

1 MW BEAM POWER IN THE FERMILAB MAIN INJECTOR*

K. Hazelwood[†], P. Adamson, R. Ainsworth, B. Brown, D. Capista, K. Danison-Fieldhouse, C. Gonzalez-Ortiz, I. Kourbanis, D. Morris, M. Murphy, M. Olander, A. Schreckenberger, M. Wren, M. Xiao, M.-J. Yang
Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

In June 2024, the Fermilab Main Injector recorded its greatest one hour average beam power delivered to NuMI. The record 1.018 MW power was the culmination of years of work, involving upgrades to various systems to allow for greater beam intensity, better loss control and faster ramping of the machine. Following the record achievement, the Main Injector complex suffered a series of failures that have prevented NuMI beam. This paper will discuss the beam power record, Main Injector's recovery efforts, and plans for even higher beam power.

INTRODUCTION

The Fermilab accelerator complex, Fig. 1, begins with an H^- ion source. These 35 keV ions are accelerated to 400 MeV in a normal conducting linac. Upon injection into the Booster, charge stripping is used to remove electrons from the H^- ions, leaving only protons. The Booster, which operates on a 15 Hz sinusoidal resonant ramp, accelerates protons up to 8 GeV before delivering them to either the Recycler Ring (RR), for high energy neutrino experiments and the muon campus, or the Booster Neutrino Beam (BNB) experiments. For the high energy neutrino experiments, the Booster sends twelve batches into the Recycler at 8 GeV, where they are combined via slip-stacking in to six double-intensity batches before extraction to the Main Injector (MI). There, the beam is accelerated to 120 GeV and delivered to the Neutrinos at the Main Injector (NuMI) beamline.

BACKGROUND

The NuMI beamline was commissioned in late 2004 [1]. At the time, the primary focus of Fermilab was not neutrino physics but rather the Tevatron collider program. Proton beam had to be budgeted between creating neutrinos and antiproton production used in Tevatron stores. The Recycler Ring did not yet contribute to the neutrino program and instead was used for accumulating and cooling antiprotons between Tevatron collider stores. Proton beam for NuMI was injected directly into MI, accelerated and extracted. NuMI became the primary program once the Tevatron was turned off in September 2011 [2].

During the Accelerator NOvA Upgrade (ANU) shutdown from May 2012 until September 2013, the Recycler Ring was repurposed from an antiproton storage ring to a proton

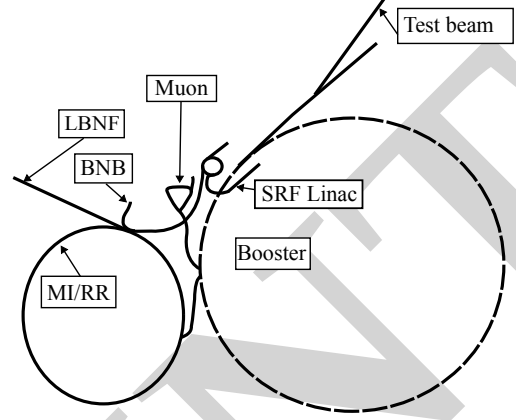


Figure 1: A schematic of the Fermilab Accelerator Complex along with experimental destinations.

stacker [3]. The design goal for the NOvA project was to deliver a 700 kW proton beam [4]. Before this shutdown, the maximum power delivered was 400 kW by slip-stacking in the MI. The beam power, P is defined in Eq. (1); where N is the number of protons per pulse, E is the energy of the protons in eV and T is the time between pulses.

$$P = \frac{NE}{T} \quad (1)$$

Moving the slip-stacking process from Main Injector to the Recycler Ring such that the RR and MI cycles could be overlapped increased MI beam power at 120 GeV by reducing the cycle length.

RECENT IMPROVEMENTS

There has been steady improvement in beam power and integrated protons on target (POT) to the NuMI experiments since 2013 [5–7] (Fig. 2). More recently, the increase in beam power has primarily come from moderate increases in beam intensity, improved loss control, and faster beam cycle times.

Beam Intensity, Efficiency and Loss

Since 2018, Main Injector and Recycler have had an average NuMI beam pulse transmission efficiency of 97.2 % and 98.3 %, respectively. Despite increasing beam intensities, both machines have been able to maintain a fairly constant normalized beam loss monitor BLM sum of 17 mrad/protons (E12) delivered to NuMI (Fig. 3).

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[†] kjh@fnal.gov

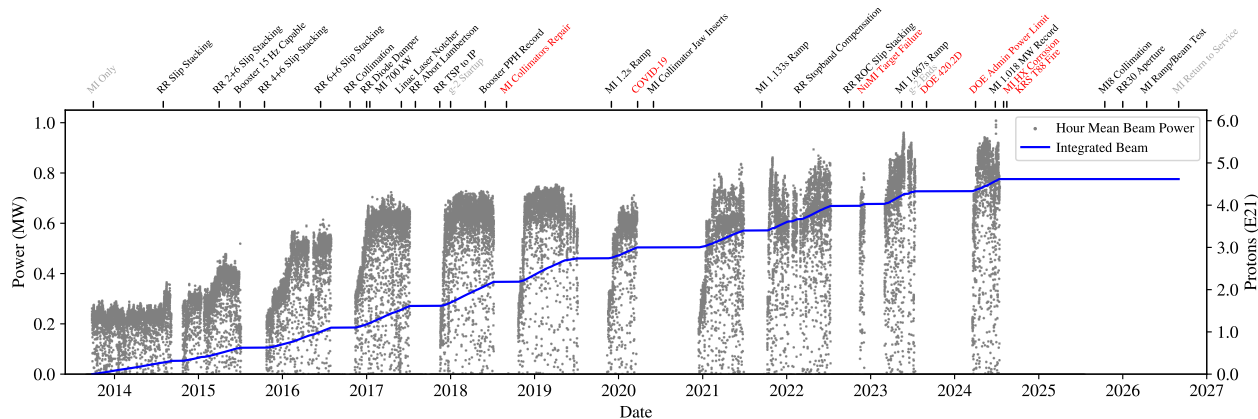


Figure 2: MI beam power since ANU upgrade showing significant events.

Main Injector tunnel enclosure residual dose rates have improved in recent years. As shown in Fig. 4, Main Injector collimator losses have been significantly reduced. This is the result of adding MI collimator jaw taper inserts in 2020 and the implementation of Recycler radial off-center (ROC) slip-stacking in 2022 [7]. Recycler machine activation has also been significantly reduced in areas where aperture upgrades have been done (locations 402, 230-307) [7]. The addition of normal and skew sextupole circuits in Recycler have helped to compensate for resonance stopbands and decreased beam losses [8].

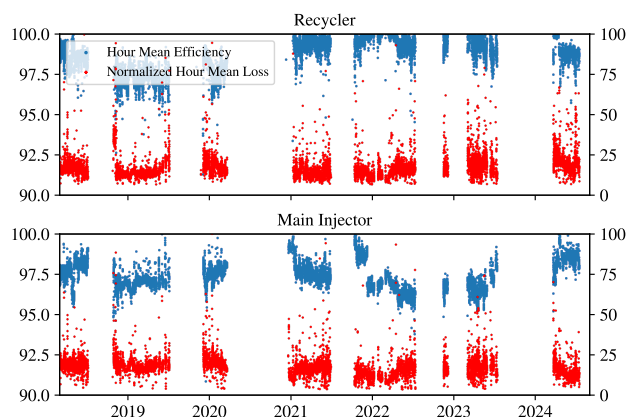


Figure 3: MI and RR beam efficiency and loss performance since 2018.

Main Injector Ramp Time Minimization

One of the greatest improvements to MI beam power has been the effort over many years to optimize the MI main bend and quad power supply (PS) ramps. Decreasing the ramp time allows for more frequent NuMI beam pulses and also allows for more flexibility budgeting timeline space for other experiments, such as BNB, SY120, or Muon experiments.

Following the ANU upgrade, the Main Injector was capable of ramping once every 1.333 s. For the first few years after ANU, the primary means of increasing beam power came from increased Booster batch intensity (Fig. 5). In 2019, the first significant improvement to the MI ramp time was demonstrated. The ramp time was decreased from 1.333 s

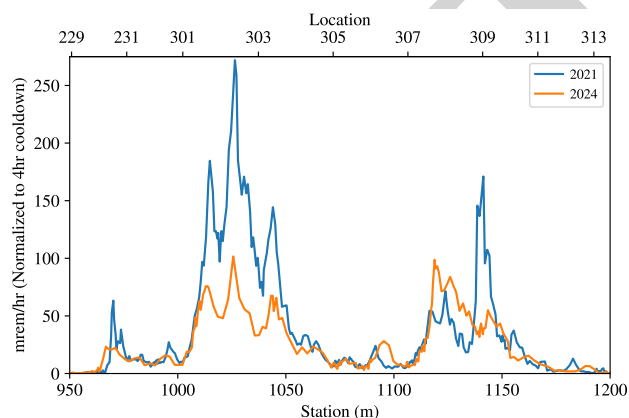


Figure 4: MI collimation region residual dose rate comparison before and after ROC slip stacking update. Survey data is taken using the DALE instrument, an automated tunnel environment logging device [9]. Residual dose rates have been normalized to levels at 4 hours after beam has been turned off.

to 1.2 s by removing dwell time from both the start and end of the ramp (Fig. 6).

After the 1.2 s ramp was established, work began immediately toward further ramp time reductions. The next benchmark was 1.133 s. To achieve 1.133 s, the MI 120 GeV flat-top time was shortened, which required coordination with the neutrino experiments. The NuMI horn PS ramp tracks the MI momentum curve, and work had to be done to ensure there were not timing and slew rate concerns. All future ramp improvements still require this careful consideration of the NuMI horn and extraction-element PS. The largest change to the ramp for 1.133 s came from decreasing the 8 GeV hysteresis ramp at the end of the cycle (Fig. 6).

Since the commissioning of the Main Injector, the ramp has had a 8 GeV hysteresis reset ramp at the end of cycle. During the collider era, the Main Injector was used to accelerate both protons and antiprotons to 150 GeV, the injection energy of the Tevatron. From past magnet measurement documents [10, 11], the magnitude of the reset ramp was intended to return MI fields from 150 GeV. The amount of reset current needed to maintain consistent 8 GeV fields

between adjacent 120 GeV was believed to be less. Different levels of reset current were experimented. Ultimately, half the reset current was found to be sufficient. Little difference in 8 GeV field between 120 GeV ramps was seen, and the injected beam did not show appreciative effects from the field difference.

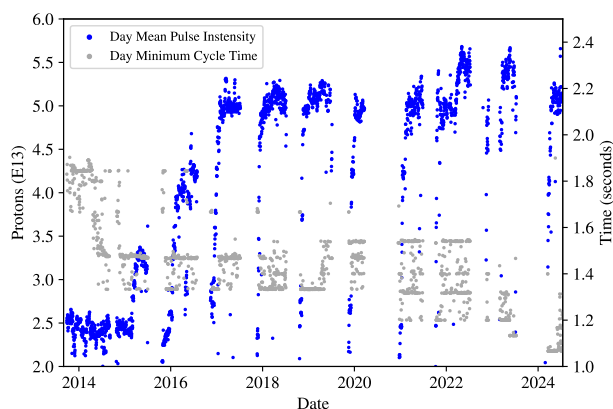


Figure 5: Main Injector daily mean pulse intensity and minimum cycle time to NuMI.

The current MI ramp time of 1.067 s was achieved by further decreasing the flattop time, increasing the down ramp rate, and most significantly, eliminating the reset ramp altogether (Fig. 6). Removing the reset ramp does affect 8 GeV magnetic fields; however it is most pronounced after resuming ramping and following pauses in the timeline. Subsequent pulses do not suffer from the lack of the reset ramp, and the increase in beam power outweighs the temporarily slightly-poorer beam quality. Importantly, this ramp began to push the limits of the existing MI quad and bend bus PS. Thermal scans revealed that the main quad supplies, originally from the Main Ring accelerator and re-purposed for the MI, needed additional water cooling for its resistors. The MI ramp is now limited on the up ramp by the amount of RF gradient that MI has, approximately 240 GeV/s. The down ramp is limited by the bend and quad PS maximum voltage, approximately 1 kV.

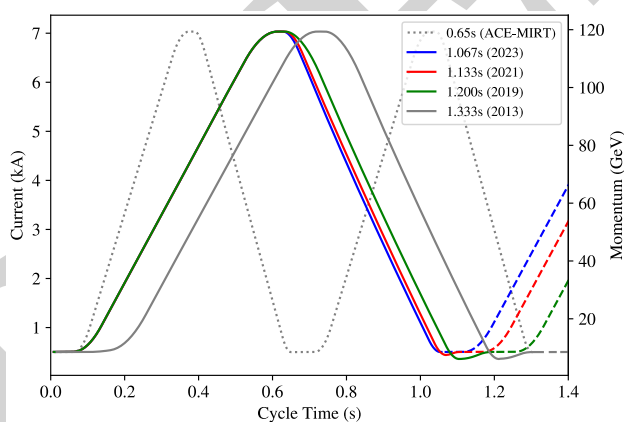


Figure 6: MI bend bus ramp waveform comparisons.

1 MW RECORD

On June 26, 2024, Fermilab was given permission to temporarily lift an administrative beam power limit put in place while new tritium mitigation processes were being reviewed at the lab, so that 1 MW operations could be demonstrated. This study was critical to test modifications made to the PS and to inform what else was needed to pursue even higher beam power for LBNF in the future. The study was given 8 hrs to attempt the record.

The Main Injector low conductivity water (LCW) heat exchanges with ponds that ring the accelerator. In June, the pond water temperature is routinely above 80 °F, near the temperature when the LCW is no longer able to regulate at its operational setpoint of 90 °F. For this reason, the study was started early in the morning while pond and service building temperatures were at their lowest. Staff were strategically positioned around the 3+ km circumference complex, such that if a component should trip, it could be recovered as soon as possible.

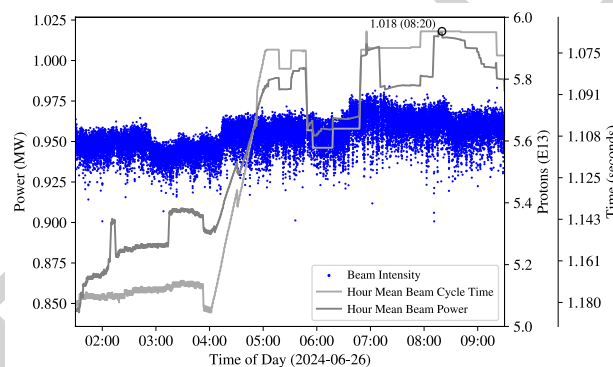


Figure 7: One hour mean MI beam power record.

In order to achieve greater than 1 MW beam power averaged over an hour, the machine must provide a beam pulse to NuMI every 1.067 s at an average of 5.6 E13 protons per pulse. Given normal beam transmission efficiencies in the 8 GeV (MI8) beamline, Recycler Ring, and Main Injector, Booster batch intensity must average no less than 5 E12 protons.



Figure 8: Picture taken shortly after achieving the record.

The study was a great success. The machine operated well, and the record of 1.018 MW was achieved after a few hours of tuning to ensure beam losses and efficiencies were

acceptable (Figs. 7, 8). The MI is capable of sustained 1 MW operations; this was the planned beam power after the summer 2024 maintenance shutdown.

POST RECORD SETBACKS

After the excitement of finally demonstrating 1 MW beam operations, the Main Injector accelerator complex suffered some significant setbacks that have paused the NuMI program while repairs were made.

KRS T88 Transformer Fire

Late on the evening of August 3, 2024, a fire broke out on Kautz Road Substation (KRS) 345|13.8 kV transformer T88; the transformer that powers beamline PS, MI sextupole PS, and Main Injector and Recycler Ring RF anode and bias PS. While the loss of one transformer may have allowed MI to continue operating, albeit at lesser capacity. The cause of the fire was determined to be a defect in the transformer bushings. Unfortunately, after inspections, another KRS transformer, T87, was also discovered to have suspect bushings. It was removed from service pending repairs. A third non-pulsed power KRS transformer, T85, was found to have a non-related issue and was also removed from service. After the investigation completed, Main Injector had only one pulsed transformer found fit for service to power the entire accelerator complex downstream of Booster.

There exists a back-feed from the Fermilab Master Substation (MSS), the original substation servicing all of the lab except the Main Injector Campus. Unfortunately, two transformers at MSS were also found to have the defective bushings and were taken out of service. Near the same time, construction work elsewhere onsite inadvertently damaged the feeder bank that carries the back-feed feeder cables. The repair of this back-feed just recently finished. The repair of the MSS and KRS transformer bushings is scheduled to take place this summer. Replacement of T88 will occur during the long shutdown. Once the transformer bushing repairs are complete, Main Injector will have sufficient electrical power to resume full beam operations.

Heat Exchanger Corrosion

Shortly after turning off the Main Injector complex for the 2024 summer shutdown, significant corrosion was discovered on 9 of the 11 heat exchangers that cool the LCW for the Main Injector complex magnets, RF, and the BNB and P1 beamlines. The corrosion was significant enough that the heat exchangers were no longer fit for service (FFS) [12]. This begun a year-long process of determining the cause, mitigation, and repair to restore Main Injector LCW cooling.

The most significant heat load, the MI itself, was off due to the KRS transformer failure. However, there was still the need to cool the Recycler, and the BNB beamline to support Muon campus commissioning and Booster neutrino experiments BooNE. A significant portion of the MI LCW valves were reconfigured such that the one FFS heat exchanger at MI30 could be used to transfer cooling water nearly 1 km

away to BNB. Later, additional valve configurations isolating many of the MI magnet secondary headers allowed the critical loads ring-wide for Recycler to resume operation as well. In all, hundreds of valves were manipulated, flows and temperatures monitored, and IR imaging taken to ensure cooling was provided [13].

Analysis of the heat exchanger end channels indicated that the corrosion was caused by a combination of galvanic and microbial-influenced corrosion (MIC) [12]. The tube shell portions of the heat exchangers were found to be sufficient and had many years of service remaining. It was decided that the best course of action was to cut off and replace the carbon steel channels on either end of each heat exchanger [13]. In the summer of 2025, 10 heat exchangers were repaired. An additional heat exchanger at MI8, made of stainless steel, was found to be corroded beyond repair, and a replacement was purchased and installed. By fall 2025, the complete MI LCW system had been restored to normal. Additional measures and monitoring are being investigated to protect the heat exchangers from future corrosion. Possible future alternative methods of cooling that do not rely on pond water are also being investigated.

MAIN INJECTOR RECOVERY

In April, the Main Injector ramped and ran beam again for the first time since shutting off for what was thought at the time to be a routine summer maintenance period in 2024. After a typical 2 – 3 month summer shutdown, it is common for dozens of issues to arise at turn-on. After 20 months of not operating, experts wanted to know the extent of the issues well before operations resumed so that they had sufficient time and personnel to address them.

Despite not having sufficient electrical power to operate, the Main Injector has been continuously inspected and maintained so that it remains fit for service. For example, in that time, eight magnets in the MI enclosure were discovered either faulted or leaking and had to be replaced. Of these, two were Main Injector dipoles. MI dipole magnets had never been replaced in tunnel before. Procedures had to be resurrected, updated, reviewed and trained on to allow for swapping the 20 ton magnets with spares.

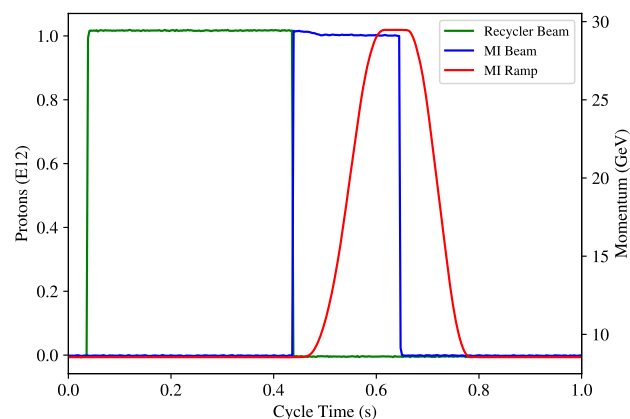


Figure 9: MI ramp and beam test performed in April 2026.

The limited ramp and beam test took a large amount of preparation and planning. The 18 13.8|1 kV MI bend and quad bus PS service building yard transformers had to be inspected. The Main Injector had never been ran from one pulsed transformer at KRS. Power distribution was altered such that the yard transformers were powered from the one pulsed transformer and warmed so that their oil could be sampled and conditioned before any load current was requested. Due to the non-standard power distribution, alternative group lock out, tag out (LOTO) procedures had to be drafted and trained on to allow personnel continued access to the tunnel during this time. Experts had to analyze and measure the power draw of each component power supply and machine utility, including many loads not associated with the MI accelerator, but also powered from T86. This was done to verify the load on T86 would not exceed conservative RMS and peak power and current limits [14]. Special Main Injector bend and quad bus ramps had to be created such that enough current was requested to properly test all the MI power supplies but not draw any more current than needed.

Once the ramp was established, beam was ran to test instrumentation and familiarize operators, many of whom had never operated the Main Injector, with running the machine. During the test, many issues were discovered. However, after a couple weeks of addressing problems and tuning, low intensity beam was successfully transmitted from Recycler to Main Injector, accelerated to 30 GeV, and extracted to the MI abort dump at reasonable efficiencies and beam losses (Fig. 9). Many items will need to be addressed before startup in September 2026. This test helps ensure that Main Injector will be ready after the KRS transformer repairs are completed.

FUTURE IMPROVEMENTS

Second Generation MI8 Transverse Collimation

An additional transverse beam collimation system has been installed in the 8 GeV beamline (MI8). This system has significantly more capacity to remove unwanted beam halo and tails originating from Booster than the current system and should help control beam losses in Recycler Ring starting this fall [15, 16].

PIP-II Project

The PIP-II project is replacing the current 1960's era 400 MeV Linac with a new SRF Linac capable of 800 MeV. Part of the project is to also retrofit the Booster from a 15 Hz to a 20 Hz resonant synchrotron. The maximum Booster batch intensity is expected to increase from 5 E12 protons to 6.5 E12 protons [17].

In Main Injector, the PIP-II project is increasing the MI RF power by adding a second power amplifier to each of the twenty existing cavities [18]. The increased RF power will offset beam loading from the increased beam intensity while ramping. PIP-II will also install a new gamma-t jump system in the MI to help reduce transition crossing losses.

The system will consist of four locations each with four high current and fast pulsing quadrupole magnets [19].

1.05 s Ramp

Current MI ramp cycle times are designed in 15 Hz multiples to align with Booster extractions and to best optimize the beam cycle timeline. When PIP-II converts Booster to a 20 Hz machine, the MI ramp time must either speed up to 1.05 s or accept idle time to best fit into the timeline. There may be further optimization possible in the ramp start and end parabolas, or the peak parabolas or flattop time. Further investigation will take place after the MI resumes operations.

ACE-MIRT Upgrade

The Accelerator Complex Evolution and Main Injector Ramp and Targetry project is a proposed effort to further increase MI beam power by achieving a combination of the following (Fig. 10) [20, 21]:

1. Shortening of the MI cycle time to 0.65 s, requiring power supply and power distribution upgrades and additional RF (Fig. 6).
2. Increasing the MI beam pulse intensity and designing LBNF targets capable of handling 2+ MW.
3. Improving overall accelerator efficiency by beam loss mitigation and enhancements of reliability.

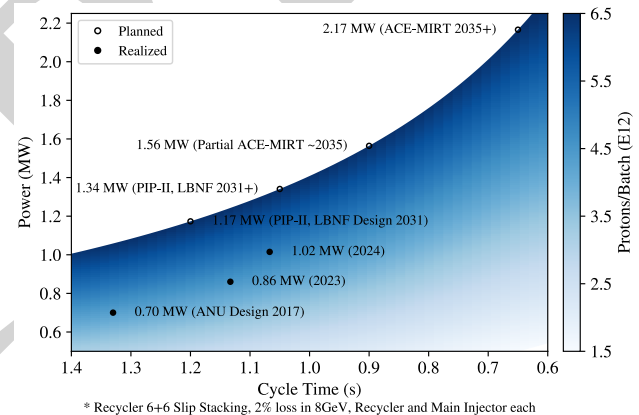


Figure 10: MI beam power for a given cycle time and batch intensity.

CONCLUSION

The 1 MW sustained beam power demonstration was an important milestone in the Fermilab Main Injector's pursuit of ever more beam power for our neutrino science programs. The KRS transformer and MI heat exchanger failures have highlighted the need for increased attention and resources to address our aging infrastructure. Despite the setbacks, MI is on track to resume operations this fall. The PIP-II, LBNF and proposed MI ACE-MIRT upgrade promise even higher beam power in the future.

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