PROCEEDINGS OF SCIENCE

Achievement in Beam Power Records for the NOvA Target System

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We began updating the NOvA target system for 1-Mega Watt (1-MW) beam operation in 2017. Major changes include maintaining the quality of neutrino beams with reliable instrumentation, reducing instantaneous beam heating on the target, increasing cooling power to handle the high power beam, and controlling tritium water production rate. We successfully achieved a one-hour beam power report of 1.018 MW in Summer 2024. This achievement marks an important milestone for Fermilab, demonstrating the capability of the accelerator complex to handle high-intensity proton beams at a fast repetition rate. We are now prepared to proceed with a new accelerator upgrade plan, known as the Accelerator Complex Evolution - Main Injector Ramp and Targetry R&D (ACE-MIRT) to support future operates at beam power exceeding 2 MW for the Long Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). We present the improvement of the target system to exceed the beam power 1-MW.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

[*] Speaker

PoS(ICHEP2024)231

1. NuMI 1-MW beamline

Fermilab operates the Neutrinos at the Main Injector (NuMI) beamline, which delivers neutrino beams to the NOvA and SBN experiments. A 120 GeV proton beam, extracted from the Main Injector (MI), strikes a 1.2-meter graphite target producing pions that are focused by magnetic horns and directed along the beam axis, eventually decaying into neutrinos and muons [1].

NuMI has been operational since 2005, with the beam power gradually increasing. The latest upgrade, started in 2017 under the Accelerator Improvement Plan (AIP), enabled the Fermilab complex to reach a 1-Mega Watt (MW) of beam power, delivering the beam intensity $\sim 5.6 \times 10^{13}$ protons/spill in 9.6μ seconds spill length, every 1.067 seconds to the target. In June 2024, an average beam power of 1.018 MW was achieved. The result provides us a confidence to prepare for the ACE-MIRT upgrade, which will boost beam intensity to 6.5×10^{13} protons/spill, with a 0.7-second repetition time, reaching 2.14 MW in the early 2030s for LBNF.

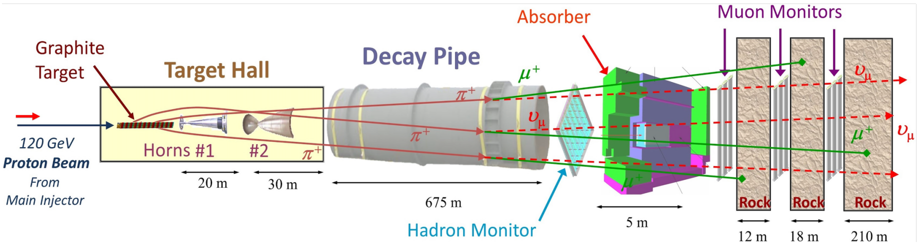

Figure 1: Layout of the NuMI target system.

2. Upgrade NuMI beam component

The main challenge in upgrading the neutrino target system for higher beam power is managing excess heat and thermal impulses from beam impacts. MARS simulations assess energy deposition, and FEA in ANSYS evaluates thermal stress and thermal distribution. If stress exceeds the material's yield stress, a cooling system is added. Radiation damage, which degrades material properties, is also a concern. Fermilab has extensive experience in predicting the lifetime of commonly used materials under sub-MW beam irradiation. This expertise must be extended to the MW scale to prepare for the LBNF, which will operate at up to 2.4 MW. To support this, the expected radiation damage is extrapolated and tested using the NuMI beam operation.

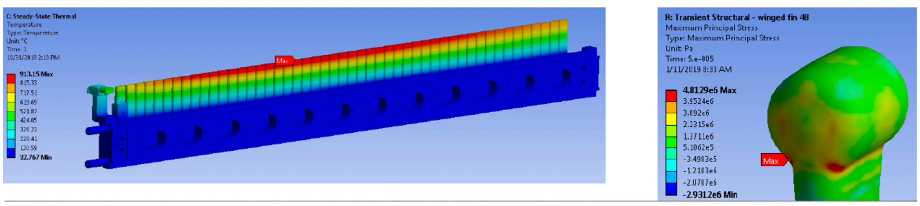

Figure 2: (Left) thermal distribution and (right) thermal distribution of the winged fin at accidental event.

PoS(ICHEP2024)231

Currently, we use graphite (ZXF-5Q) as the target material. The NOvA target consists of 48 segmented fins, totally 1.2 m in length, housing in a canister filled with atmospheric helium gas. To keep the maximum temperature below 1,000° C for graphite, several modifications were made for the 1-MW target. First, the RMS beam spot size was increased from 1.3 to 1.5 mm, leading to an increase in fin width from 7.4 to 9.0mm, based on the 6-sigma beam distribution. Second, the cooling power was increased by upgrading the water chiller. This improvement also ensures that the downstream Beryllium beam window below its critical temperature. Figure shows the estimated temperature distribution for 6.5×10^{13} POT. Additionally, winged fins were implemented on the first four fins, reducing the beam density of mis-steered beams by 10 %, which helps protect the upstream decay pipe window.

The 360-meter-long NuMI beamline transports a 120 GeV proton beam from the MI [2]. The beam is directed downward below ground level to aim the neutrino beam at the detectors. As a result, the proton beam is not circular on the target, with some vertical dispersion remaining. The first 50 meters of the beamline match the optics, followed by an 80-meter FODO cell. A Collins like optics design creates a 50-meter drift section, and the final focusing section is formed in the last 100 meters. Two beam optics options were investigated to enlarge the beam spot size at the target (Figure), with Option 2 selected for present operations due to reduced dispersion.

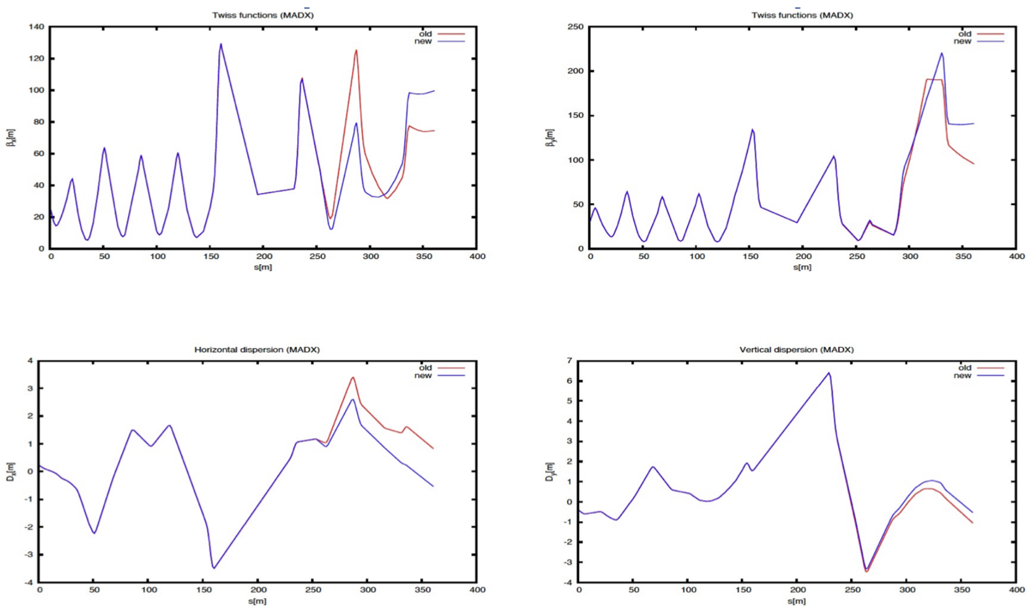

Figure 3: A red and blue curves are estimated Twiss values in the old and new optics, respectively.

References

[1] "Exploring the Focusing Mechanism of the NuMI Horn Magnet", K. Yonehara et al., arXiv:2305.08695, https://doi.org/10.48550/arXiv.2305.08695,

[2] "A Modular Optics Design for the NuMI beamline", J. Johnston, FERMILAB-TM-2174, https://lss.fnal.gov/archive/2002/tm/TM-2174.pdf.