BEAM LOSS STUDIES FOR THE 2-MW LBNE PROTON BEAM LINE *

A.I. Drozhdin†, S.R. Childress, N.V. Mokhov, I.S. Tropin, R. Zwaska,
Fermilab, Batavia, Illinois, 60510, USA

Abstract

Severe limits are put on allowable beam loss during extraction and transport of a 2.3 MW primary proton beam for the Long Baseline Neutrino Experiment (LBNE) at Fermilab. Detailed simulations with the STRUCT and MARS codes have evaluated the impact of beam loss of 1.6×10^{14} protons per pulse at 120 GeV, ranging from a single pulse full loss to sustained small fractional loss. It is shown that loss of a single beam pulse at 2.3 MW will result in a catastrophic event: beam pipe destruction, damaged magnets and very high levels of residual radiation inside and outside the tunnel. Acceptable beam loss limits have been determined and robust solutions developed to enable efficient proton beam operation under these constraints.

DESIGN CONSIDERATIONS

The main criteria which have guided design of the LBNE [1] primary beam line is transmission of high intensity beam with minimum losses and precision of targeting, keeping activation of components and ground water below the regulatory limits.

The beam line passes through the aquifer regions, therefore radiation requirements are quite stringent and vary from region to region. Another serious consideration is given to accidental beam losses which can cause beam line component damage. Prompt radiation may not be a major issue because of substantial depth of the deep beam line tunnel, and may be one of the main issue in the above-grade target option.

Extraction kicker, quadrupole and bending magnet power supply ripples, and closed orbit position deviation are the main sources of beam position instability on the target and South Dakota detector as well as increased beam loss along the beam line. If variation of the element strength happens over minutes or hours, it can be corrected. Otherwise, if variation is caused by pulse to pulse jitter, the specification would have to be met directly.

Important part of study is a choice of interlock detectors location required for ground water protection from irradiation and against significant activation of primary beam line components. Additional study is required for positioning of technological protective gate required for the LBNE tunnel and buildings construction and equipment installation during the Main Injector operation.

Proton beam extracted from the MI-10 straight section is transported through a 375 m beam line to the LBNE target located 11.4 m above the Main Injector elevation.

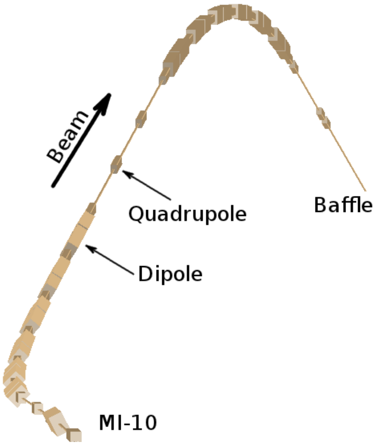

Figure 1: ROOT [5] based MARS geometry model for the LBNE primary beamline. Baffle is a mask to protect target and horns.

Beam loss studies in the LBNE primary beam line (Figure 1) are done using the STRUCT [2] and MARS [3] codes, with distributions of primary beam loss along the beam line obtained with STRUCT, and energy deposition, ground water and component activation calculated with MARS using the former as a source term.

Transverse coordinates and directions for the beam core particles within 3σ (30π mm-mrad) emittance are simulated in STRUCT using gaussian. A $\sim 1/r$ distribution is used for halo tails continued up to $r_{max} = 10.4\sigma$ or 360π mm-mrad. Momentum spread is supposed to be $\Delta p/p = 0.0004$ with cut-off at $\Delta p/p = 0.0028$. The beam intensity is assumed to be 1.6×10^{14} per a 1.33-second Main Injector cycle (2.3MW case), that is a factor of 6 higher compared to the NuMI design [4]. The effects of a magnet power supplies instability on beam distributions at the target and Baffle are calculated for the nominal emittance of 30π mm-mrad.

PRIMARY BEAM LOSS

Horizontal and vertical 3σ beam distributions at the Baffle entrance as a function of the dipole power supply instability are presented in Figure 2. They are a sum of 100 independent ones for magnet strengths in the line.

Calculations are done for a common power supply for several magnets with the LBNE quadrupole instability of $\Delta G/G = \pm 0.001$, extraction kicker instability $\Delta B/B = \pm 0.005$, Lambertson magnet $\Delta B/B = \pm 0.002$, Main Injector quadrupoles $\Delta G/G = \pm 0.001$, and Main Injector closed orbit instability $\Delta A = \pm 1\sigma_{x,y}$ or $\Delta A_{max} =$

---

* Work supported by Fermi Research Alliance, LLC, under contract DE-AC02-07CH11359 with the U. S. Department of Energy.

† Email: drozhdin@fnal.gov

± 1.3 mm. The effect of the quadrupole strength instabilities on the resulting beam size is much less compared to that for the dipole magnets.

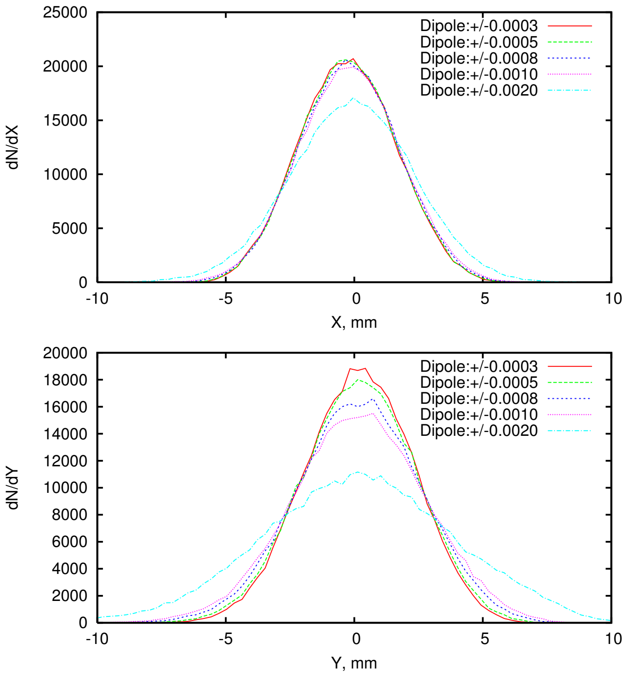

Figure 2: 3σ beam distributions at Baffle entrance for various $\Delta B/B$ in dipoles.

The halo loss distribution along the LBNE line with a common power supply for several magnets are shown in Figure 3. It is a sum of 100 distributions for independent random distributions of magnet strengths in the line. The 360π mm-mrad amplitude corresponds to 13.2 mm at the Baffle. With a Baffle aperture radius of 7.5 mm, it intercepts ≈ 15 kW of power from the beam halo.

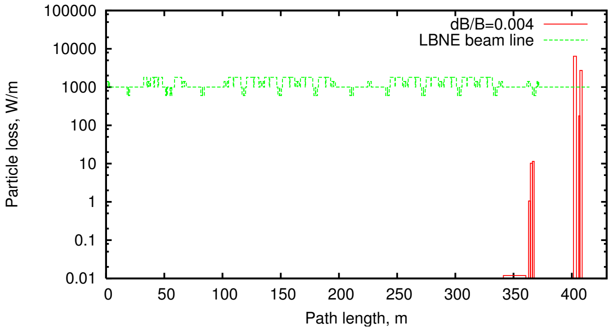

Figure 3: Beam halo loss distribution along the beam line for magnet strength instabilities of $\Delta B/B = \pm 0.003$ and quadrupole strengths of $\Delta G/G = \pm 0.005$.

The halo and core beam loss along the primary beam line and at the Baffle as a function of the dipole magnet power supply instability with a common power supply for several magnets are presented in Figure 4. NuMI operates now at 0.4 MW with fractional beam loss of 1×10^{-5} from the total intensity. For 0.7 MW LBNE, the safety level will be 5.7×10^{-6}, and for 2.3 MW it will be 1.7×10^{-6}. To have a viable operational margin, one has to keep normal beam loss an order of magnitude better than this. From this point of view, the dipole instability should be less than $\Delta B/B < \pm 0.0025$, that keeps losses below 1 W/m. The dipole instability should be less than $\Delta B/B < \pm 0.001$ to keep the power load at the Baffle from halo and core of the beam below 20 kW. For 2.3 MW at 60 GeV, these numbers are 0.003 and 0.001, respectively.

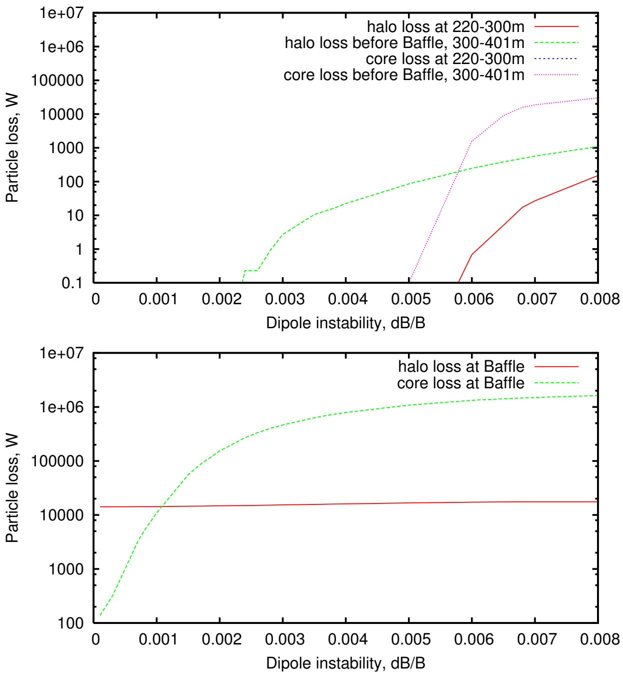

Figure 4: The halo and core beam loss along the LBNE primary beam line and at the Baffle.

Calculations for 60 GeV are done using the 120 GeV lattice with the beam emittance corresponding to 60 GeV, and with an increased aperture of the beam line in the region of Lambertson magnets and final focus quadrupoles, assuming that beam position and beam size in these regions may be adjusted for low energy to eliminate losses at existing aperture of elements. Also, the Baffle and target aperture were increased from $R = 7.5$ mm to $R = 10$ mm.

RESIDUAL ACTIVATION

Beam line component activation can be severe in the MI extraction region and along the beam line where aperture of elements is tight. Residual dose rate for one of the considered beam loss scenarios, when 0.003 of the entire intensity is lost on a single beam line element during 30 days irradiation followed by one day cooling, is shown in Figure 5. In the given scenario for the hot region, the contact dose on the tunnel walls ranges from 100 to 500 mRem/h (top).

The residual dose rate in a quadrupole magnet, following a pointed dipole, where beam particles are lost, reaches 50

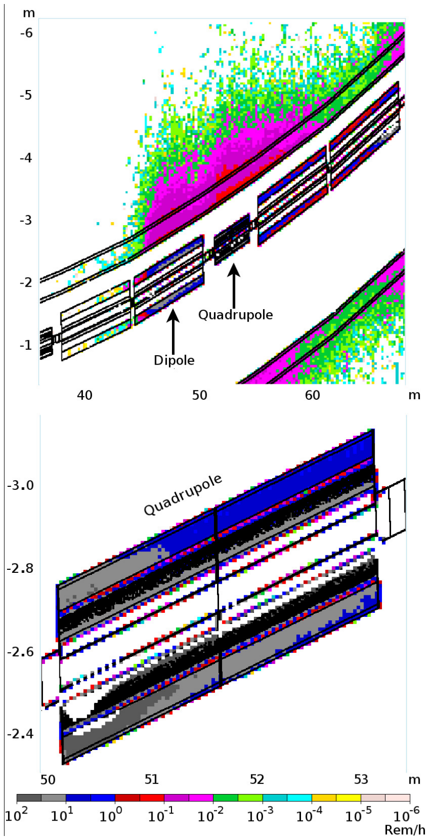

Figure 5: Contact residual dose rate for loss of 0.003 of entire intensity during 30 days followed by one day cooling.

Rem/h (bottom). That is three orders of magnitude higher than a good-practice limit of 50 mRem/h. Ground water is protected by the appropriate concrete shielding around the tunnel.

LOCALIZED FULL BEAM LOSS

An accidental localized beam loss can cause beam line component destruction and have a severe impact on environment. The MARS calculation show (Figure 6) that for the upgraded LBNE intensity of 1.6×10^{14} ppp and realistic impact angle in a dipole magnet, a peak beam pipe temperature of twice the melting point for stainless steel is reached with a single lost full beam pulse. At initial LBNE intensity of 4.9×10^{13} ppp, beam pipe failure is probable after 4-5 lost full beam pulses. Large beam loss for even a single pulse needs to be robustly prevented.

CONCULSION

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 six years of robust operation for the 400 kW NuMI primary beam. Planned hardware for LBNE includes: (1) Comprehensive beam permit system verifying readiness prior to each beam extraction; (2) BLM/LLM loss monitoring system with fully redundant coverage; (3) Four ”in the tunnel” Scarecrow radiation safety detector to provide failsafe capability for preventing repetitive large beam loss.

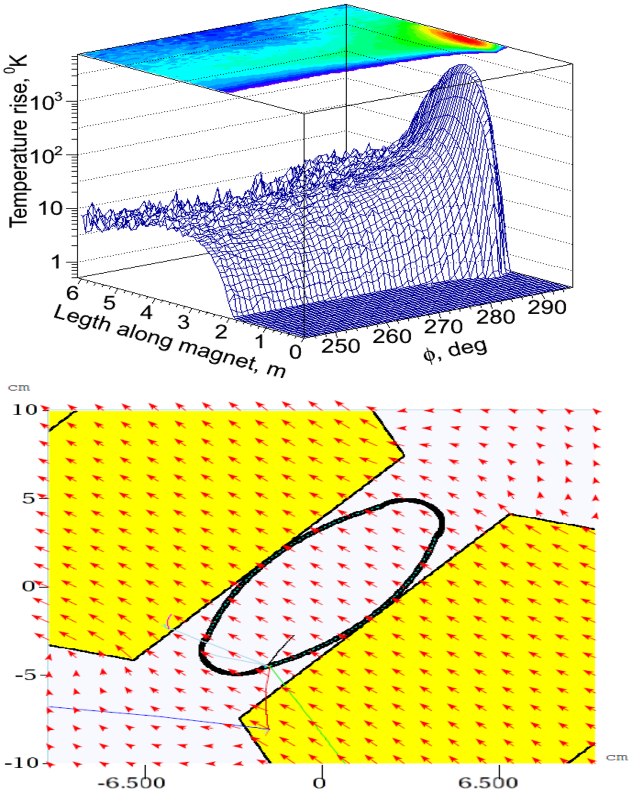

Figure 6: Instantaneous temperature rise (top) in the beam pipe of a dipole magnet (bottom) at localized loss of a single beam pulse.

REFERENCES

[1] Long-Baseline Neutrino Experiment, http://lbne.fnal.gov

[2] I.S. Baishev, A.I. Drozhdin, N.V. Mokhov, X. Yang, “STRUCT Program User’s Reference Manual,” *SSCL report, MAN-0034 (1994).*

[3] N.V. Mokhov, “The Mars Code System User’s Guide,” Fermilab-FN-628 (1995); N.V. Mokhov and S.I. Striganov, *Hadronic Shower Simulation Workshop Proceedings, Batavia, Illinois, 2006*, (Melville, New York: American Institute of Physics, 2007), 50-60, Vol. 896.

[4] The MINOS Experiment and NuMI Beamline, http://www-numi.fnal.gov

[5] http://root.cern.ch/download/doc/18Geometry.pdf