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PHYSICS STUDIES FOR THE LBNF GRAPHITE TARGET DESIGN

J. J. Back*, University of Warwick, Coventry, UK
on behalf of the DUNE collaboration

Abstract

We present the simulated physics performance of the Long-Baseline Neutrino Facility (LBNF) graphite target that is being designed by the RAL High Power Targets Group for the Deep Underground Neutrino Experiment (DUNE). We first compare three conceptual cylindrical target design options as a function of target length (up to 2.2 m): downstream supported, two individual targets and an upstream-supported cantilever. Choosing the cantilever design as the baseline, we show the effect of widening the upstream inner conductor of the first focusing horn to provide extra space for supporting the target. We also give estimates of the expected performance of the 1.5 m prototype and 1.8 m production cantilevered targets. Furthermore, we show the effects of the main engineering updates made to the other two focusing horns since the DUNE TDR.

INTRODUCTION

The LBNF at Fermilab (USA) will deliver the world's most intense on-axis neutrino beam to the DUNE near and far detectors [1], with the aim of discovering matter-antimatter asymmetries from charge-parity (CP) violation when neutrinos oscillate between (three) flavour states, which could help explain the dominance of matter in the early universe. The LBNF beamline [2] will collide a 120 GeV, 1.2 MW proton beam (upgradable to 2.4 MW) onto a graphite target, creating secondary charged pions which are focused by three magnetic horns before they decay, via $\pi^+ \to \mu^+ \nu_\mu$ and $\pi^- \to \mu^- \bar{\nu}_\mu$, to produce an intense flux of muon neutrinos or antineutrinos towards the DUNE detectors. Here, we show the simulated physics performance of conceptual, prototype and production targets for the 3-horn focusing system, using Geant4 [3] software with the QGSP_BERT hadronic model.

CONCEPTUAL TARGET DESIGNS

The Rutherford Lab (RAL) High Power Targets Group is designing, and will build, the LBNF target. Three conceptual designs were considered for the helium-cooled cylindrical graphite target, namely a long (up to 2.2 m) target supported by a downstream (DS) frame, two targets (where the first one is always 1 m long) with their own supports, and an upstream-supported cantilever. For each case, the target is fully inserted inside the first 2.2 m-long focusing horn "A" (24 cm outer conductor radius), and the graphite core target radius is fixed at 8 mm, equal to 3 (Gaussian) proton beam widths. Each target is inside a 1 mm-thick tapered cylindrical titanium container (3.7 cm to 2.7 cm radius) filled with helium cooling gas, surrounded by a nitrogen atmosphere.

* J.J.Back@warwick.ac.uk

Figure 1 shows the CP sensitivity σ as a function of target length for the three options, with no changes made to the 3 focusing horns, which each have an azimuthal magnetic field $B = 0.02I/r$ T between their inner and outer conductors, for series current $I = \pm 293$ kA (negative for antineutrinos) and radius r (cm). The sensitivity σ is equal to the minimum value of $\sqrt{\Delta\chi^2}$ for measuring CP-violation that is satisfied by 75% of the neutrino oscillation phase δ_{CP} values between $\pm 180°$. The $\sqrt{\Delta\chi^2}(\delta_{CP})$ distribution is found using GLoBES software [4] (assuming normal mass ordering) with neutrino flux spectra from the Geant4 simulations, for 3.5 years each of neutrino then antineutrino running at 1.2 MW, corresponding to 1.1×10^{21} protons-on-target per run year (204.5 calendar days), with a 40 kt liquid argon far detector located 1297 km downstream at the Sanford Underground Research Facility in South Dakota (USA) [5].

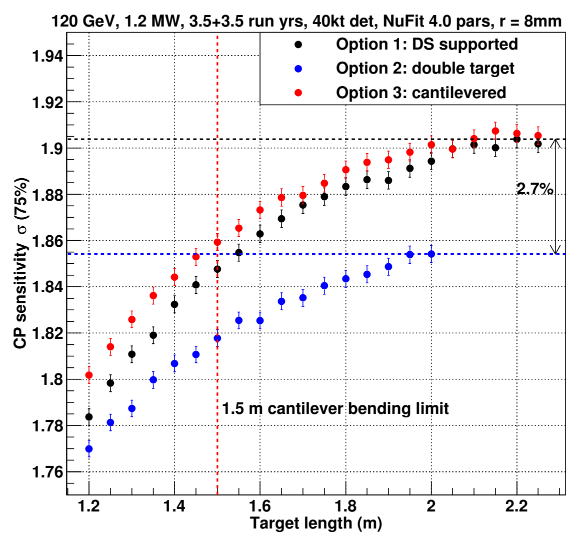

Figure 1: CP sensitivity σ (for 75% of the δ_{CP} range) versus core target length for the 3 conceptual design options.

For a given target length, the best performance is achieved with the cantilevered option, followed closely by the DS-supported target, which produces a slightly reduced neutrino flux owing to the extra titanium supports absorbing and deflecting useful secondary pions away from the beamline. However, gravitational bending limits the cantilever target to a maximum practical length of 1.5 m, and so the DS option is better for longer targets. Using two targets gives a worse performance, since there is a graphite gap of around 20 cm in the middle, reducing pion production. Interestingly, the performance of the 1.5 m-long cantilever option matches the 2 m double target.

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CANTILEVER DESIGN OPTIMIZATION

The cantilever target was chosen as the best option following a conceptual design review of the manufacturing methods, remote handling procedures and physics performance. To maximise the useful neutrino flux, the target needs to be as long as possible, as shown in Fig. 1. Increasing the cantilever length from its bending limit of 1.5 m requires making its outer container stiffer at the upstream end, which can be achieved using a cone. This needs an equivalent conical section to be removed from the horn A inner conductor. Figure 2 shows the layout of the target inside horn A with the upstream conical support structure, which has a fixed (maximized) base radius of 14 cm and an apex position z_A = 40 cm (45 cm height) along the beam axis z.

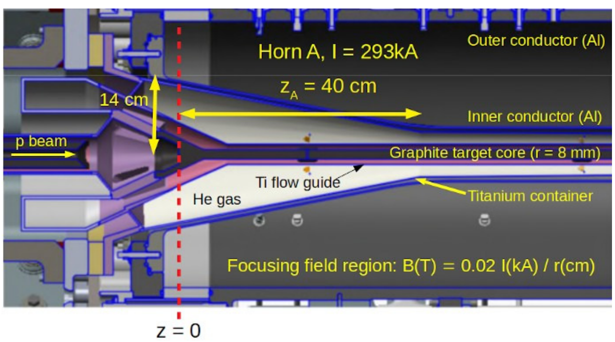

Figure 2: Layout of the target inside the first focusing horn.

Figure 3 shows how the CP sensitivity changes with cone apex z_A for different cantilever target core lengths between 1.5 and 2 m. The sensitivity remains roughly constant up until z_A = 40 cm for all target lengths, since most of the secondary particles from the hadronic shower inside the target appear after one interaction length (48 cm for the graphite density 1.78 g cm^{-3}). It then decreases due to the reduction in the focusing field volume. The blue curve gives the approximate engineering limit, showing the region of points which have the minimum allowed z_A that ensures adequate structural support for the various target lengths. The red curves show the approximate physics limits for maintaining or improving the CP sensitivity, as well as retaining at least 98% of the useful neutrino flux. We can see that z_A = 40 cm ensures that the physics performance matches the no-cone scenario (z_A = 0) and allows target lengths up to 1.8 m.

DESIGN UPDATES SINCE THE TDR

The Technical Design Report (TDR) [1] used the 2.2 m-long DS-supported target option for simulating the neutrino flux for studying the near and far detector technology options. Since then, the cantilevered design with the z_A = 40 cm support cone will be used for the prototype and production LBNF targets, with core lengths equal to 1.5 m and up to 1.8 m, respectively. Furthermore, engineering updates have been made to the 4.7 m-long second ("B") and 3 m-long third ("C") horns since the TDR (with z focal positions at 3.0 m and 17.5 m, respectively), specifically a reduction in their

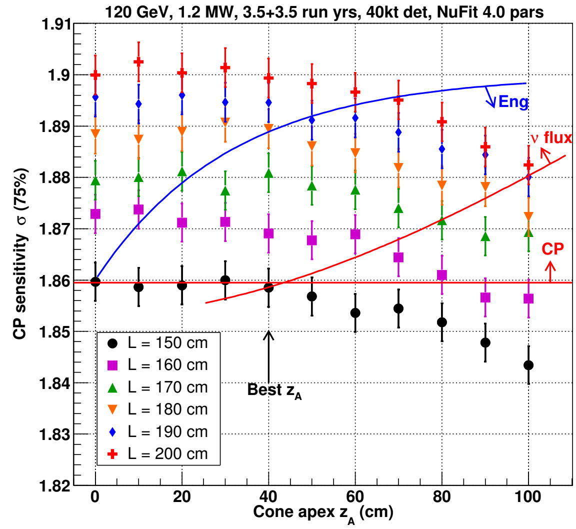

Figure 3: CP sensitivity σ versus the horn A upstream inner conductor cone apex z_A for different cantilever target core lengths. The blue and red curves indicate the engineering and physics (neutrino flux and CP σ) limits, respectively.

outer conductor radii from 63.4 to 60.0 cm to fit inside the target hall infrastructure, as well as standardization of their current equalization sections and striplines. Dipole magnetic fields, obeying the right-hand current rule, are assumed for the striplines, with $B = 0.04[\delta/(h+\delta)]^2$ T, where δ is the stripline thickness (1 cm) and h is the perpendicular distance from the nearest stripline plane.

Figure 4 compares the predicted (unoscillated) muon neutrino signal flux spectra at the far detector for various target and horn design updates since the TDR; similar distributions are obtained for the muon antineutrino signal spectra. The binned flux for the 1.8 m production cantilevered target with the TDR horns is reduced by a few percent for neutrino energies below 2 GeV, although it increases at higher energies. The shorter target reduces the chance of secondary pions reinteracting, leading to fewer (more) low (high) energy neutrinos. Including the upstream support cone inside horn A does not significantly change the neutrino flux. However, larger changes are seen when horns B and C are standardized, reducing (increasing) the binned flux below (above) 2.7 GeV by up to 9% (14%). This is mainly due to their smaller outer conductor radii, which decreases the focusing field volumes by around 10%; the stripline fields only change the binned flux by a relative 1%. Adjusting the lengths of horns B and C, as well as their relative focal positions, did not significantly improve the neutrino flux spectrum, since gains made at low energy bins were offset by losses at high energy. Finally, we see that the binned flux for the 1.5 m prototype target is reduced (enhanced) by up to 14% (27%) for neutrino energies below (above) 2.7 GeV when compared to the TDR distribution.

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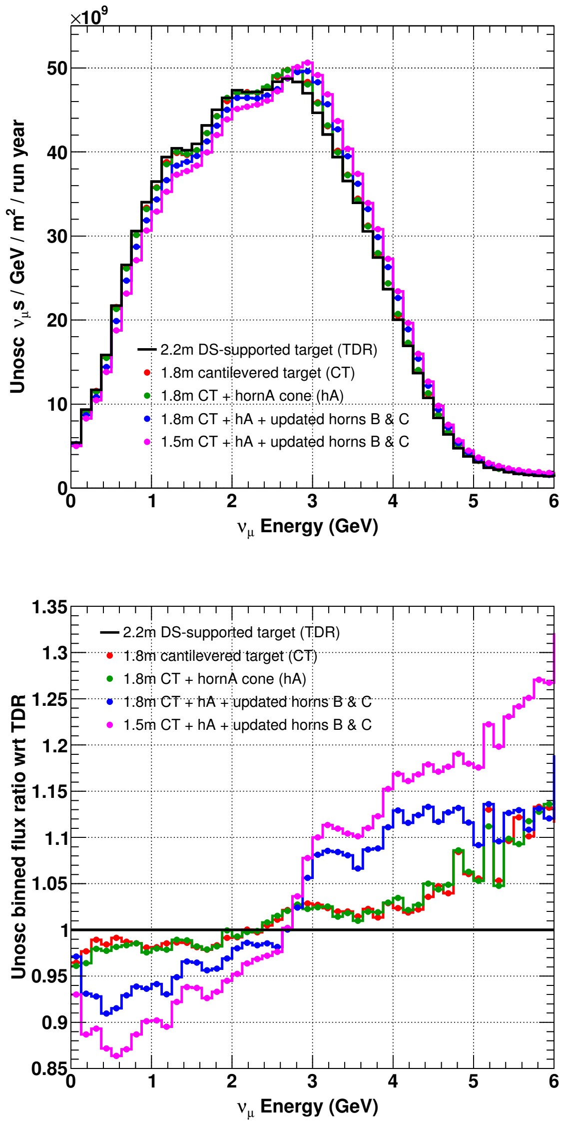

Figure 4: Top: unoscillated muon neutrino flux at the far detector for different target-horn design iterations. Bottom: Flux ratio with respect to the TDR design (2.2 m target).

The target and horn design updates significantly reduce (enhance) the low (high) energy neutrino flux. Figure 5 shows how these design iterations affect the CP sensitivity as a function of exposure, defined as the product of the fixed far detector mass (40 kt) with time (run years). By taking exposure ratios, we can estimate the extra runtime that will be needed to match the TDR performance for measuring CP violation at the 3σ level, for 75% of the δ_{CP} range. For 1.2 MW, the 1.8 m cantilevered target (with or without the upstream support cone) needs an extra 6 days per run year, which increases to 11 days when horns B and C are standardized, while the shorter 1.5 m prototype target needs an extra 23 days per run year. The target exchange downtimes are estimated to be roughly one week for the cantilevered design and around three weeks for the 2.2 m DS-supported (TDR) target; this two week difference is longer than the extra physics runtime needed for the 1.8 m cantilevered target.

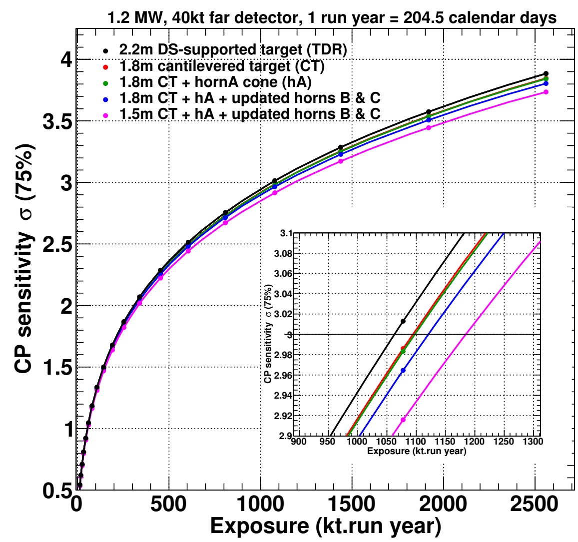

Figure 5: CP sensitivity σ versus exposure (detector mass times runtime) for different target-horn design iterations. The inset shows the zoomed-in region near $\sigma = 3$.

SUMMARY

We have shown the simulated physics performance for different LBNF cylindrical graphite target designs, along with Fermilab engineering updates made to the 3-horn focusing system. The helium-cooled, upstream-supported, cantilevered target will be built by the RAL High Power Targets Group. The prototype will have a length of 1.5 m and the goal is to have a 1.8 m-long production target.

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