# Recent Progress in High Intensity Operation of the Fermilab Accelerator Complex

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NAPAC

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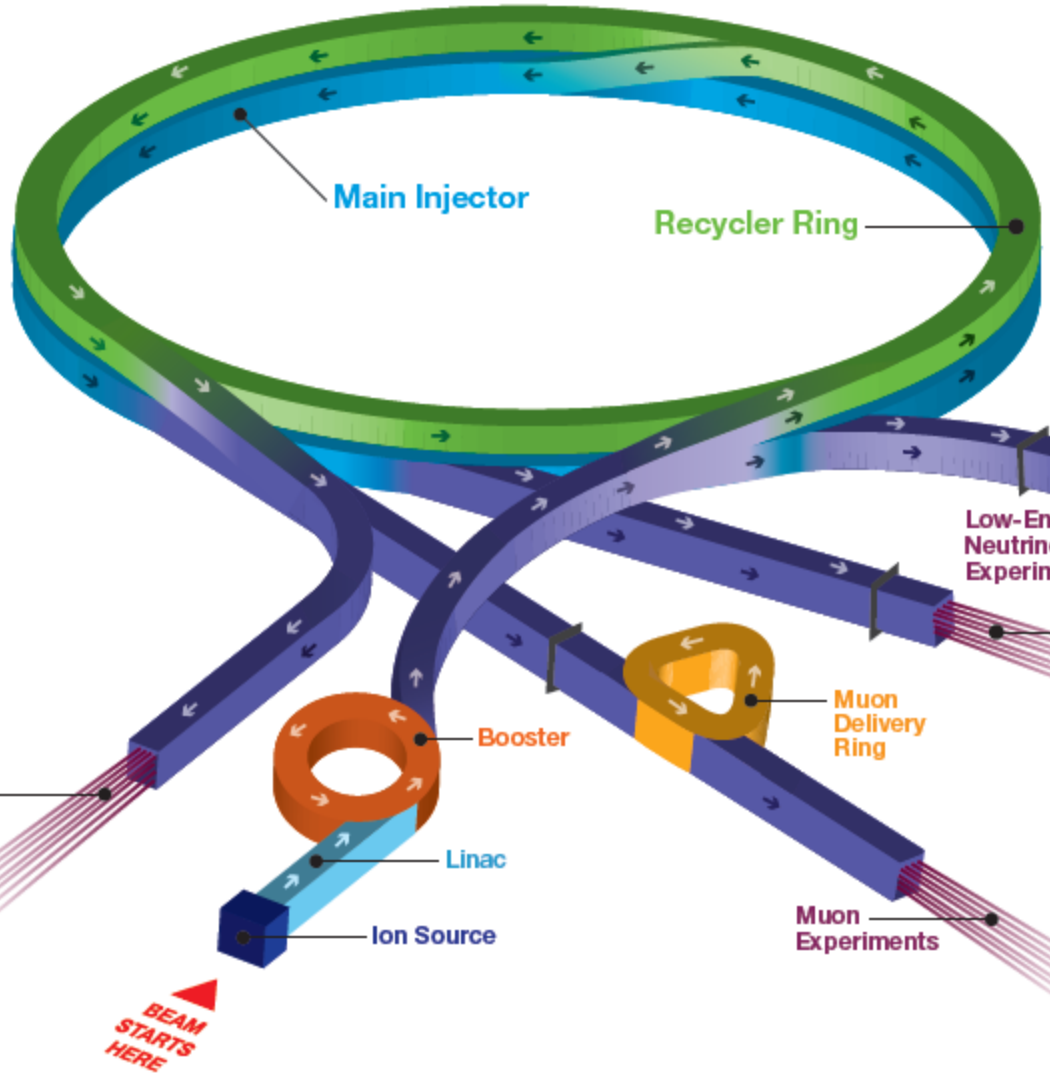
# Fermilab Accelerator Complex




Short Baseline Neutrino: MicroBooNE (ICARUS, SBND)

SwitchYard 120: SeaQuest, LArIAT, test beam

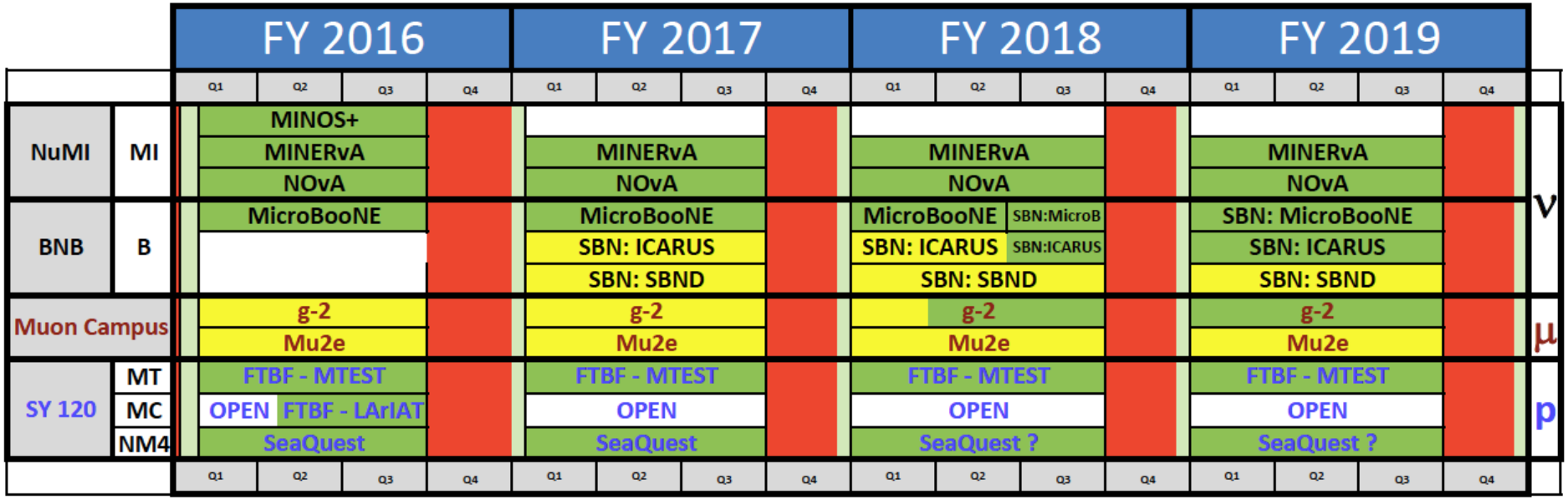
Long Baseline Neutrino: NOvA, MINERvA (LBNF/DUNE)

Muon Campus: (g-2, Mu2e)



Fermilab

# Fermilab Experiments' Run Schedule



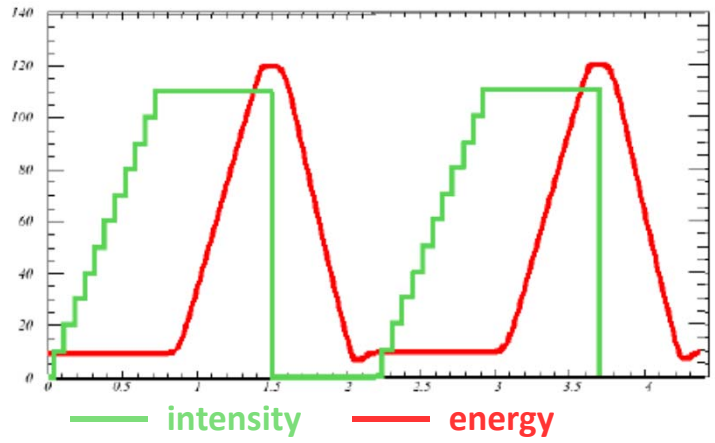

| | |
|---|---|
| RUN / DATA | Length of mid-year maintenance shutdowns for FY16 and beyond under discussion |
| STARTUP/COMMISSIONING | Transition from SeaQuest to Polarized-DY under consideration |
| INSTALLATION/COMMISSIONING | MINOS+ runs through FY16 and is then completed. |
| M&D (SHUTDOWN) | g-2 hope to get some data during the commissioning period in FY17, just before the summer shu |

# Accelerator Operations Goals

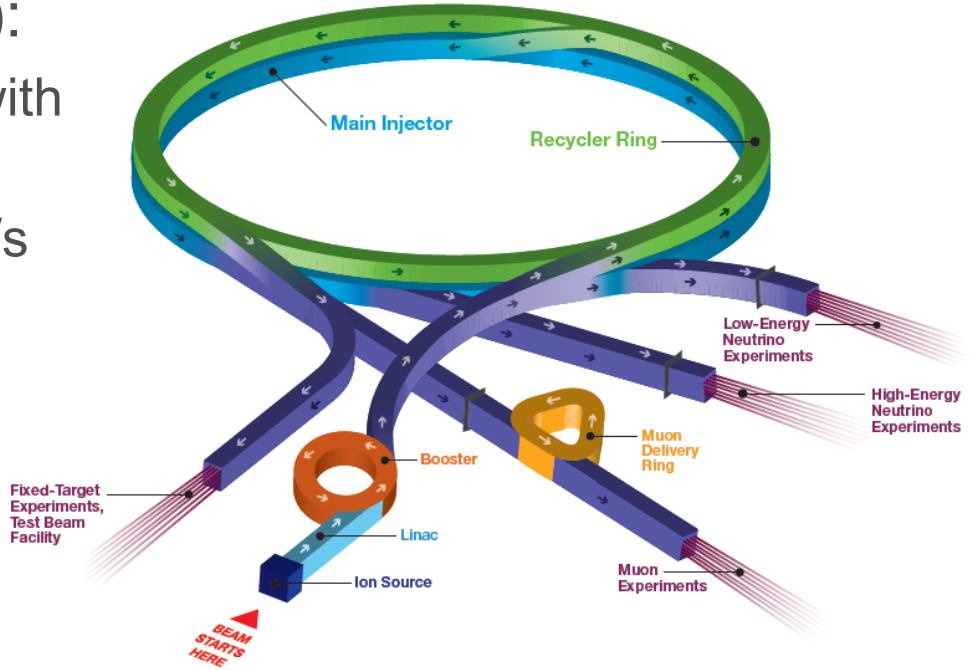
- 700 kW beam power to NOvA (world record for $\nu$ production)
- Higher proton flux in the Booster (>$2 \times 10^{17}$ protons/hour) to support full experimental program
- Complete the Muon Campus construction in 2017, then start to commission and operate beam to the g-2 experiment
- Build an upgraded horn and power supply in the Booster Neutrino Beam target station for Short Baseline Neutrino

# Neutrino Beam from Main Injector (NuMI)

- Previous operation (320 kW):
  - 11 batches into Main Injector with RF slip-stacking
  - Ramp to 120 GeV at 204 GeV/s and extract to NuMI target
  - 3.7e13 / 2.2 s cycle → 323 kW




  - Recycler used for storing antiprotons for the Tevatron




Main Injector:

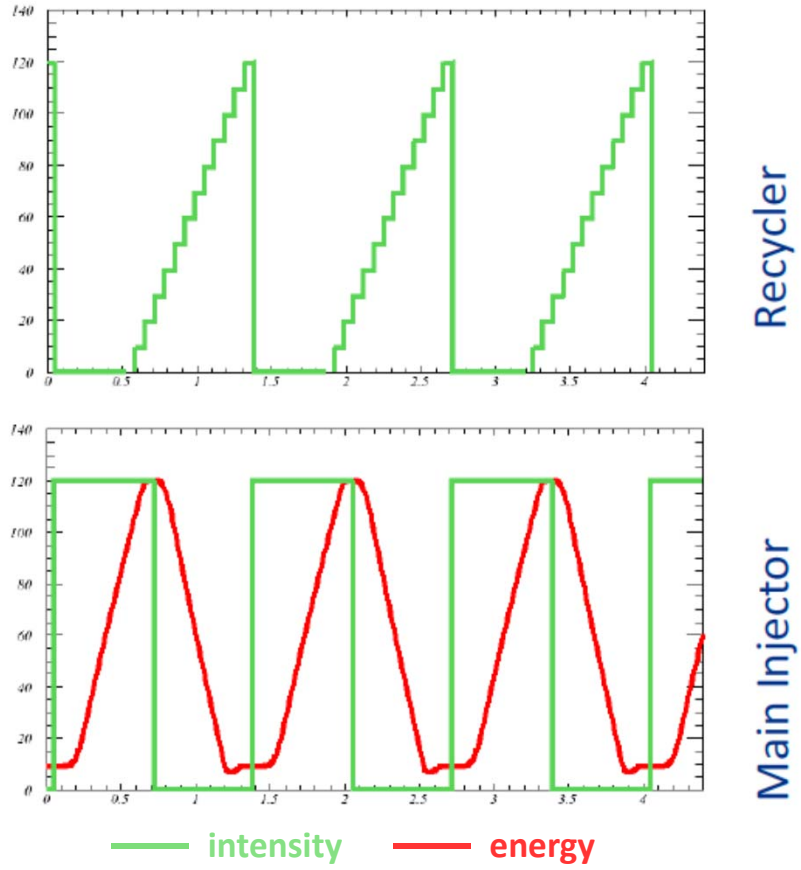
Accelerates 8 → 120 GeV (150 GeV for Tevatron)

Recycler:

Fixed 8 GeV KE ring

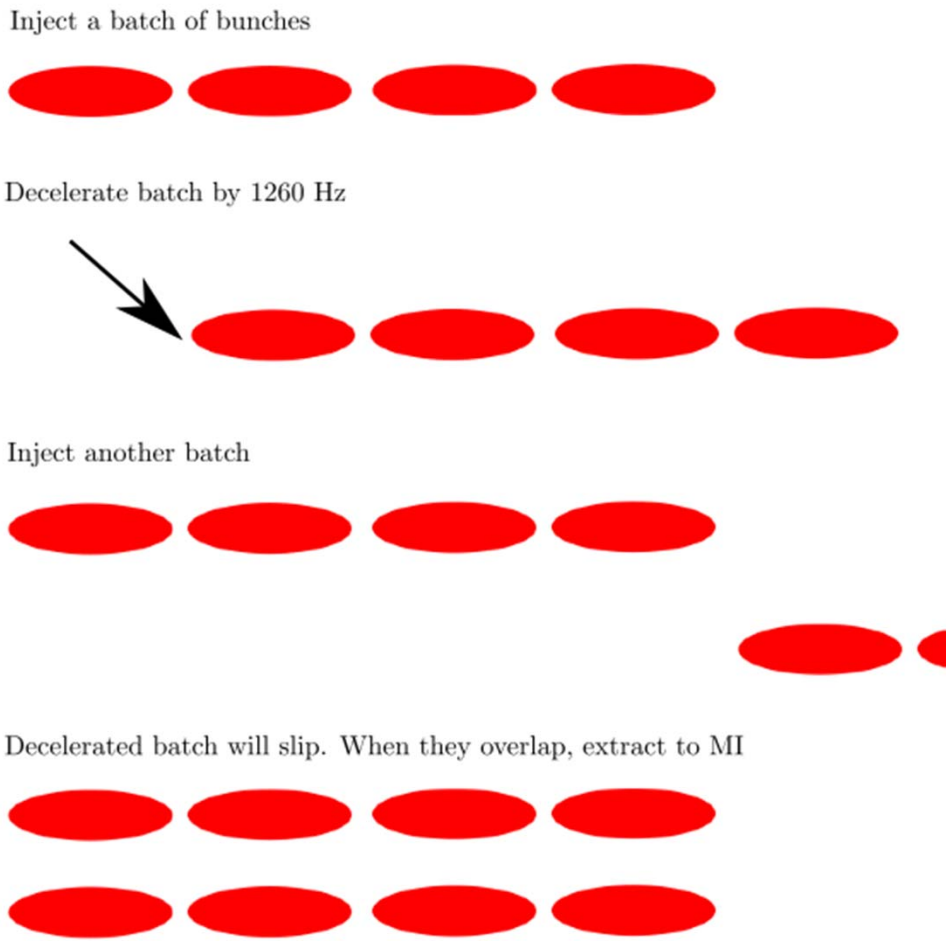
# Increasing Beam Power to 700 kW

- Moved slip-stacking to Recycler
- Increased number of batches 11→12
- Increased Main Injector ramp rate
  - 204 GeV/s → 240 GeV/s
- 1.33s cycle
- Can reach 700 kW with only ~10% increase in per-pulse intensity



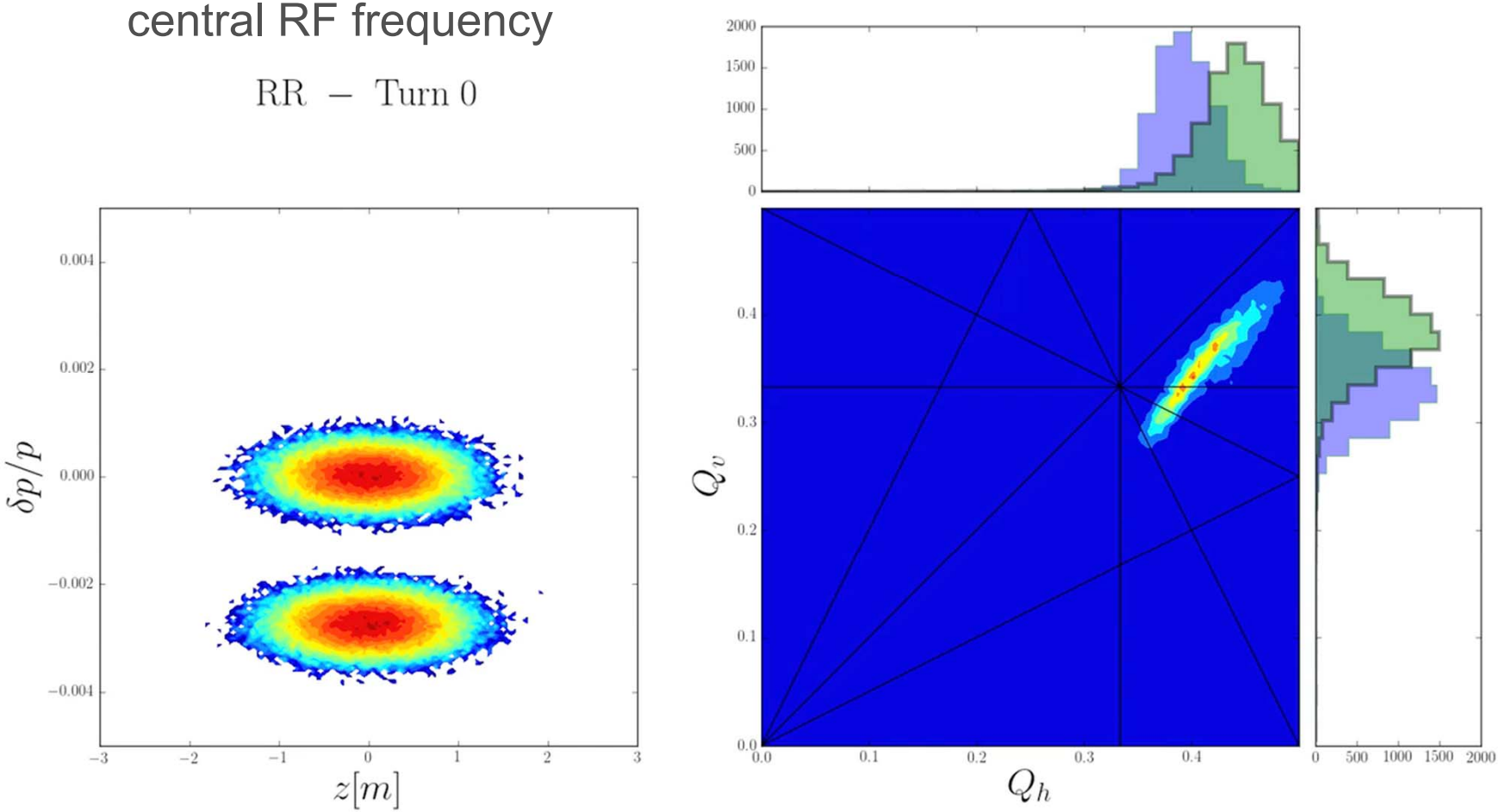
# Slip-stacking

- Double intensity of bunches using RF slip-stacking



# Challenges at High Intensity

- Space charge tune shift when bunches overlap
- Run at high chromaticity to avoid resistive wall instability
  - Leads to tune shift between decelerated bunches and those on the central RF frequency

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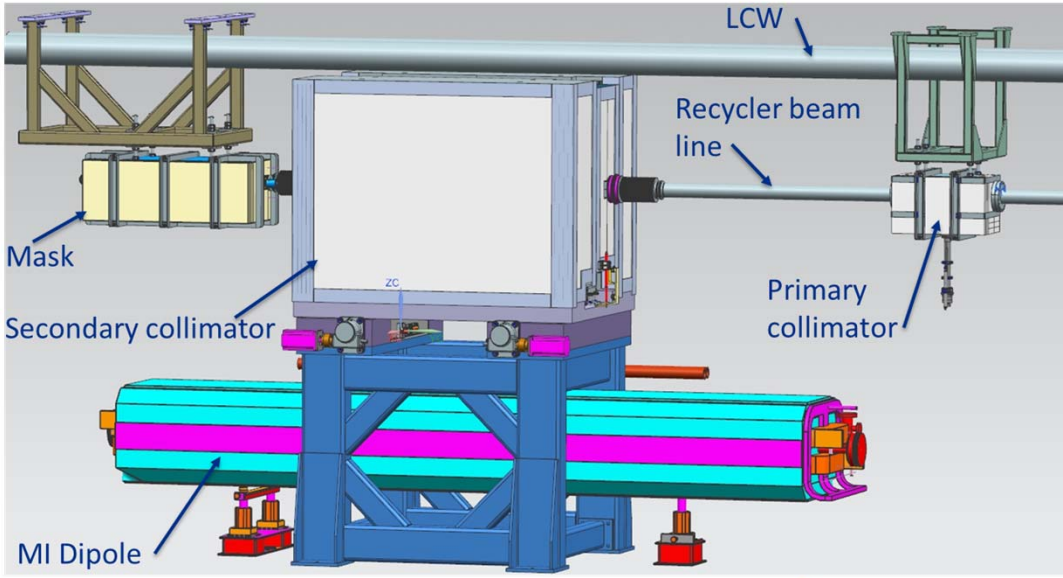
# Other Requirements for 700 kW Beam to NuMI

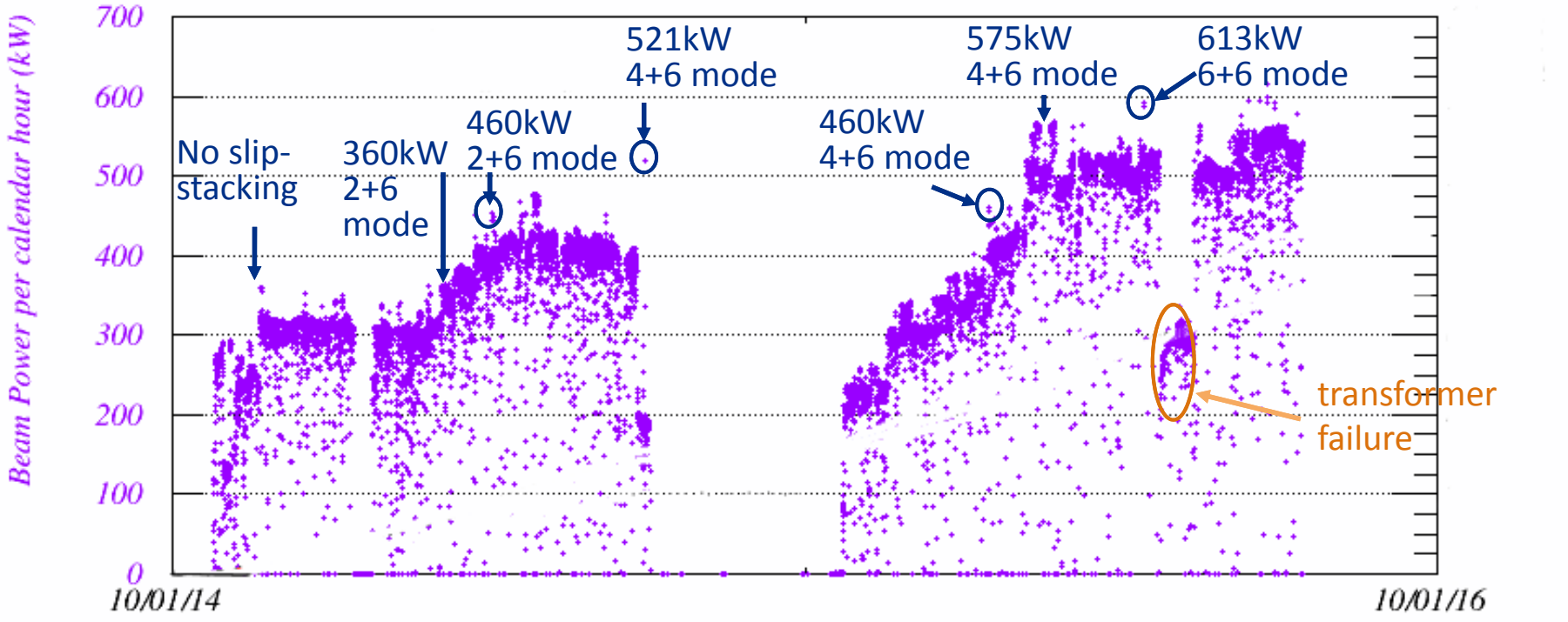
- Beam from Booster at 9 Hz (15 Hz to support full program)
- Reliability improvements
  - Recycler vacuum upgrade: replacing depleted titanium sublimation pumps with ion pumps – better suited for new mode
  - Corrosion resistant beampipe in high radiation areas
- Maintain high efficiency and control losses
  - Collimators in Recycler to capture losses that would otherwise irradiate limited-aperture injection and extraction magnets



# Collimators Installed during Shutdown

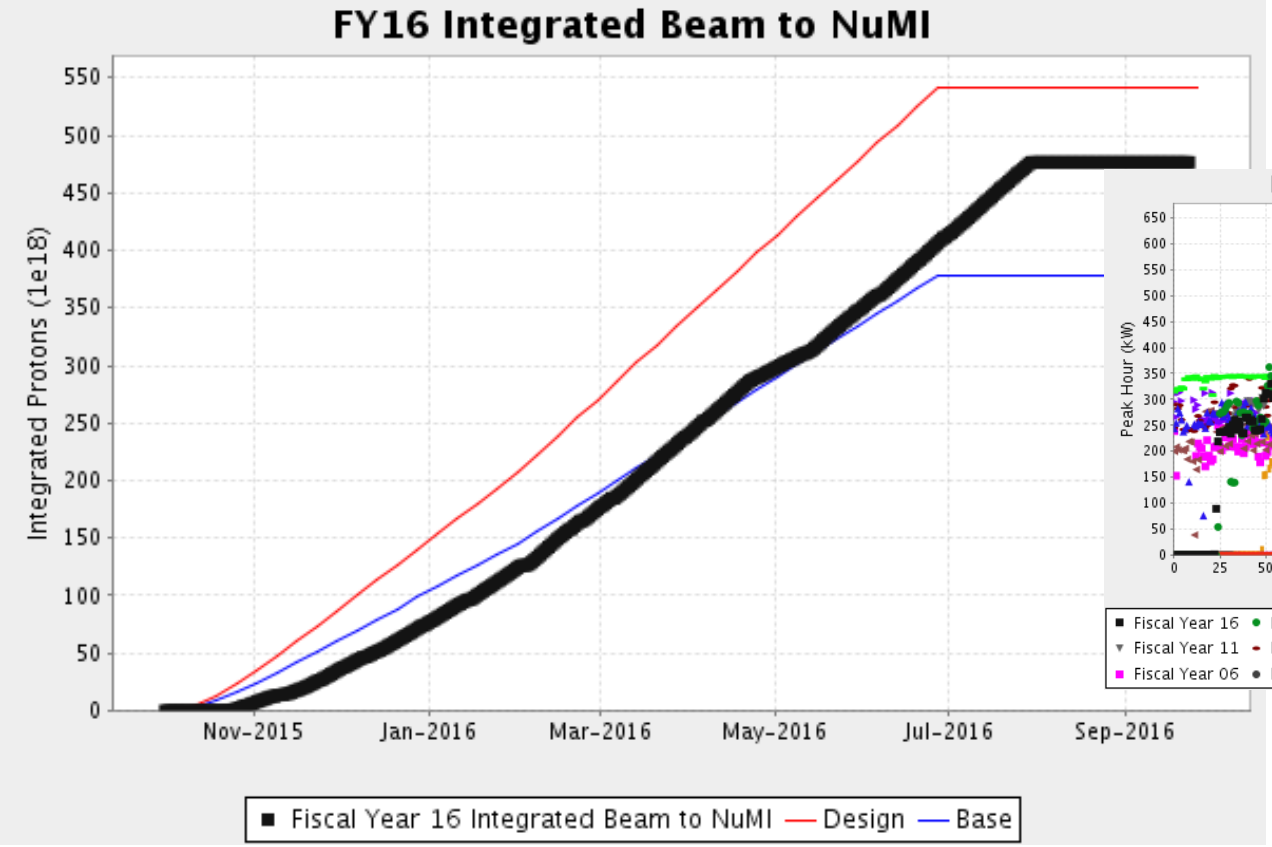
# Ramping up Beam Power to 700 kW for NOvA

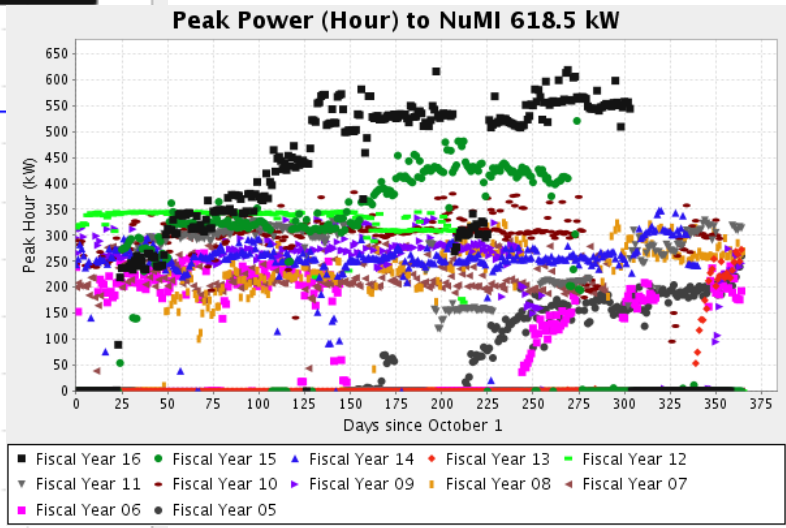
- (Note that SY120 takes 10% of timeline, 700 kW → 630 kW)




- Increase number of batches slip-stacked in Recycler in steps
- At each step, increase intensity while tuning for efficiency, losses
- Successfully demonstrated 700 kW for one cycle
- Regular 700 kW operation after this shutdown

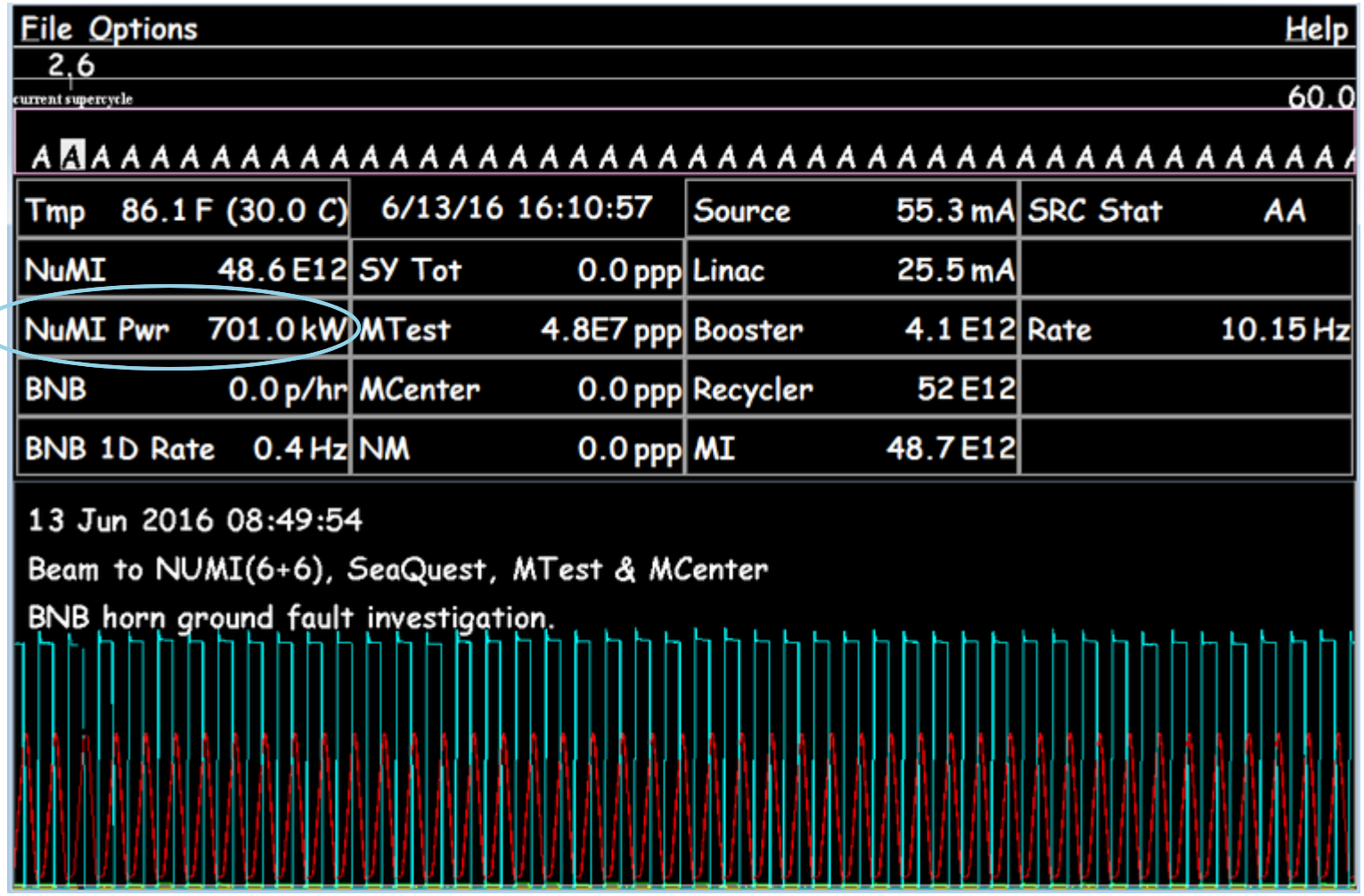
# Achieved FY16 Goals for Beam to NuMI



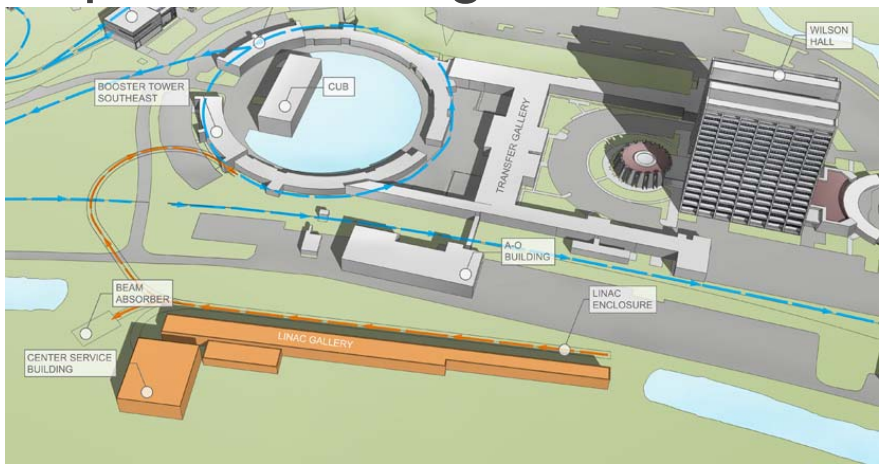

- Based on milestones for achieving 700 kW beam power
- Ran consistently at 550 kW (w/ SY120) prior to shutdown, make last ~10% push once collimators installed

# 700 kW Beam to NuMI



# Beyond 700 kW

- Plan for the next year is to run reliably at 700 kW
- PIP-II Project aims to provide >1 MW starting in 2025 with new 800-MeV superconducting Linac



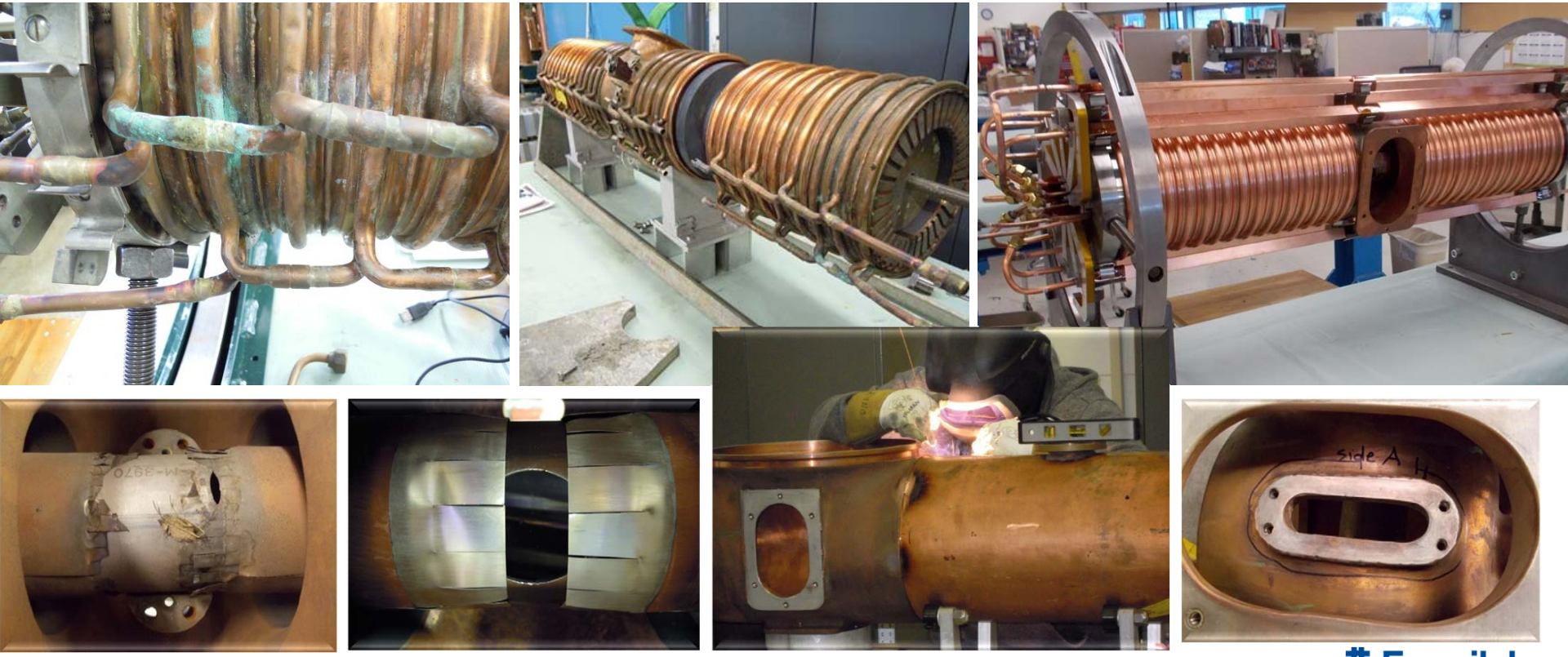

- In the meantime, beam power could be increased by
  - Increasing Booster batch intensity (increases losses)
  - Shortening MI ramp for ~1.2s cycle and increasing Booster rep rate from 15 Hz to 20 Hz (requires new Booster RF systems)

# Proton Improvement Plan

- Multi-year campaign funded through accelerator operations
- Includes RF upgrades, instrumentation and beam physics improvements, utilities…
- Initiated in 2011; ~60% complete
- Goals:
  - Increase the beam repetition rate from ~7 Hz to 15 Hz
  - Increase the proton source throughput, with a goal of reaching > $2 \times 10^{17}$ protons/hour (from $1.1 \times 10^{17}$)
  - Eliminate major vulnerabilities and maintain reliability (>85%) at the increased repetition rate / flux
  - Ensure a useful operating life of the proton source through at least 2025 – later changed to 2030

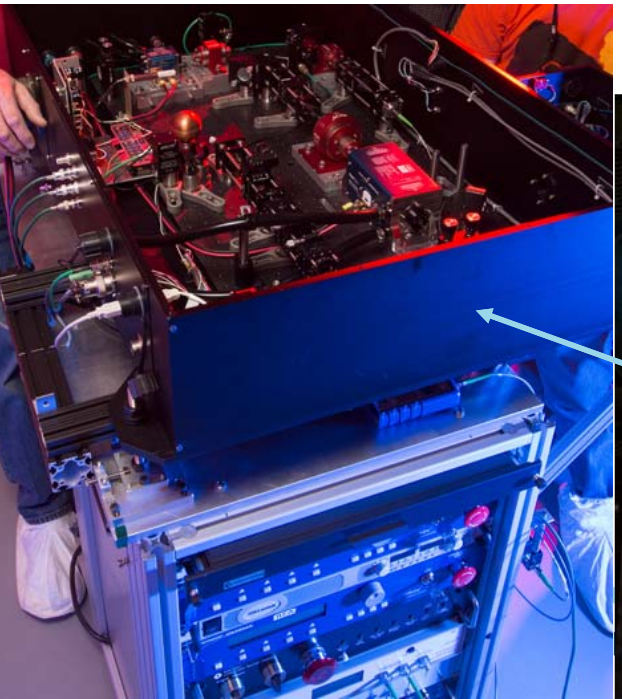
# PIP Highlights – RF Cavity Refurbishment and New Tuners

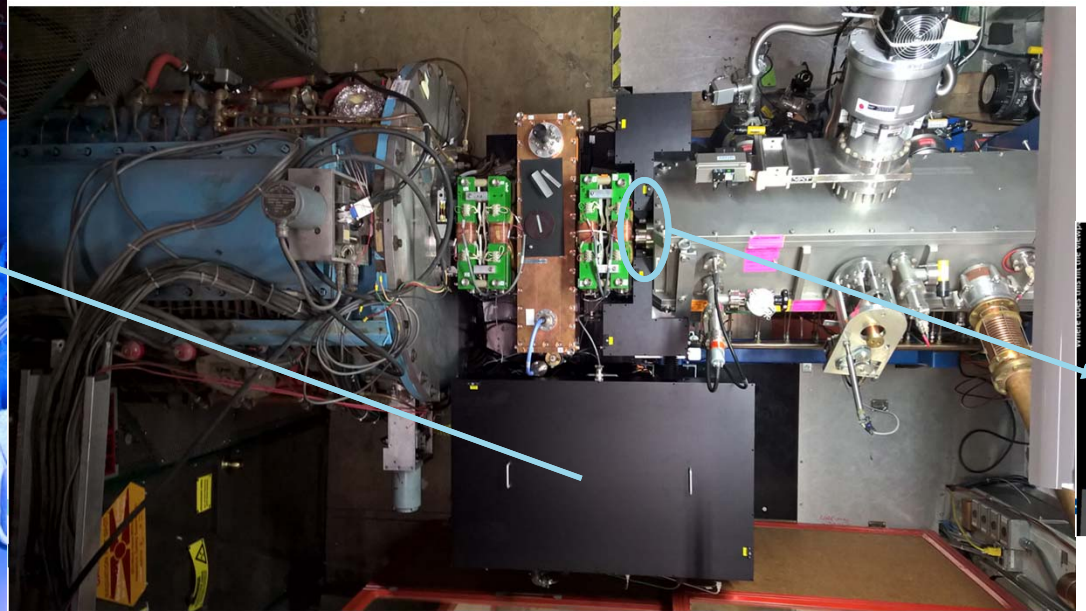
- Spent 4 years refurbishing water, vacuum, electrical and mechanical connections of 19 cavities to run at 15 Hz
- Also built new tuners to allow quick repairs
- Rebuilding 3 additional older cavities (one already installed)

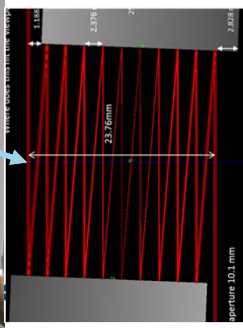


# PIP Highlights – Laser Notcher

- Currently use collimator system in Booster to notch out beam where Booster extraction kicker fires
- Significantly reduce Booster losses by notching beam upstream in the PreAcc (750 keV)
- Burst mode fiber/solid state MOPA laser transported to optical zig-zag cavity (20x less laser energy required) in vacuum flange of RFQ, neutralizes the H- beam

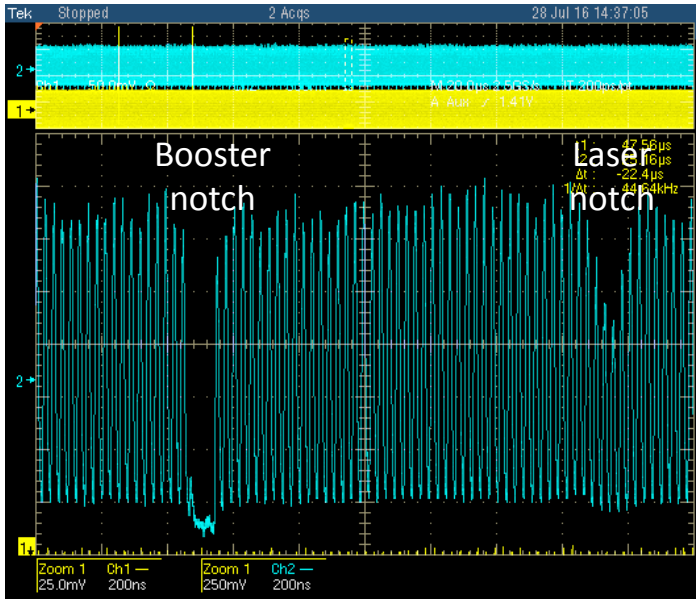






# PIP Highlights – Laser Notcher (cont.)

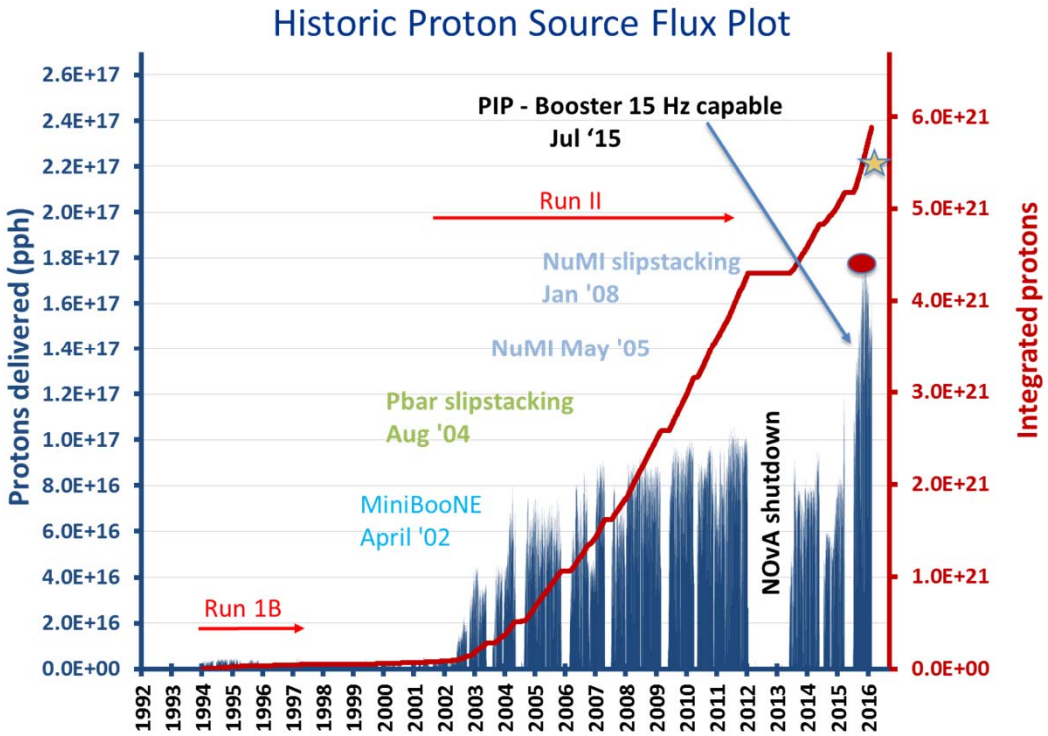
- New accelerator development – never been done before!
- Installed and tested just prior to summer shutdown
- Achieved 70% neutralization, notch survived at 40% level in Booster




- Finish commissioning and start routine operation after shutdown

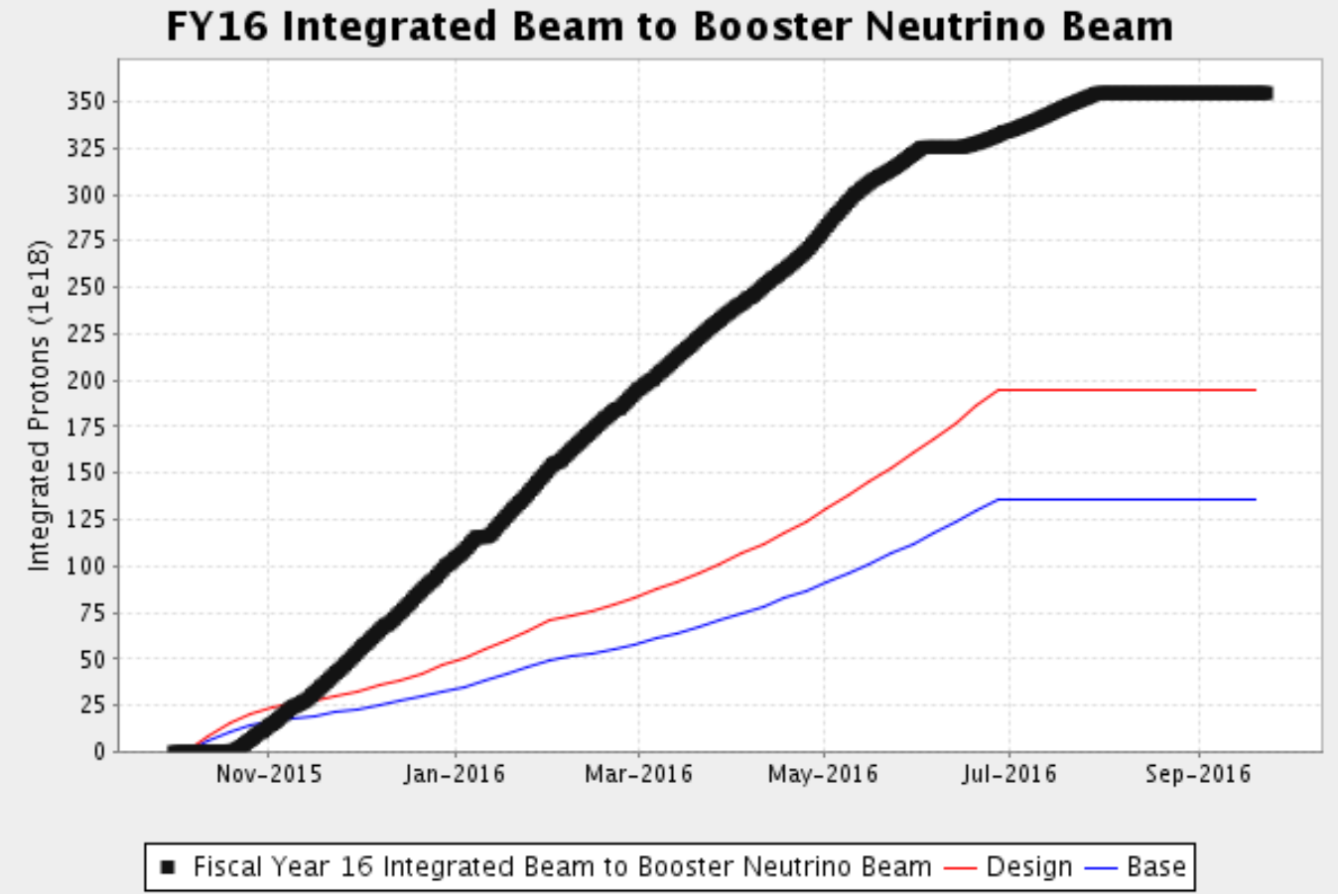
# Booster 15 Hz Running

- Capable of 15 Hz Booster beam since June 2015
- Delivering record proton flux!
- Enables us to supply beam to NuMI (at 700 kW), BNB, and the future Muon Campus




Currently limited by Booster shielding assessment – new assessment taking into account use of Total Loss Monitors to allow $2.5 \times 10^{17}$ pph under review

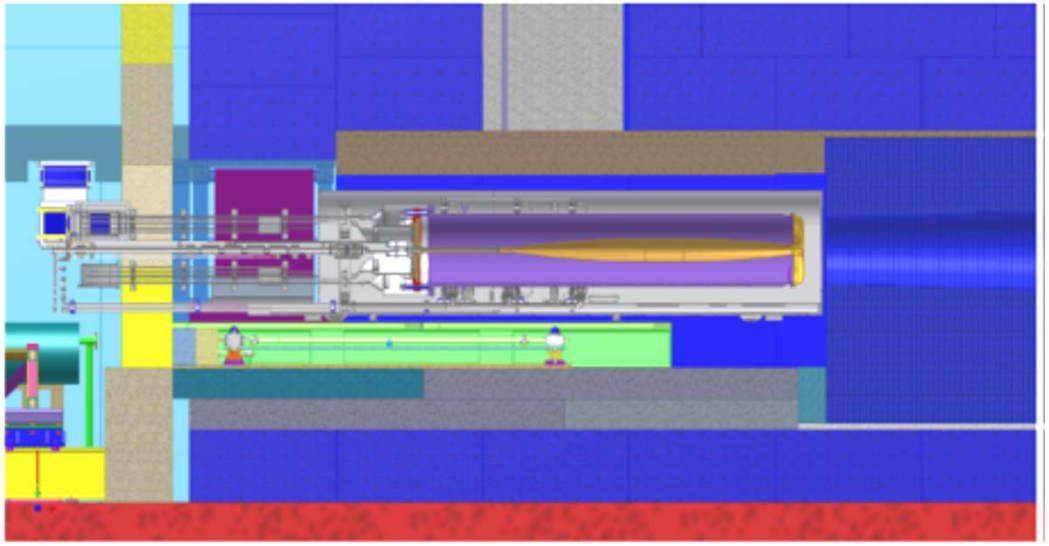
# Surpassed FY16 Goals for Beam to BNB

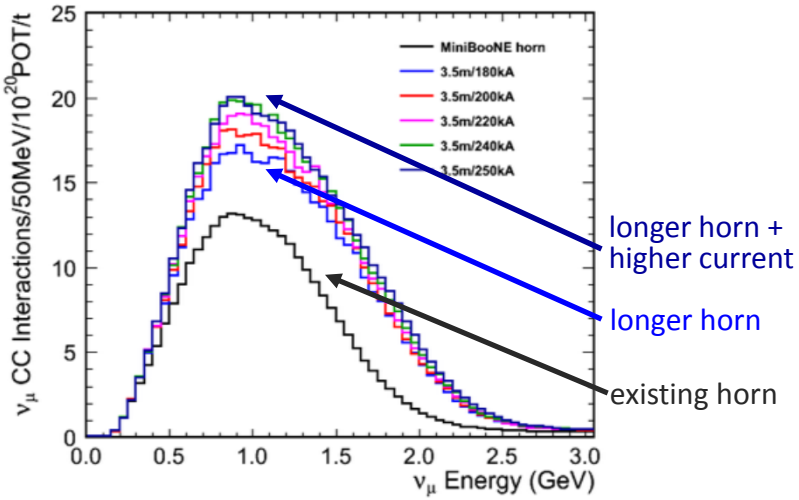



- Booster ramp-up in flux (15 Hz and intensity) much faster than assumed

# BNB Upgrade for Short Baseline Neutrino Program

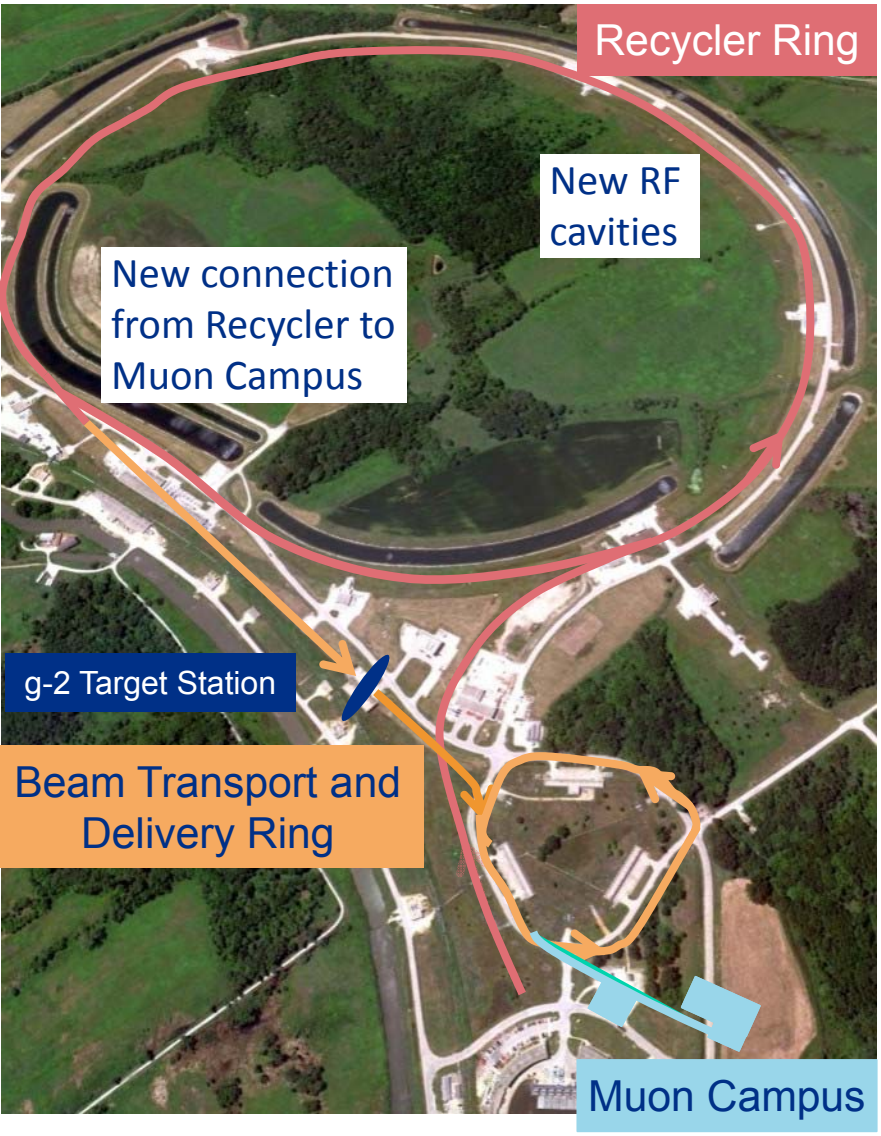
- Optimized horn design can increase neutrino yield by up to 70%
  - Inner conductor shape optimized for given length and current for efficient focusing
  - Longer horn
- Upgrade power supply to allow running at higher current and/or repetition rate





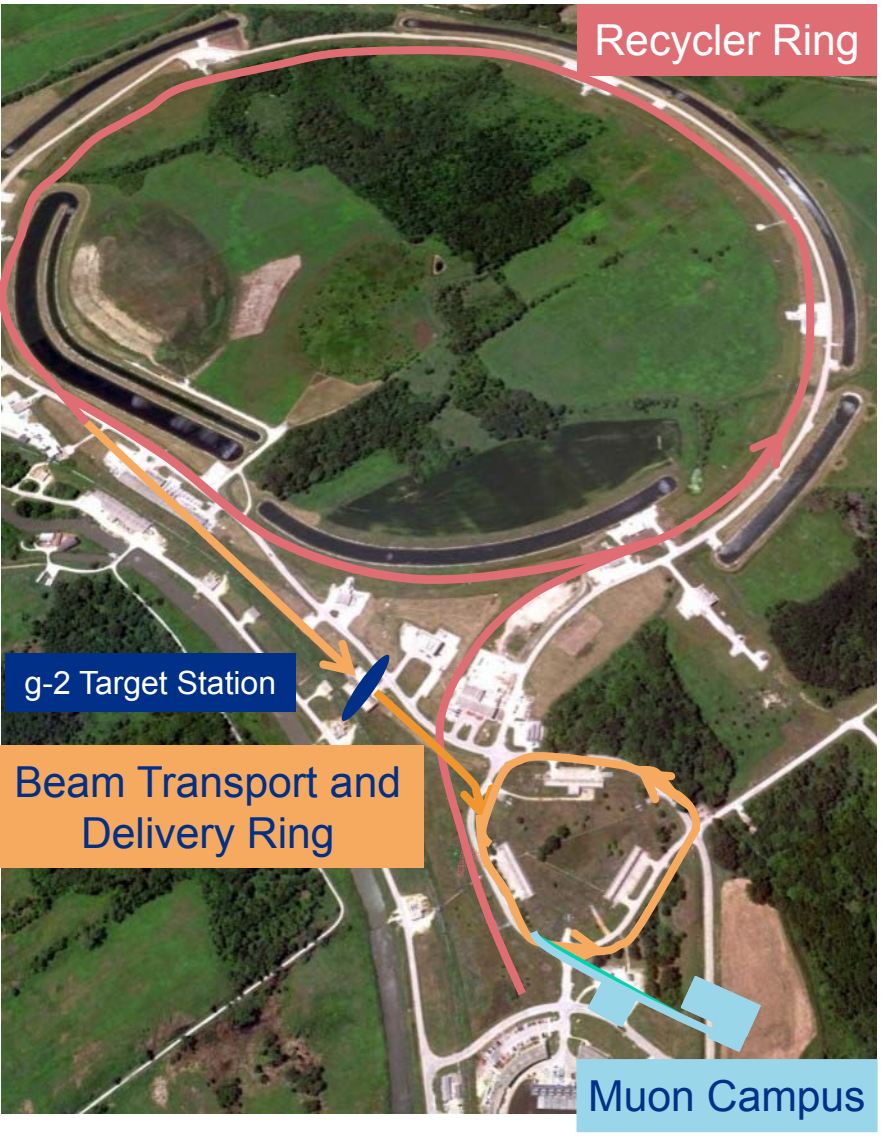

- Fabrication and installation planned for 2018-2020

# Muon Campus – Recycler Modifications



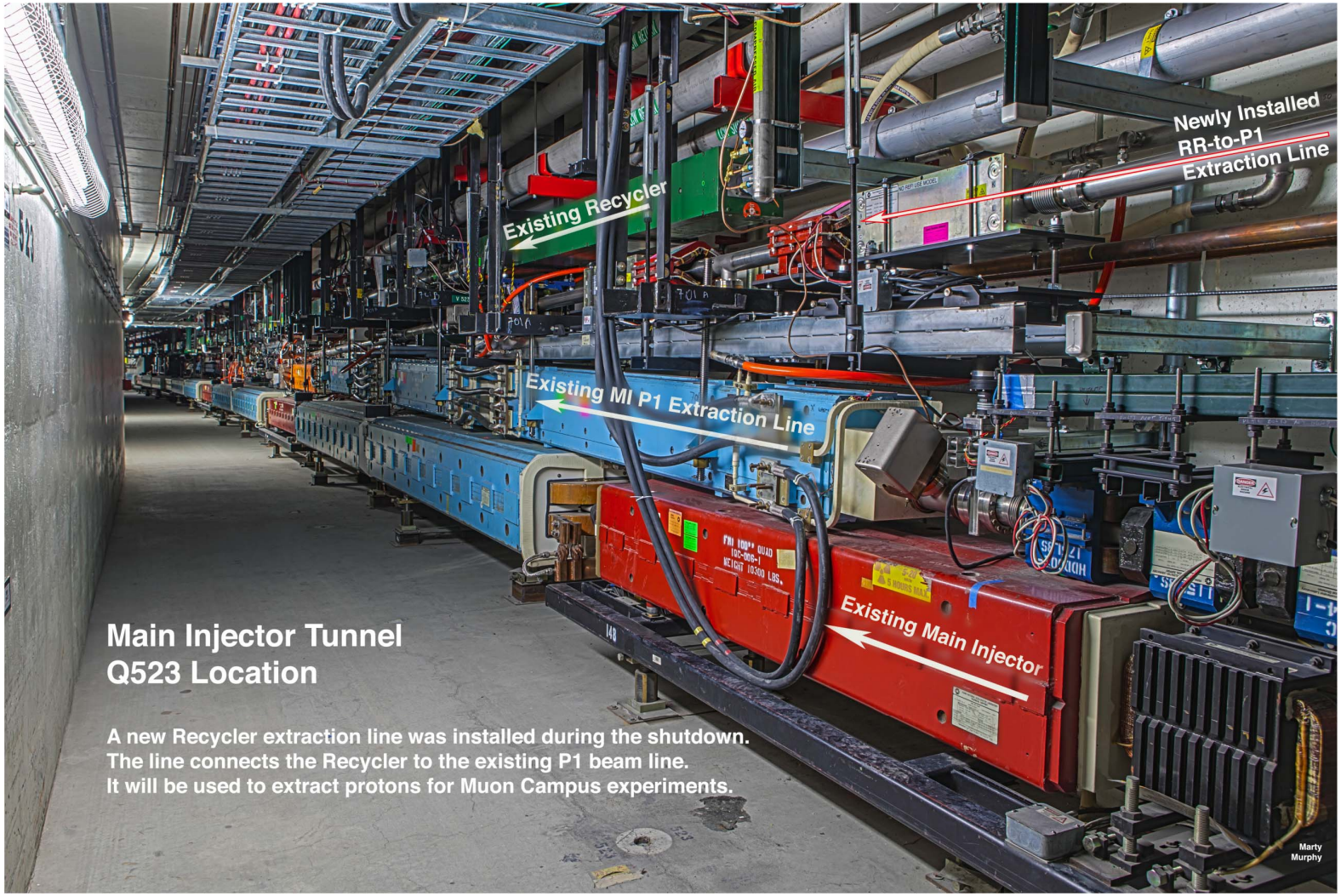

- New 2.5 MHz RF in Recycler for re-bunching primary 8 GeV protons from Booster
  - Bunch of $4 \times 10^{12}$ protons re-bunched into 4 bunches of $10^{12}$ protons with needed bunch length for g-2/Mu2e
- New connection from Recycler to Muon Campus
  - Protons to Antiproton Source came from Main Injector (120 GeV)
  - Protons extracted from Recycler to Muon Campus in 100 Hz bursts

# Muon Campus – Conversion of Antiproton Source



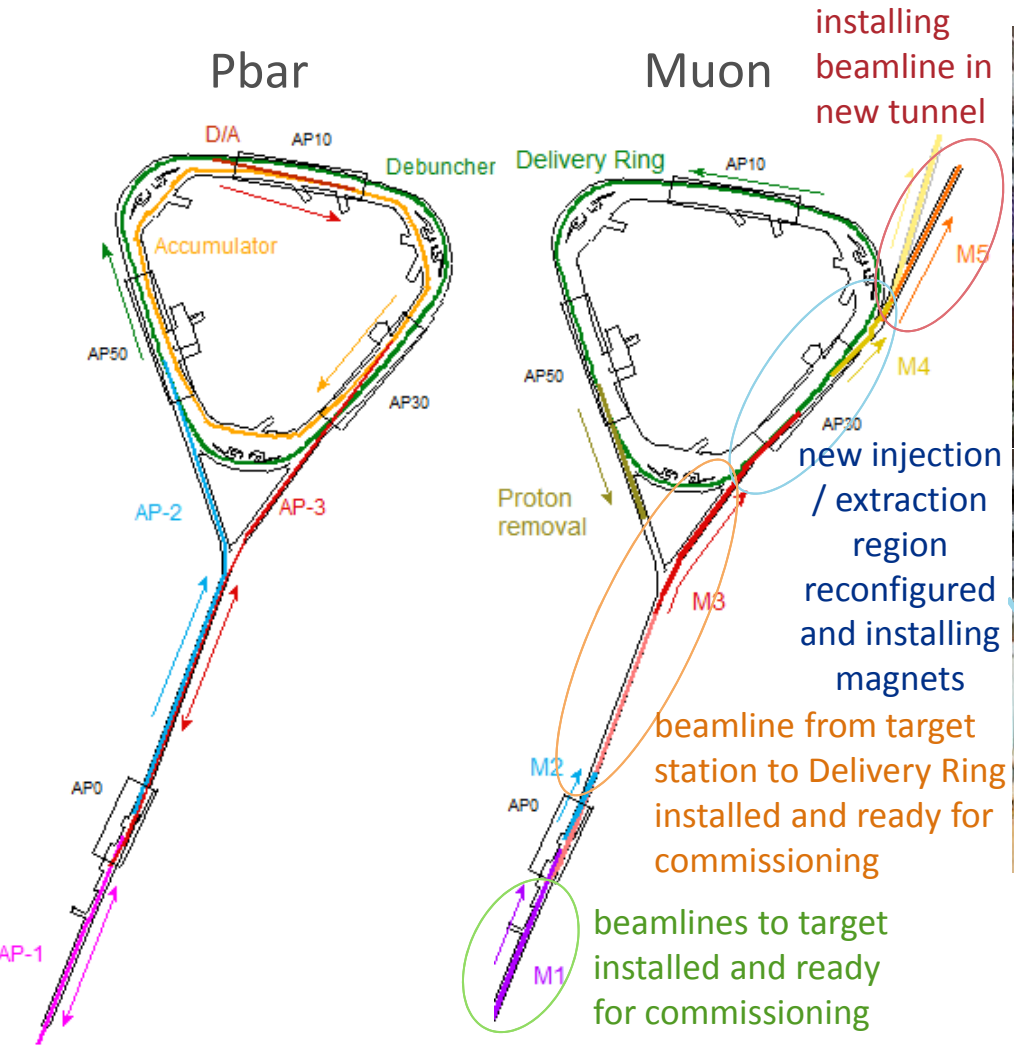

- Re-use Pbar target station for g-2 with new pulsed power supplies (100 Hz burst rate)
- Pbar Debuncher ring converted to Delivery Ring
  - Beamline (4 turns) for $\pi$ decay and $\mu$ capture for g-2
  - Resonant extraction of primary protons to Mu2e
- New beamlines from Delivery Ring to g-2 storage ring and to Mu2e target
  - Using magnets from Pbar Accumulator as well as from BNL g-2 beamline

# New Connection from Recycler to Muon Campus



# New Recycler 2.5 Mz RF for Muon Campus

# Muon Campus Beamline Construction




installing beamline in new tunnel

new injection / extraction region reconfigured and installing magnets

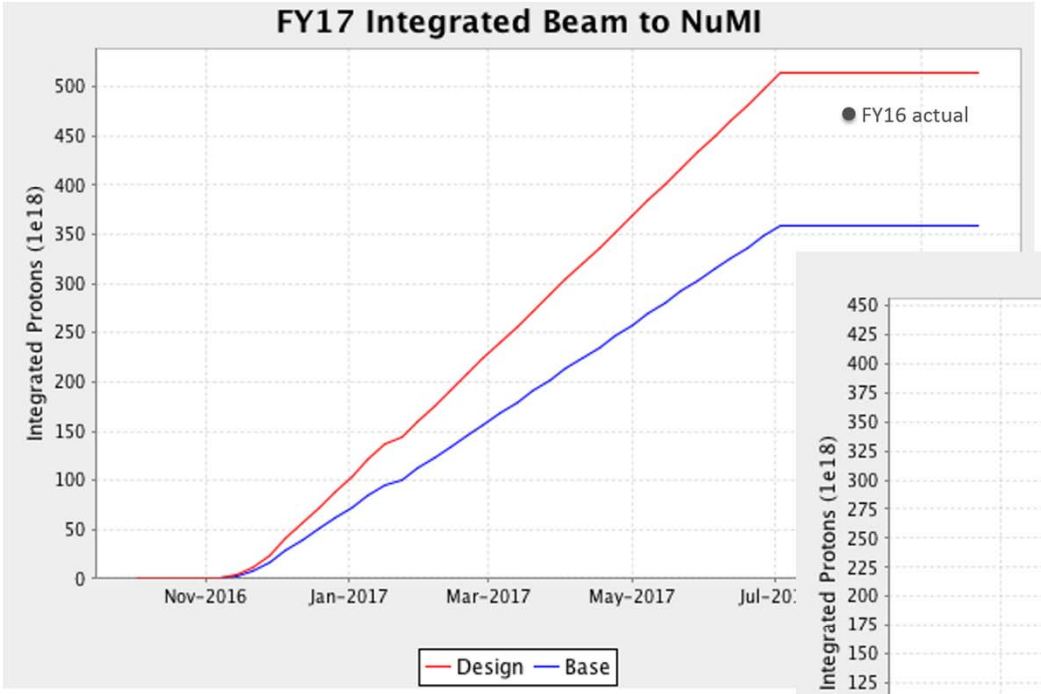
beamline from target station to Delivery Ring installed and ready for commissioning

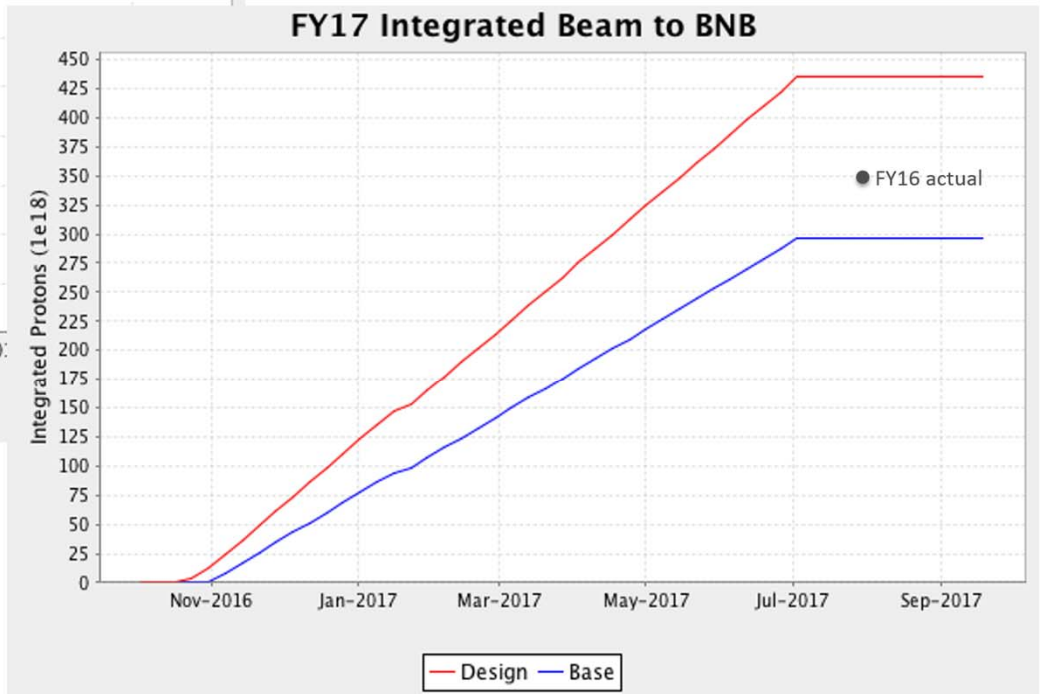
beamlines to target installed and ready for commissioning



# Accelerator Operations Goals for FY17

- Accelerator shutdown planned to end early November
- Expect similar integrated beam to NuMI and BNB as FY16




- Establish muons to the g-2 storage ring

# Conclusions

- Ready to run at world record 700 kW beam power for NOvA after summer shutdown
- Many of the PIP improvements in beam delivery have been realized already; work to ensure reliability remains
- Optimizations for the SBN program of building an upgraded horn and power supply could increase neutrino yield by up to 70%
- Muon Campus construction is on track and will be ready to commission and operate beam to g-2 starting this spring