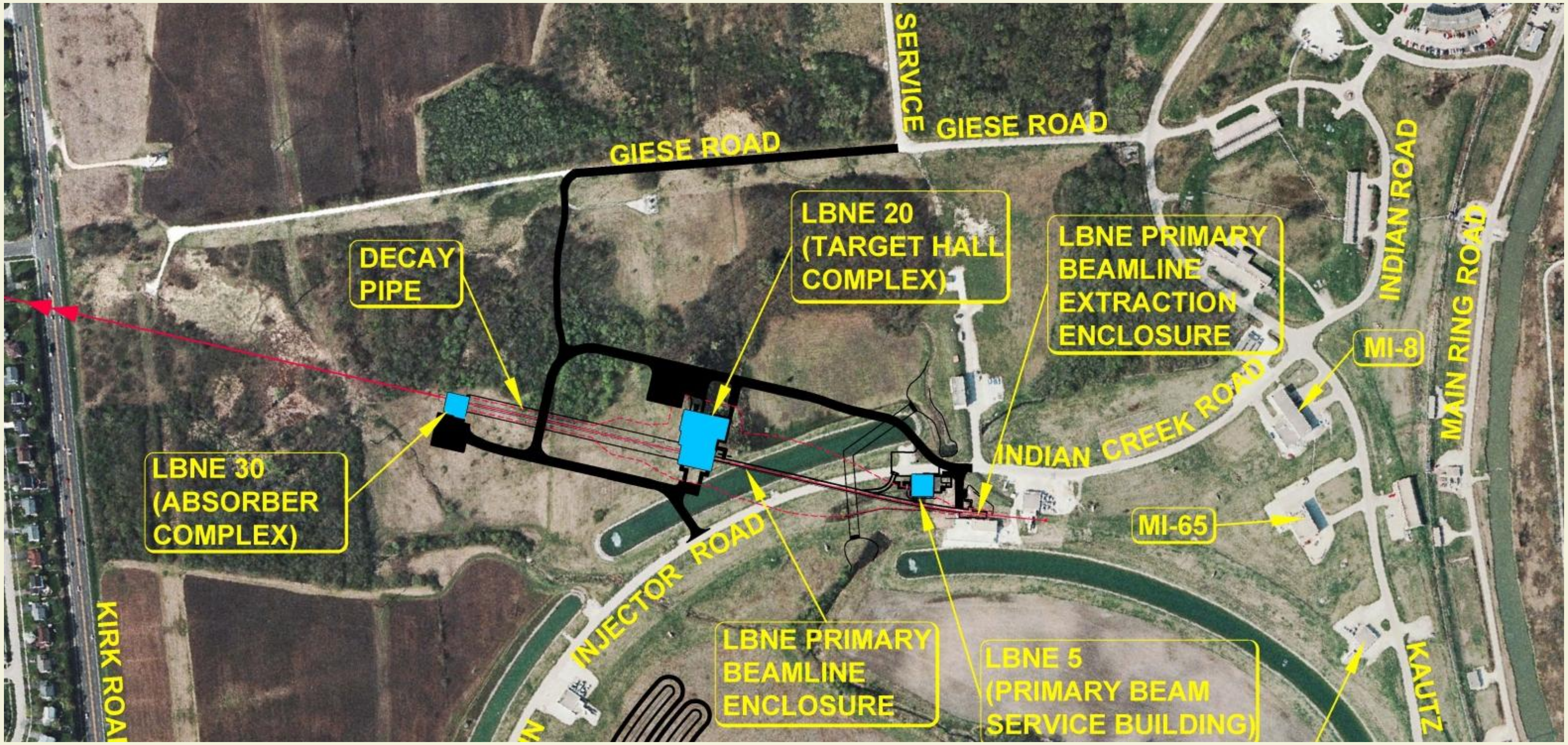
Profile View for Shallow LBNE Beam Facility



Significantly shorter decay than NuMI (675 m) enables target hall elevation placement out of rock - chosen to balance construction requirements for elevated proton beam versus decay region and absorber located partially in rock. Potential advantages of reduced cost and improved tritium mitigation.

Project decision this week for beam facility choice

Plan View of MI-10 Shallow Beam Facility



Some Shallow Beam Radiation Protection Impacts

- For our Shallow Beam Design, the very large radiation protection advantage compared to a Deep Beam design is that for ground water protection.
  - With a careful design process, we should be able to gain a large factor in reduction of tritiated water problems as experienced with NuMI. This is due first to the large impedance to water flow provided by the underlying glacial till, now between most of our beam system and the protected aquifer region in the rock.
  - Maintaining a dry target hall and absorber region should also pay large dividends in reduction of moist air in contact with tritium produced in the system shields.
  - A significant additional benefit is reduction of corrosion in the target hall chase.
- The challenges for Shallow Beam radiation protection then come in maintaining appropriate above ground shielding for the very intense beam system.

Shallow Beam Radiation Protection Challenges

- For the target hall, a thick walled concrete building structure for the above grade facility is required to provide needed environmental radiation protection beyond the internal shield above target and horns.
- For the absorber hall, which is at depth, shielding to achieve ground water protection is the key requirement. Mitigation of possible ground water inflow enables a dry environment.
- Needed ground water shielding for the decay region is provided by a 5.5 meter concrete shield around the decay pipe, plus an environmental soil shield above. The large downward bend angle greatly mitigates possible above grade muon radiation issues.
- Providing appropriate shielding for the primary beam region, and especially for beam accident conditions, is greatly mitigated by rigorous beam loss control as has been done for NuMI. Some details for this follow.

Challenges for LBNE Primary Beam Loss Protection

- The Shallow MI-10 extraction primary beam transport for LBNE is very different in design from our current most powerful primary beam system, the NuMI Deep beam.
- Comparison of some key features and issues for LBNE vs. NuMI designs:

System	Power	Intensity (per pulse)	Geometry	Ground water protection	Residual activation	External shielding
LBNE	2.3 MW	1.6 e14	Above natural grade target	Easier	Challenging	Challenging
NuMI	0.4 MW	0.4 e14	Target deep in dolemitic rock	Challenging	Challenging	Easier

- But as will be discussed, in spite of the major design differences, the needed systems for preventing beam loss are very similar for NuMI and LBNE.

Primary Beam Loss Protection Challenges

External Shielding: beam-on personnel protection

•This was easier to address for NuMI due to the extensive soil/rock cover above the primary beam enclosure. Also, the downward beam pitch further enhanced shield effectiveness.

•For LBNE, external shield design needs careful attention especially with much of the primary beam transport above natural grade level.

•Additional constraints must also be considered for design of the external shielding for LBNE primary beam beyond radiological calculations:

- Close proximity to the Main Injector, potential for impacting MI alignment and also limited MI enclosure soil bearing capability
- Limited distance from LBNE beam to site boundary
- Adding external shield height is expensive due to the large footprint needed using defined maximum slope limits.

•MARS calculations of needed external shielding have been done for continuous (normal) and accidental beam losses, determining both onsite and offsite dose rates. Determination of realistic, conservative numbers for these beam loss limits has been a major focus

LBNE Systems for Preventing Beam Loss

For LBNE we need to accomplish beam loss control at similar limits for absolute loss as has been done for NuMI. With the higher LBNE beam power, these limits are proportionally more severe than for the 400 kW NuMI beam, but still within operational NuMI experience.

- Needed for LBNE is a similar comprehensive system for preventing beam loss to that which has been very successful for NuMI. This is of such critical importance that many system improvements are being done for the 700 kW NOvA upgrade for the NuMI beamline, and many others are envisioned for LBNE.
- As for NuMI, the heart of the protective system is a robust beam permit system sensitive to status of a very large number of parameters prior to enabling each beam extraction, and which can respond to very small beam loss (< parts per million) anywhere along the beam transport. The success of this approach is such that the NuMI permit system has been a model for similar systems with other FNAL intense primary beams, and also for beam loss protection systems for CNGS and T2K proton beams.

Determination of Maximum Credible Beam Loss

The integrated NuMI protection system for preventing repetitive beam loss was developed to provide a robust capability for ground water protection with an allowed upper limit of ~ 2 lost full beam pulses per week averaged over a year. This has been accomplished very successfully over the 7 years of NuMI beam operation with a large safety factor.

Considerations of a maximum credible LBNE beam loss accident:

•The beam permit system design is intended to limit many possible common mode failures.

- It is hardware based and independent of functioning of the ACNET control system
- Beam loss measurements have significant redundancy, with individual BLM's on every large magnet, as well as full coverage extended length LLM's
- A possible full beam loss pulse could occur with concurrent failure of two independent types of system inputs, while along the primary transport additional after the pulse inhibits should preclude a repetitive bad pulse.
- The failure mode of greatest concern with the current NuMI permit system would not produce a beam loss along the primary transport, but a trajectory change for targeted beam which could damage a target hall component. This is of course inside the large target hall shield.

Maximum Credible Beam Loss

Maximum credible LBNE beam loss accident (continued):

•For LBNE, beam transport vacuum failure will occur very quickly in the case of a localized full beam loss – expected between 1 and 4 beam pulses dependent on intensity. While this in itself does not preclude additional lost beam pulses, a number of additional independent beam permit inhibits will be triggered providing greater protection against sustained beam loss.

•Backup protection which is feasible with a small number of credited radiation safety interlocks provides a fundamental protection against beam loss accidents which can not be otherwise accomplished even with very comprehensive improvements to the existing beam permit system. This is having the checks and balances provided by a different organizational structure with a primary focus for ES&H. Different protection features of the beam permit system can be readily masked to address operational issues of the moment, with the possibility of unintended consequences, while the Safety interlocked systems cannot be easily disabled.

Shielding Requirements for LBNE Primary Beam

For the LBNE primary beam, the most challenging radiological issue we must address is that of controlling residual activation within the beam enclosure to be ALARA.

- The requirement developed by detailed MARS modeling is for sustained localized fractional beam loss to be less than 3 parts per million for the 2.3 MW LBNE proton beam.
- For a single localized full pulse beam loss, we need to rigorously preclude repetitive lost pulses, and have probably already sustained a beam vacuum failure.

External shielding requirements for 2.3 MW beam power have been developed to minimize dose to personnel, and are presented here.

- An initial safety factor applied is to calculate shielding requirements for a sustained fractional beam loss of 10 parts per million (1 e-5), and accidental localized beam loss of 2 pulses per hour.

Shielding Requirements for Primary Beam

		1E-5 loss rate
Dose Rate (DR) Under Normal	Controls	soil (ft)
DR < 0.05 mrem/hr	No precautions needed.	21
0.05 $\leq$ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.	19
0.25 $\leq$ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy (occupancy duration of less than 1 hr).	14.5
5 $\leq$ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker	10.5
100 $\leq$ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no	
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.	

Soil Shielding Requirements for the Primary Beam Transport for Continuous Beam loss at 1 e-5 Fractional Loss Rate

Shielding Requirements for Primary Beam

		2 full pulses
Maximum Dose (D) Expected in One hour	**Controls**	soil (ft)
D < 1 mrem	No precautions needed.	**23**
1 < D $\leq$ 10 mrem	Minimal occupancy only (duration of credible occupancy < 1 hr) no posting	20
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed. Radiological Worker Training required.	**21**
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy (duration of occupancy of less than1 hr). The Division/Section/Center RSO has the option of imposing additional	16.5
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological	**14**
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no	13
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.	

Soil Shielding Requirements for the Primary Beam Transport for Accidental Losses

Shielding Design for LBNE Primary Beam

Conceptual Design for the LBNE facility has been developed with external primary beam soil shielding of 23 ft., accomplishing the most conservative calculated LBNE requirements .

- 21 ft. for continuous fractional beam loss of 1 e-5 at 2.3 MW
- 23 ft. for 2 localized full beam pulses lost per hour at 2.3 MW

with these calculations in each case being for unlimited occupancy above the berm with no precautions needed. This design also provides an appropriate longitudinal muon shield needed for limiting dose at the site boundary. At 23 ft. of shielding 2 full pulses per hour accident would add about 15% of the annual dose offsite from all LBNE operations. The goal is to keep this total dose about 1 mrem/year.

This is a very robust design which can be efficiently constructed with appropriate measures to mitigate adverse effects which could otherwise impact the Main Injector accelerator.

Primary Beam Loss Protection Summary

A comprehensive solution has been developed for primary beam loss protection for the intense 2.3 MW LBNE proton beam, addressing radiological safety requirements and ALARA issues.

The developed solution is solidly based on the beam control approach used during seven years of robust operation for the 400 kW NuMI primary beam. Planned hardware for LBNE includes:

- Comprehensive beam permit system verifying readiness prior to each beam extraction
- BLM/ LLM loss monitoring system with fully redundant coverage
- Four “in the tunnel” Scarecrow radiation safety detectors to provide failsafe capability for preventing repetitive large beam loss

The LBNE facility conceptual design then incorporates an external shield providing required radiological protection and enabling unlimited occupancy above the primary beam enclosure system.

Possibly our Greatest LBNE Shallow Beam Radiation Protection Challenge

- An area where we still have much work to do, is protection against release of activated air.
- For the Deep NuMI beam design, this has been well controlled (except for tritium impact!)
- Now, for a very intense LBNE Shallow Beam, much more careful design must follow.