PROCEEDINGS OF SCIENCE

# Megawatt upgrade of NuMI target system

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Fermilab operates the world's highest power neutrino target system, called the Neutrinos at the Main Injector (NuMI) to provide intense neutrino flux to the NuMI Off-axis $\nu_\mu$ Appearance (NOvA) near and far neutrino detectors to reveal mysterious property of neutrinos. We report a progress of the NuMI beam power upgrade plan at Fermilab to transport a 1-Mega Watt (MW) proton beam to the high power neutrino target. The latest beam power record is 870 kW in Fall 2021.

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## 1. Introduction

The Fermilab beam power upgrade plan had begun since 2012 after the collider program at Fermilab had been ended [1]. It is called the Proton Improvement Plan (PIP) for gaining a high statistic and low beam-related systematic uncertainty neutrino events for the neutrino experiments including NOvA and Booster Neutrino Beam (BNB), and providing a bright muon beam production for g-2 and Mu2e experiments. Figure 1 shows a schematic drawing of the Fermilab accelerator complex. Our first missions in PIP were refurbishing the old accelerator system which had never been major upgraded for over 40 years of operation, re-optimizing beam optics to increase the beam quality (intensity, stability and flexibility), and running a slip stacking in the Recycler Ring (RR). Especially, shifting the slip stacking process from the Main Injector (MI) to the RR was crucial to increase the proton beam power [2]. By this change, the MI can accelerating the beam while the RR runs the slip stacking. The beam repetition rate could be increased and the available beam power at the NuMI target system became almost double [3].

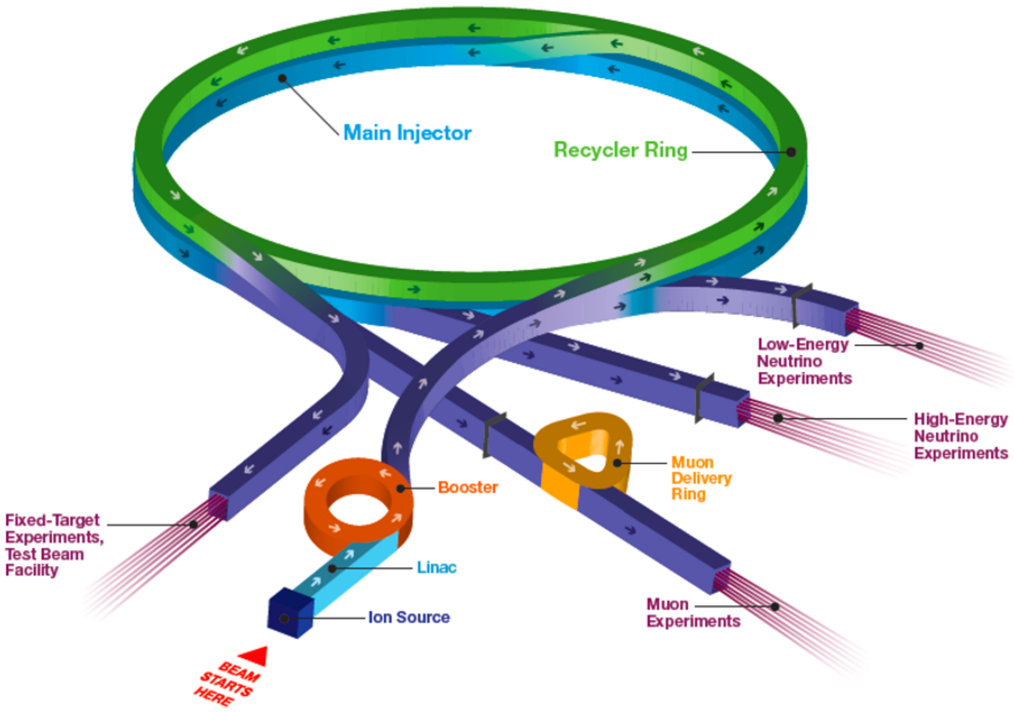


**Figure 1:** Layout of the Fermilab accelerator complex.

The PIP has been extended (PIP-I+) to achieve the beam power 900 kW at the target since 2017. The beam optics in the RR and MI were further optimized and were understood better than before. Compensating higher order resonance and space charge effect in the rings are particularly important to accelerate a multi-MW beam [4]. The Fermilab accelerator complex has gradually been improved to be ready for a 1-MW beam operation.



PoS(NuFact2021)107

## 2. Target system upgrade

The NOvA target operation had begun from 2014 and reached the operational beam power 700 kW at the target in 2016. The design study for the NOvA target system was published in 2017 to ramp up the tolerance of proton beam power 1-MW [5]. The new high power NOvA target has been installed in 2019 and the 1-MW horn system has been installed in 2020. Table 1 shows the designed target parameter.

| | Original design | NOvA | 1 MW upgrade |
|---|---|---|---|
| Primary proton momentum | 120 GeV/c | 120 GeV/c | 120 GeV/c |
| Design beam power at the target | 400 kW | 700 kW | 1 MW |
| Neutrino energy spectrum | Wide energy range | Medium Energy | Medium Energy |
| Operation year | 2003-2014 | 2014-2018 | 2019-present |
| Beam cycle time (s) | 1.87 | 1.33 | 1.2 |
| Protons on target per spill | $4.0\times10^{13}$ | $4.9\times10^{13}$ | $6.3\times10^{13}$ |
| Spot size (mm) | 1.0 | 1.3 | 1.5 |
| Spill pulse width | 10 $\mu$sec | 10 $\mu$sec | 10 $\mu$sec |

**Table 1:** Designed target parameter

### 2.1 Target core

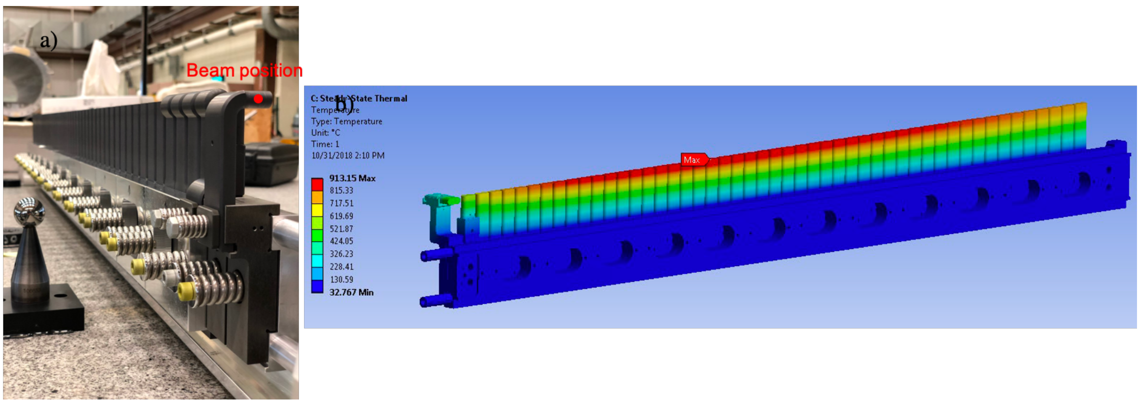


**Figure 2:** NOvA target core.

Figure 2 a) shows the target core for the 1-MW beam operation. The target core is made of carbon graphite. One of the biggest challenges for the high power target is to mitigate an instantaneous thermal shock on the target core when the beam impacts the target. Luckily, because the NOvA target is designed for medium energy neutrinos physics, the target core is located outside the horn system. It is less geometrical constraint which gives us an engineering advantage. For example, the NOvA target can be transversely larger than the old low neutrino energy target, and a thick cooling water pipe can be installed underneath the target core. The target consists of 2 Budal fins, 4 winged fins, and 44 normal fins. The net length of NOvA target is about 120 cm which is about two interaction lengths. First two fins are the Budal fin, which is used for finding a beam position at the target by observing the knocked-off electrons from the Budal fin. The four winged fins and the beam baffle which is located upstream of the Budal fin are used for protecting a downstream beam element, like a horn neck and a decay pipe window, etc from the mis-steered beam. The mis-steered beam, which does not strike the normal fin, will hit either the upstream baffle, or a winged part of the winged fin, or both. The beam density will be reduced by factor 9 by penetrating through four winged fins, or significantly reduced by the baffle. The designed beam spot size is big to mitigate the thermal shock for the MW upgrade. The fin width is also wide. The engineering study shows in Figure 2 b) the estimated peak temperature of the target core with a 1-MW beam. A highest temperature will be 913°C which is located around one-interaction length. By this change, the neutrino flux per proton will be reduced by a few percent.

The target core is located in the target can which is filled by an atmospheric pressure helium gas to avoid oxidation of carbon graphite. The downstream target beam window is heavily exposed by the secondary particles. In the past operation, the window was broken due to radiation damage. A new window for the 1-MW target is slightly wider than before and an electric blazing is used to attach the window on the flange to mitigate a radiation damage. Besides, a cooling water loop was installed near the window. We have monitored the flange temperature by using a thermocouple sensor during the beam operation.

### 2.2 Magnetic horn and air diverter

The NuMI target system has two magnetic focusing horns. An air diverter is installed on the horn 1 (the closest horn from the target) to cool down the stripline. Figure 3 shows a new air diverter. Air blows from top and bottom of the stripline to the flared part for cooling. Engineering study shows the estimated maximum temperature increment up to 140°C. We have monitored the ambient air temperature by using a thermocouple sensor.

Air penetration and stripline feedthrough in the shielding block are also a big challenge. One time, a small metal piece was fell a part and down into the stripline feedthough and touched the ground.

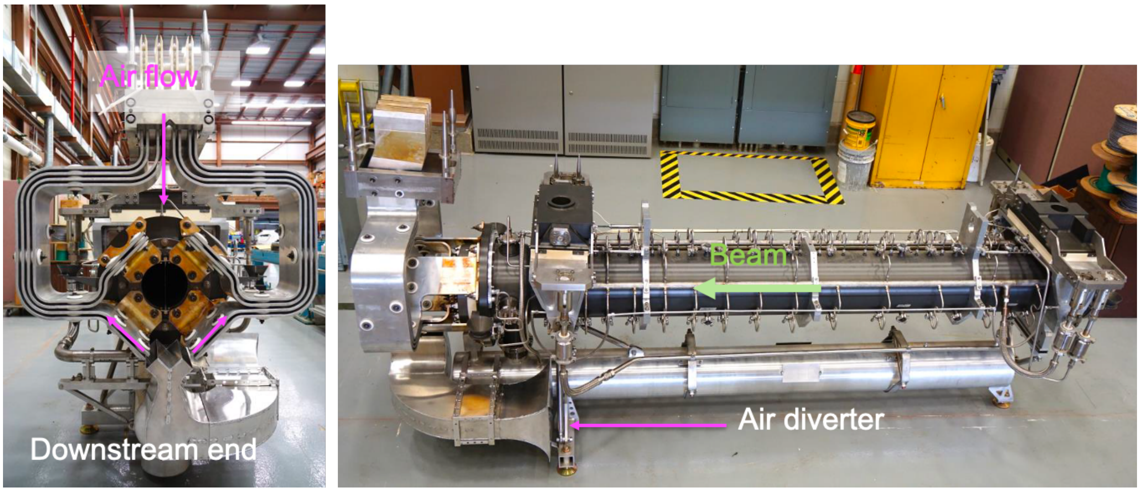


**Figure 3:** New stripline and air diverter.

### 2.3 Beam Monitor

Four-layer of pixeled ionization chambers downstream of a decay pipe in the NuMI target system are used for monitoring the neutrino beam quality. The first chamber, called the hadron monitor, closest to the target to monitor any kinds of charged particles from the target, is exposed by extremely high radiation. Therefore, the output signal of the monitor used to be degraded during the beam operation. The new hadron monitor is built in 2021 which is made of a radiation hardened signal cable and electrical feedthrough, and a high radiation tolerated ceramic insulator for the electrode. It is designed simpler than the past one which also makes the monitor more radiation robust. It has already been operated with 870 kW proton beams, but no signal degradation has been observed.

Phase space evolution of muons in the NuMI target system has been studied by using the last three ionization chambers, which is called the muon monitor. There is a different thickness of material in front of the muon monitor which range out most charged particle except for muons and the muons which reaches to the monitors are also selected by their energies. A Machine Learning (ML) algorithm is applied for the muon monitors which is trained by the 243 pixel signals with the primary beam parameters. The target system ML has demonstrated and the accuracy of prediction for the beam position at the target is less than 0.1 mm, and the horn current is 0.2 kA. It is particularly useful to monitor the target health because there is no in-situ target health sensor on the NOvA target system due to severe radiation environments. The target system ML also predicts the target density degradation within 1 % accuracy. Because the magnetic focusing horn has a chromaticity, we have tried to reconstruct the initial pion phase space from the pixel image from each monitor. To this end, we plan to train the target system ML with numerical simulations for predicting neutrino events in near and far detectors.

## 3. Acknowledgements

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