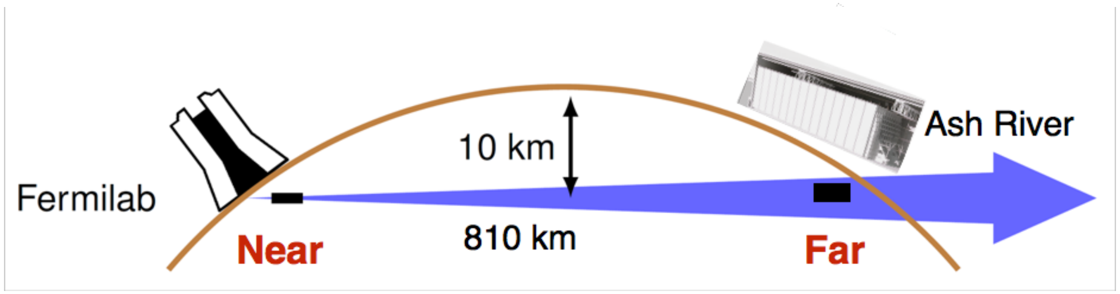
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

NuMI Beam Power Upgrade

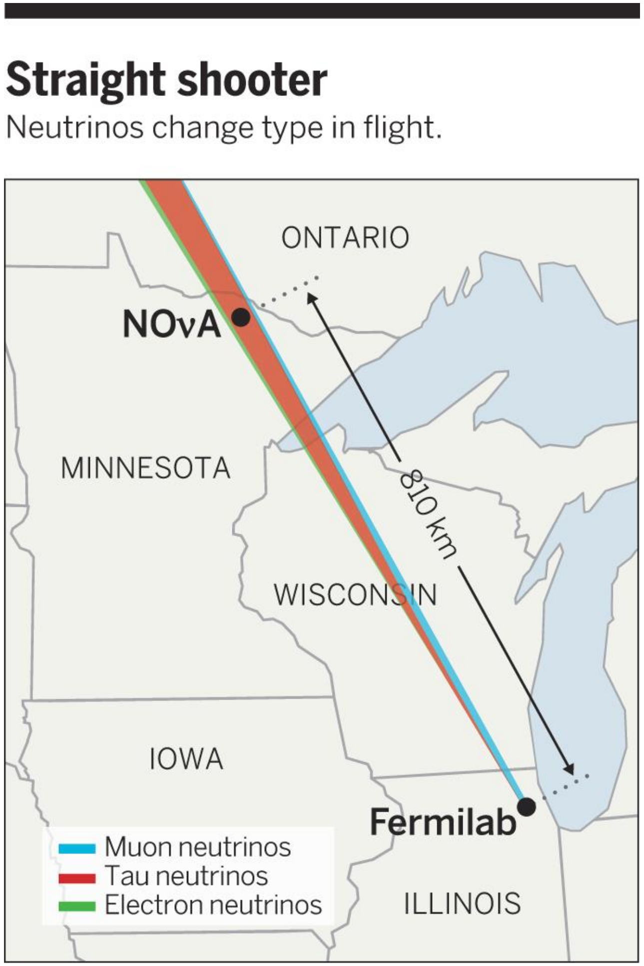
Katsuya Yonehara
On behalf of Fermilab AD & TSD groups
NuFACT 2021
September 08, 2021

NuMI Neutrino Beam to NOvA

- NuMI (Neutrinos at the Main Injector) provides a high-quality neutrino beam to the NOvA (NuMI Off-axis ν_e Appearance) Near/Far Detectors (ND/FD)
- Mission is creating **high statistic and low systematic** accelerator neutrino events in NOvA ND/FD

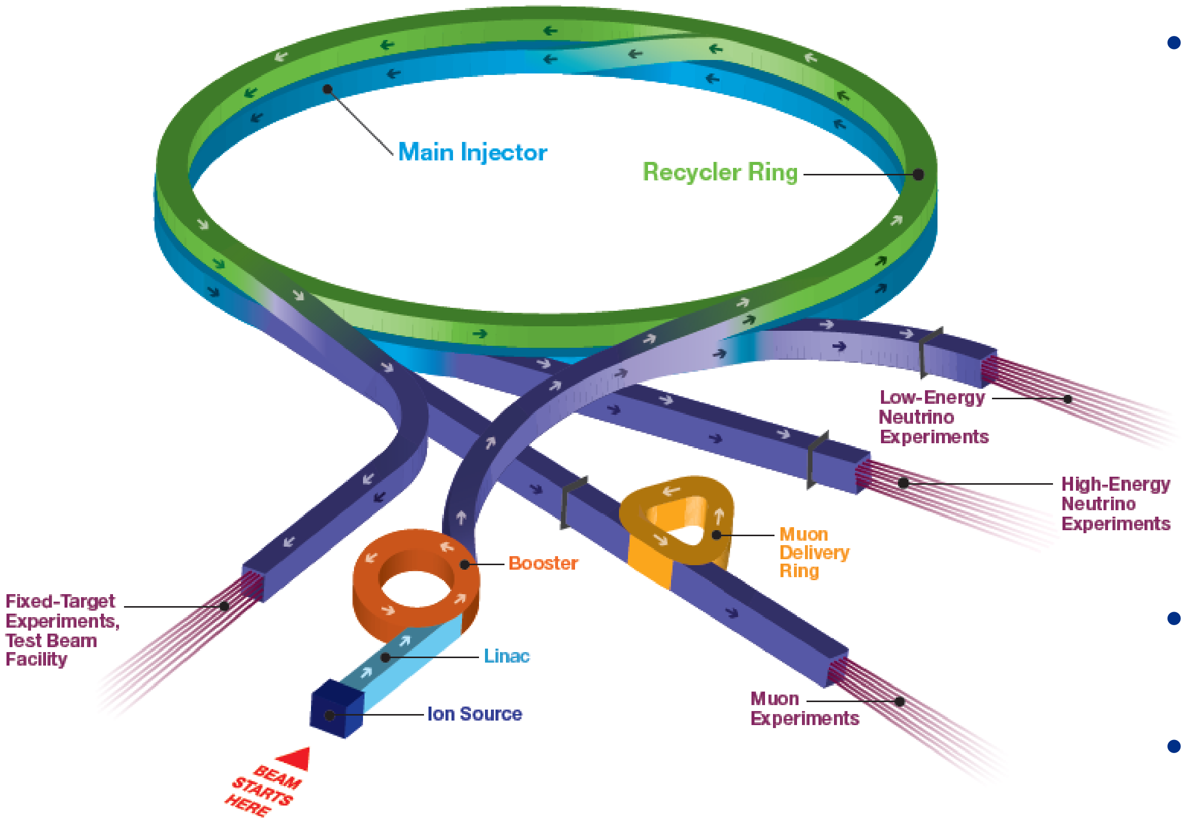


J. Wolcott, FNAL JETP Seminar Sept. 18, 2020



K. ENGMAN/SCIENCE 345, 6204

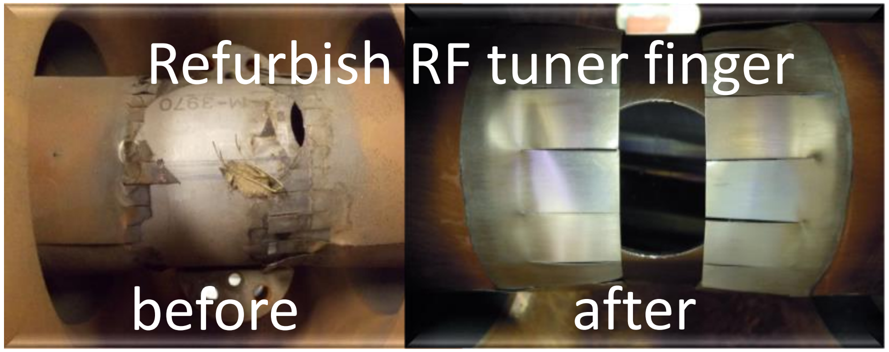
Upgrade Fermilab Accelerator Complex



- Tevatron (collider program) shut down in 2011
- Proton-Improvement-Plan (PIP) has begun since 2011 to reprogram 8 GeV proton beam system for Muon campus (g-2 & Mu2e) and Booster Neutrino Beamline (BNB), and 120 GeV/c proton beam system for NuMI and Fermilab Test Beam Facility
- Refurbish Linac and Booster for 15 Hz beam operation
- Reoptimize Recycler ring and Main Injector
- Present goal proton beam power 900+ kW for NOvA

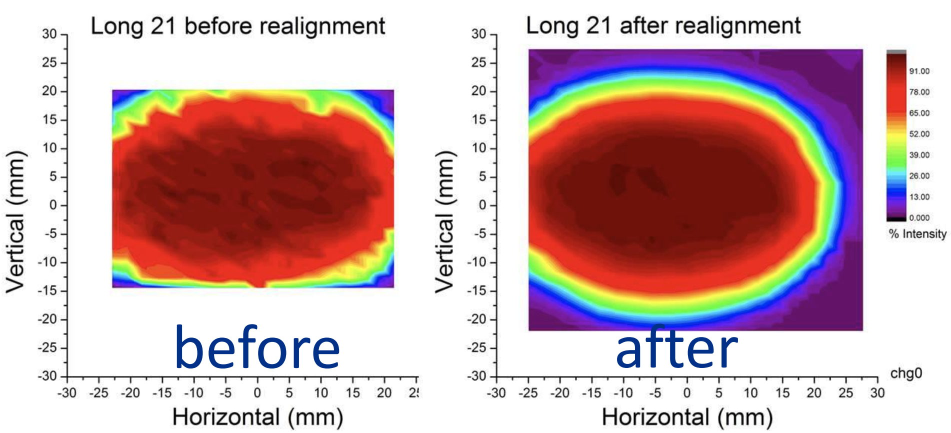
W. Pellico, Fermilab S&T review, 2013
M. Convery, ICHEP 2016

PIP on Linac and Booster

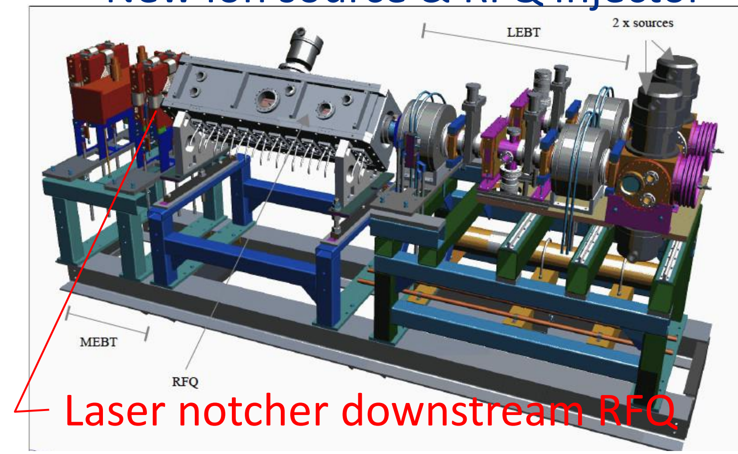


New booster fast kicker

Increment of dynamic aperture of booster after optics beam alignment



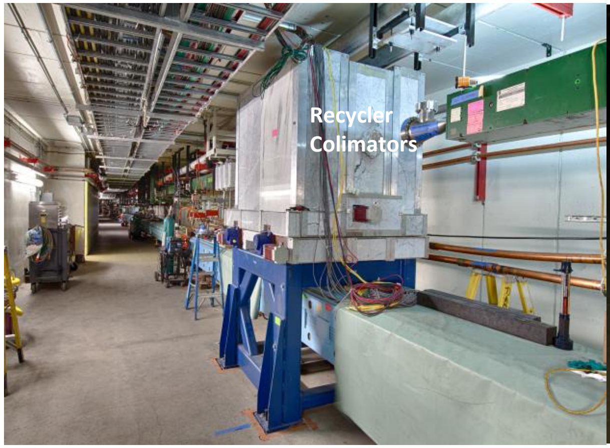
New Ion source & RFQ Injector



- Fermilab Linac and Booster have serviced beam over 40 years!
- Refurbish/restore device
- Replace old system
  - RF power system
  - Kicker
- Reoptimize beam optics
  - Higher order correction
  - Add more BPM
  - Add more cavities
- Improve system
  - Laser notcher, Booster Notcher + Absorber, etc

PIP on Recycler Ring (RR) & Main Injector (MI)

- Beam loss control
  - Install collimators in Recycler & Main Injector
    - MI collimators for un-captured beam
    - RR collimators for beam lifetime losses
  - Recycler vacuum upgrade: replacing depleted titanium sublimation pumps with ion pumps –better suited for new 15 Hz mode
  - Corrosion resistant beam pipe in high radiation beam area

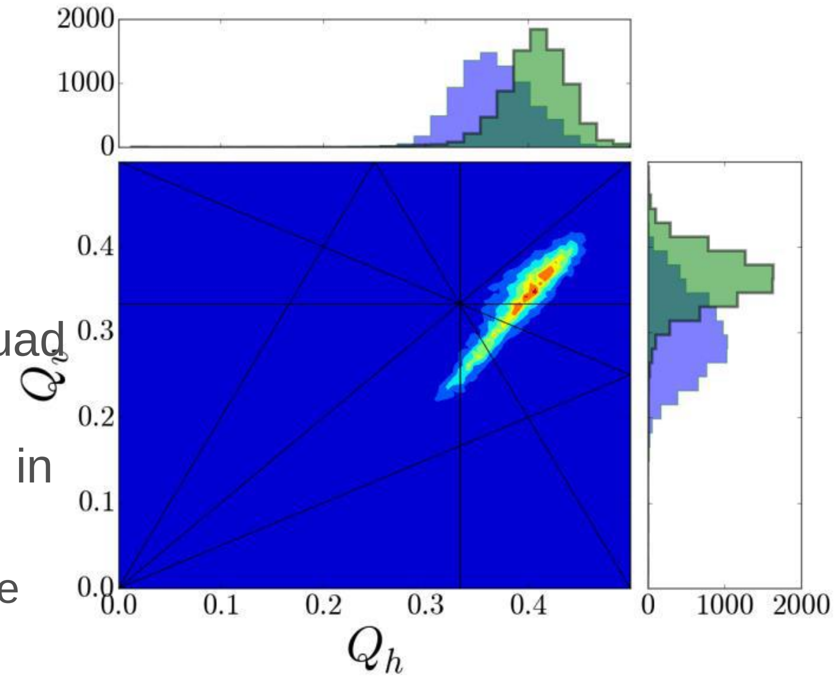


I. Kourbanis, FNAL MI Power Upgrades and Impacts, 2020

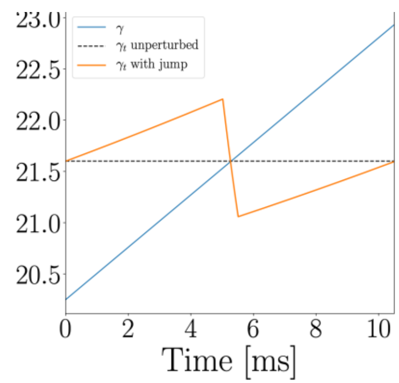
Study beam dynamics in RR and MI

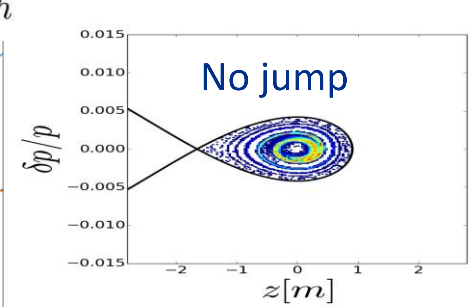
R. Ainsworth, FRIB seminar 2020

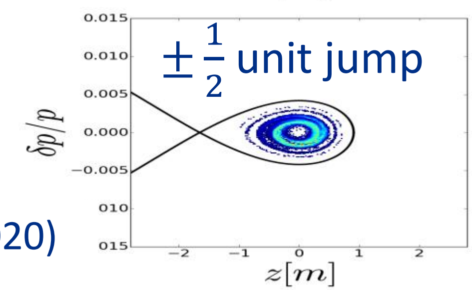
- Space charge effect in RR
  - Found emittance growth during stacking with SYNERGIA
    - Found solutions to minimize the effect
  - Experimentally demonstrated 3rd order resonance correction by using a skew quad
  - Propose frequency change from 1260 to 1680 Hz for PIP-II beam for slip stacking in RR
    - Larger separation results in better capture efficiency but larger emittance



- Gamma-t jump in MI
  - Large longitudinal emittance requires gamma-t jump in MI
  - Effectively cross transition quicker using ramped quads
  - Found a possible gamma-t parameter which mitigates emittance growth and loss in MI



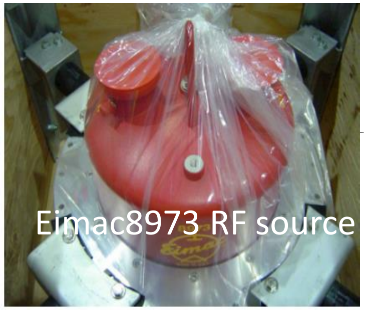


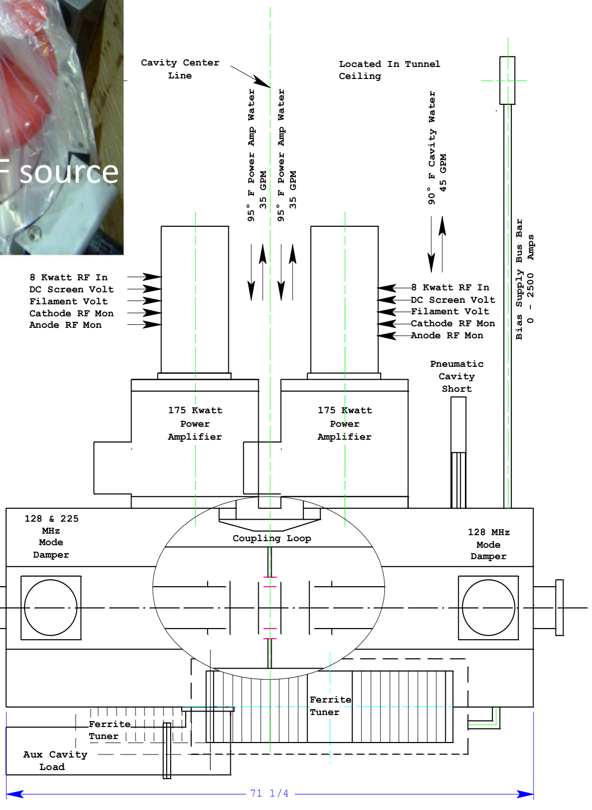


R. Ainsworth et al PRAB 22 (2020), PRAB 23 (2020)
J. Eldred 54 ICFA HB14

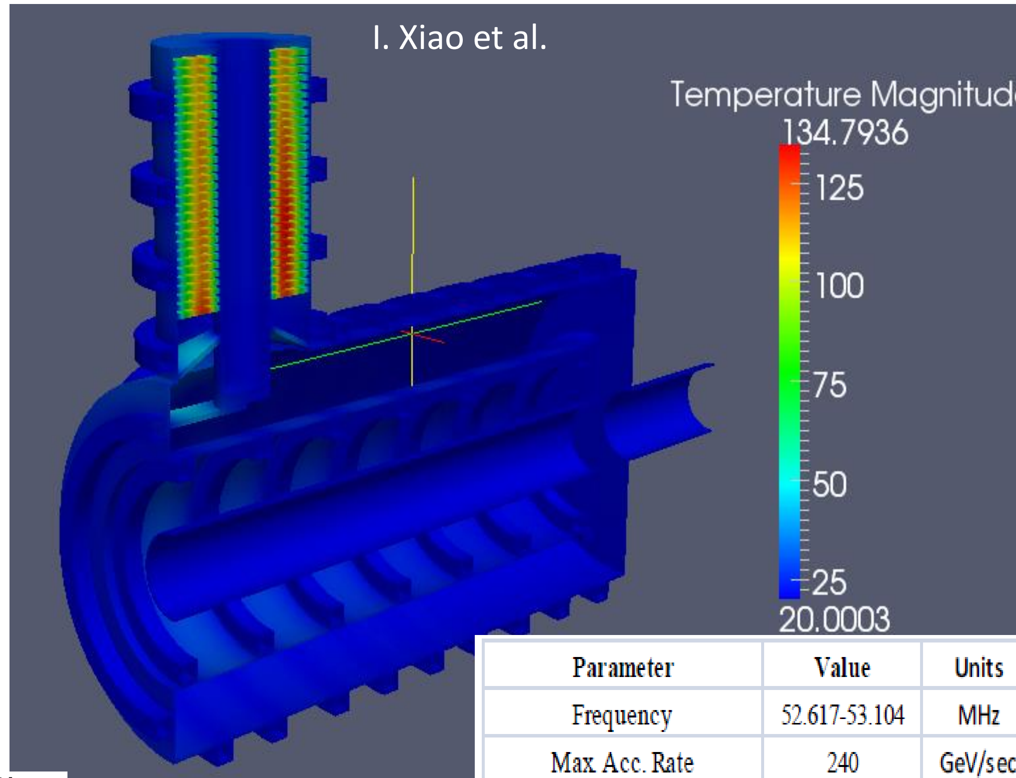
MI RF power upgrade

I. Kourbanis FNAL MI Power Upgrades and Impacts 2020





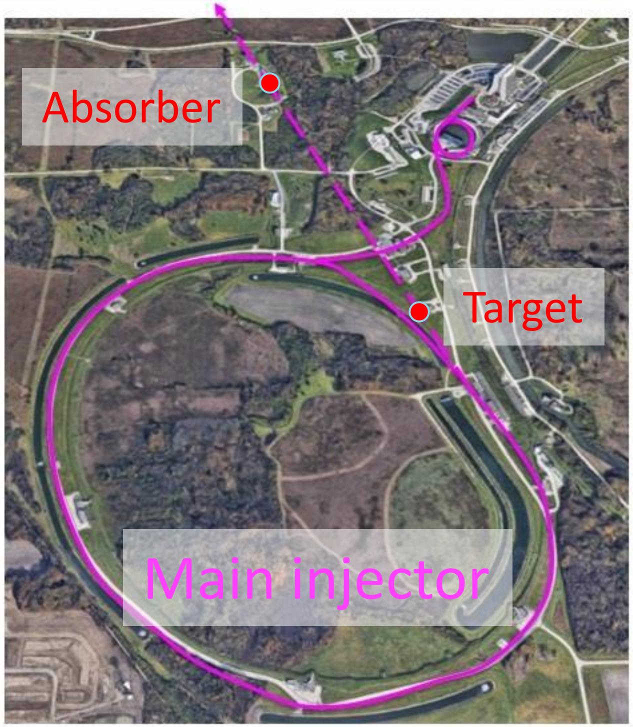
Modified Main Injector Cavity for Two Power Amplifiers



Parameter	Value	Units
Frequency	52.617-53.104	MHz
Max Acc. Rate	240	GeV/sec
Frequency Slew Rate	1.6	MHz/sec
Acceleration Voltage	2.7	MV
Peak Beam Power	6.2	MW
Average Beam Power	3	MW
Peak Voltage	4.7	MV
Average Beam Current	2.3	A
Fundamental RF Current	3.7-4.1	A

Adding another PA to each of the MI cavity will allow us to accelerate up to 1.1E14 with 240 GeV/sec (~1.8 MW).

Upgrade NuMI target system

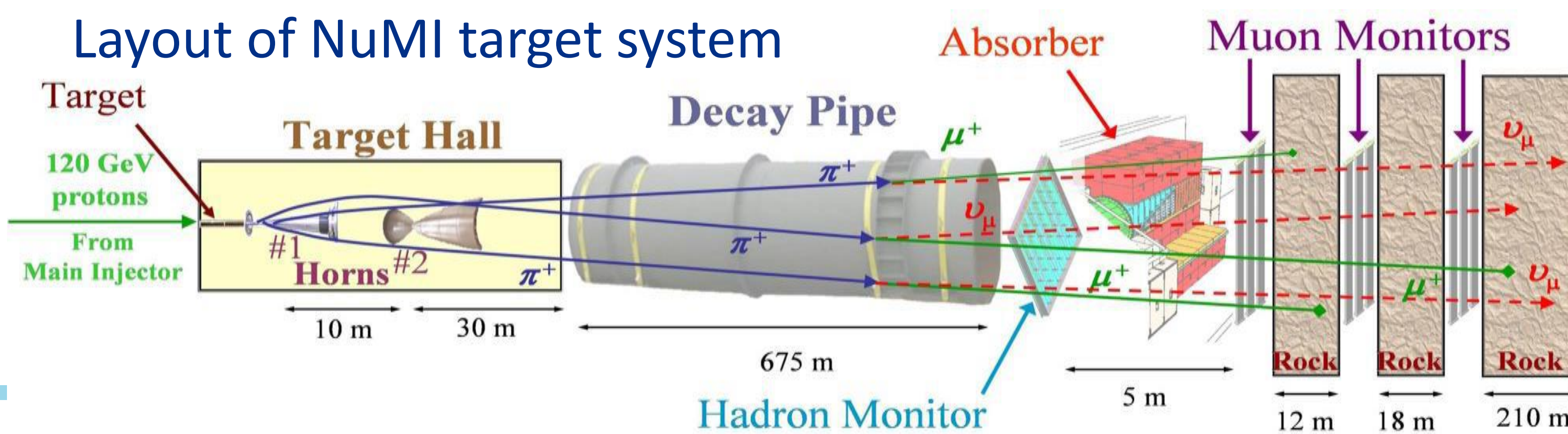


NuMI beam parameter

Present target goal

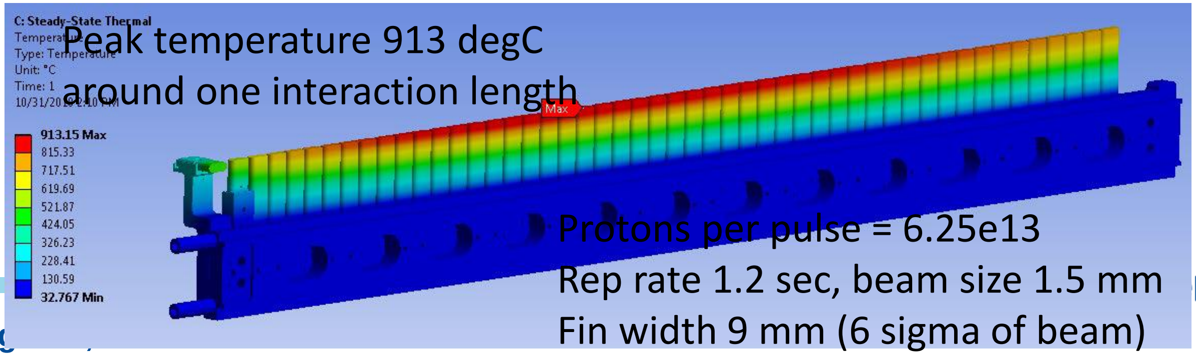
	NuMI Design	NOvA	1 MW upgrade
Proton beam energy	120 GeV		
Beam power (kW)	400	700	1 MW
Energy Spectrum	Low Energy	Medium Energy	
Cycle time (s)	1.87	1.33	1.2
Protons per spill	4.0×10^{13}	4.9×10^{13}	6.5×10^{13}
Spot Size (mm)	1.0	1.3	1.5
Beam pulse width	10 microsec		

Layout of NuMI target system



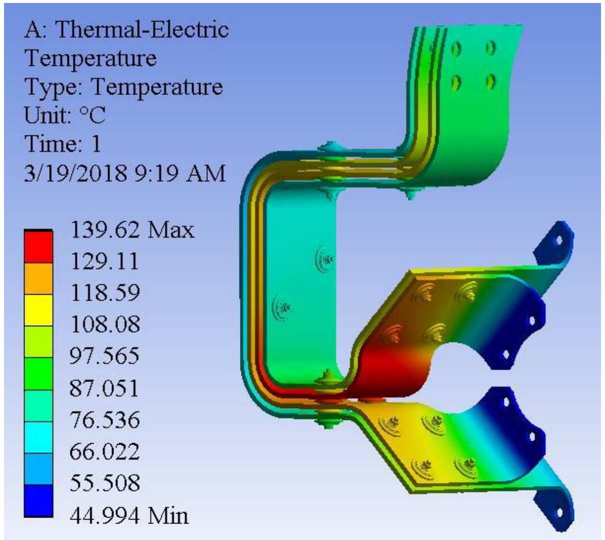
1-MW capable Target core

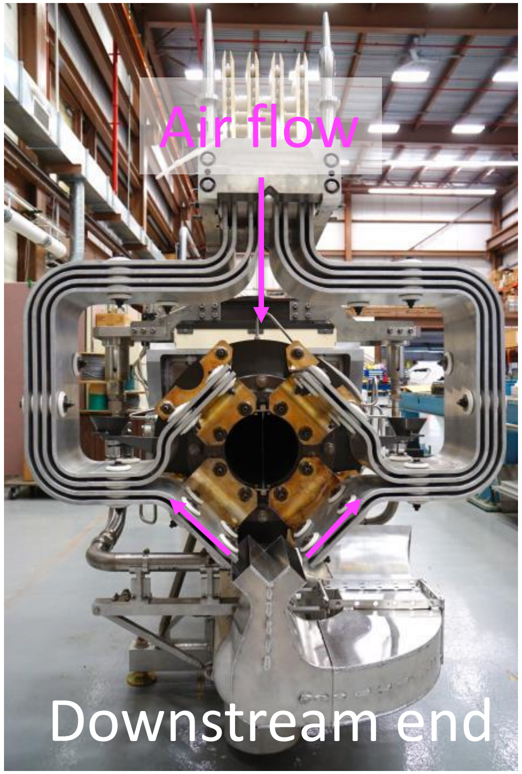
- Carbon graphite (POCO ZXF-5Q) which is known to be annealed by the beam energy deposition
- First two fins are a Budal fin
- Four winged fins for protecting horn neck and decay windows
- Totally 48 fins + 2 Budal fins
- Total length is 1.2 meters

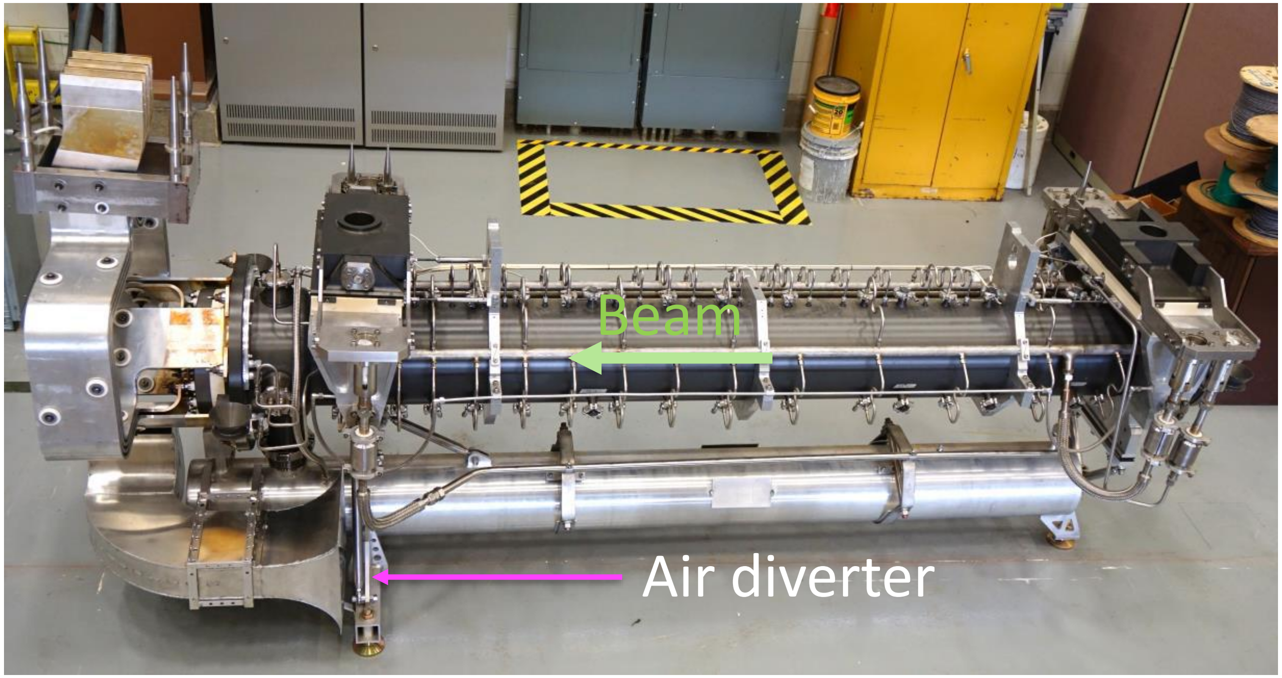


1-MW horn

- Peak horn current 200 kA, 2.3 ms (half sin wave)
- Convectional air flow on a stripline for 1-MW through air-diverter

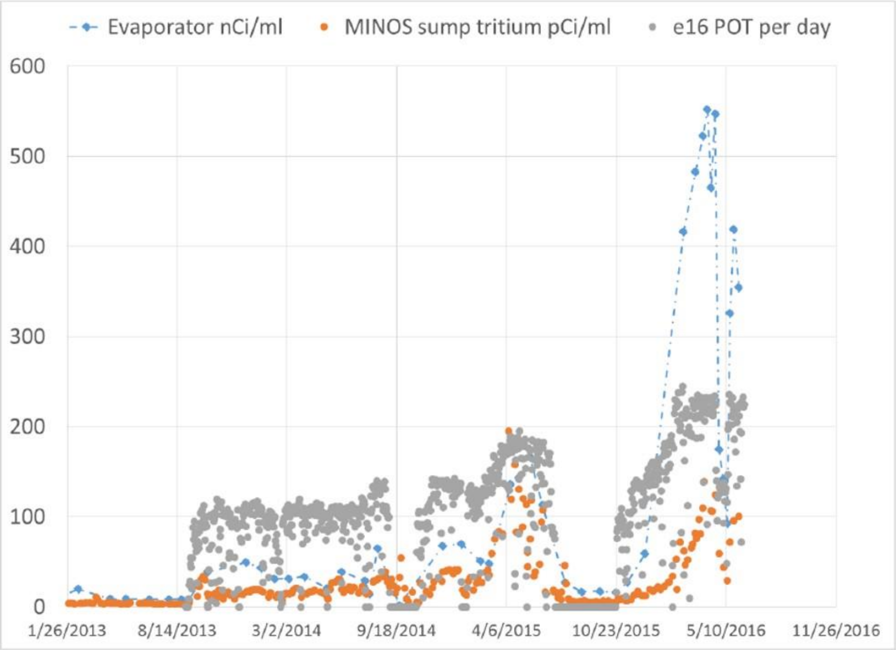






Tritium Mitigation

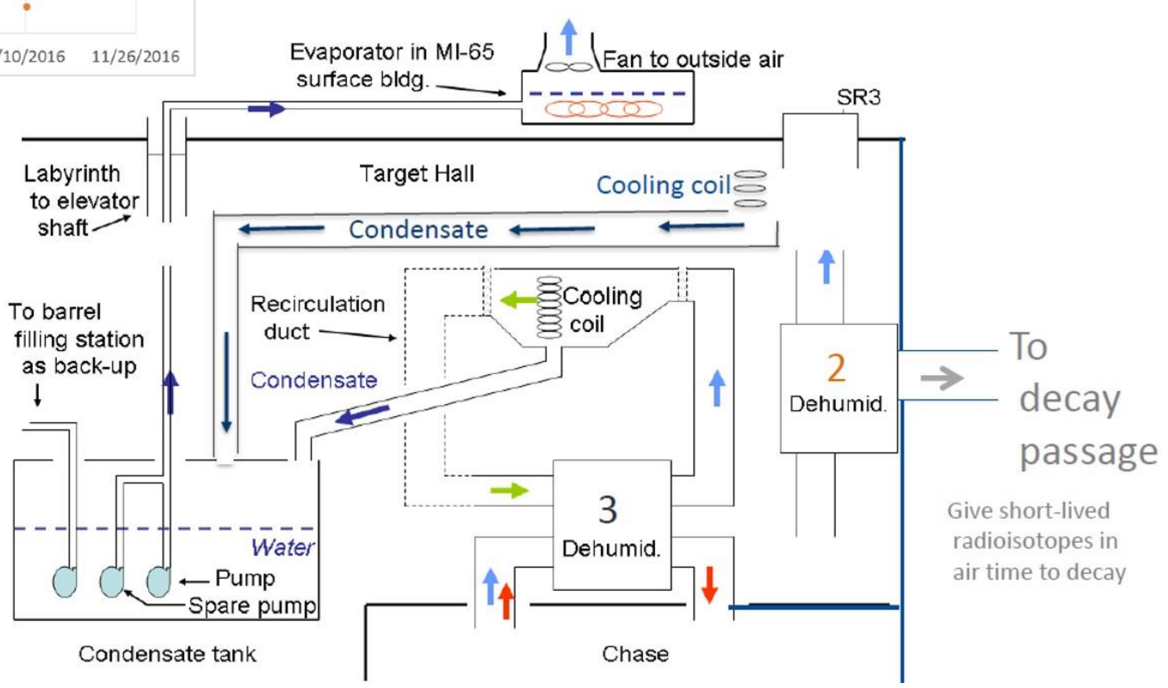
J. Hylen TSD NuMI-AIP, 2019



- High beam power (630 kW) heats up target pile, tritium increases non-linearly with beam power
- Analysis for 1-MW operation is completed, with results showing discharge to be ~210 Ci/yr, which is below the site-limit

Techniques for air emissions control are:

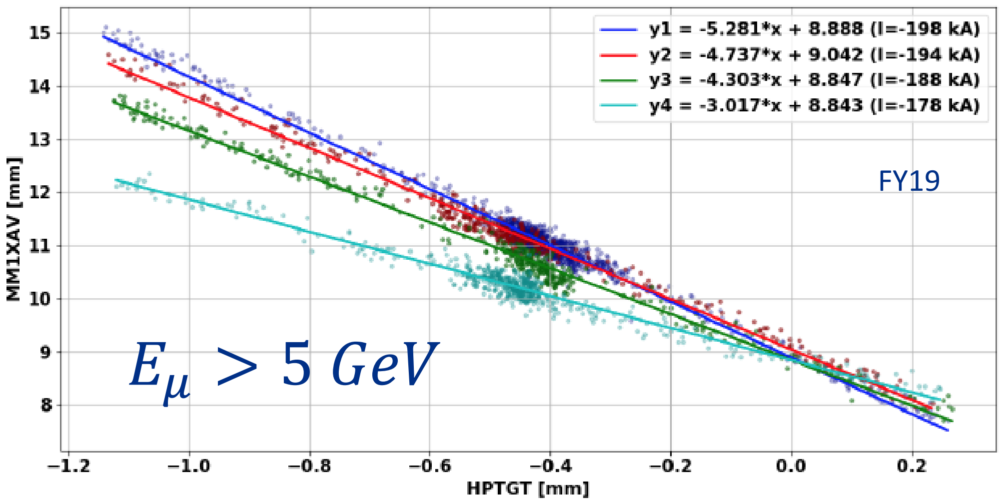
- Better evaporative disbursement (with larger fans, increase chimney height)
- Additional air balancing and instrumentation



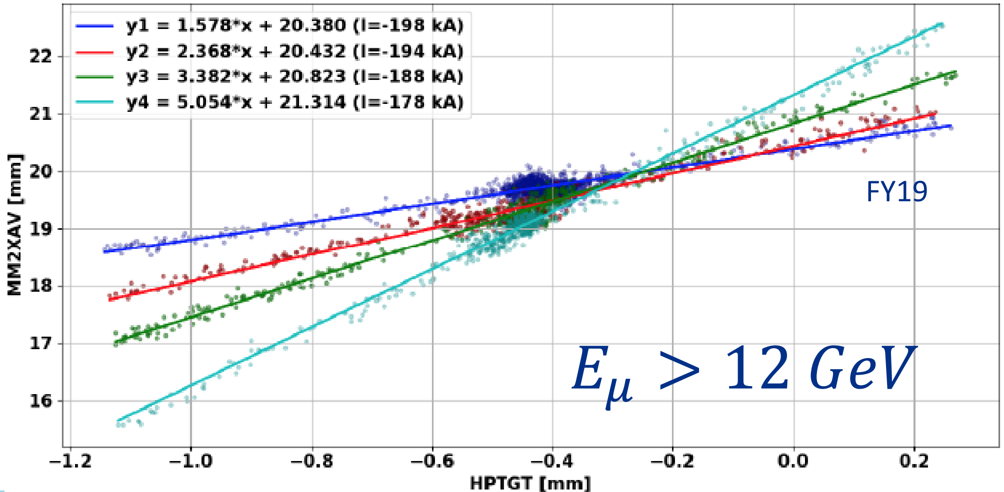
NuMI Horn Chromaticity Aberration Study

Horizontal scan

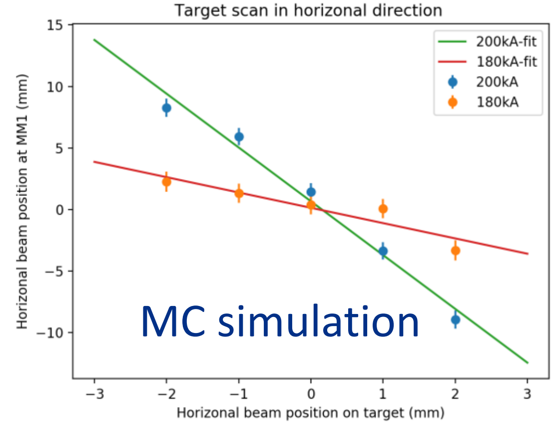
MM1



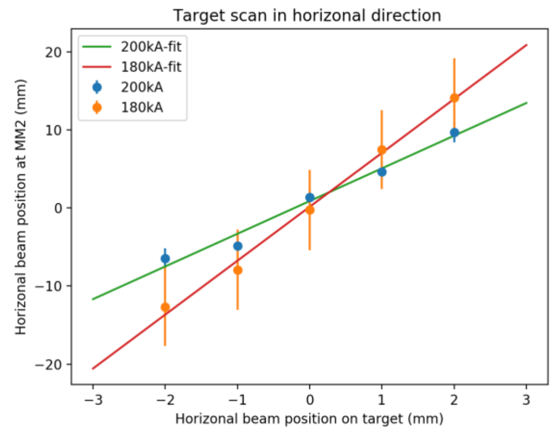
MM2



Linear correlation between primary proton beam and muon beam centroid on Muon Monitors



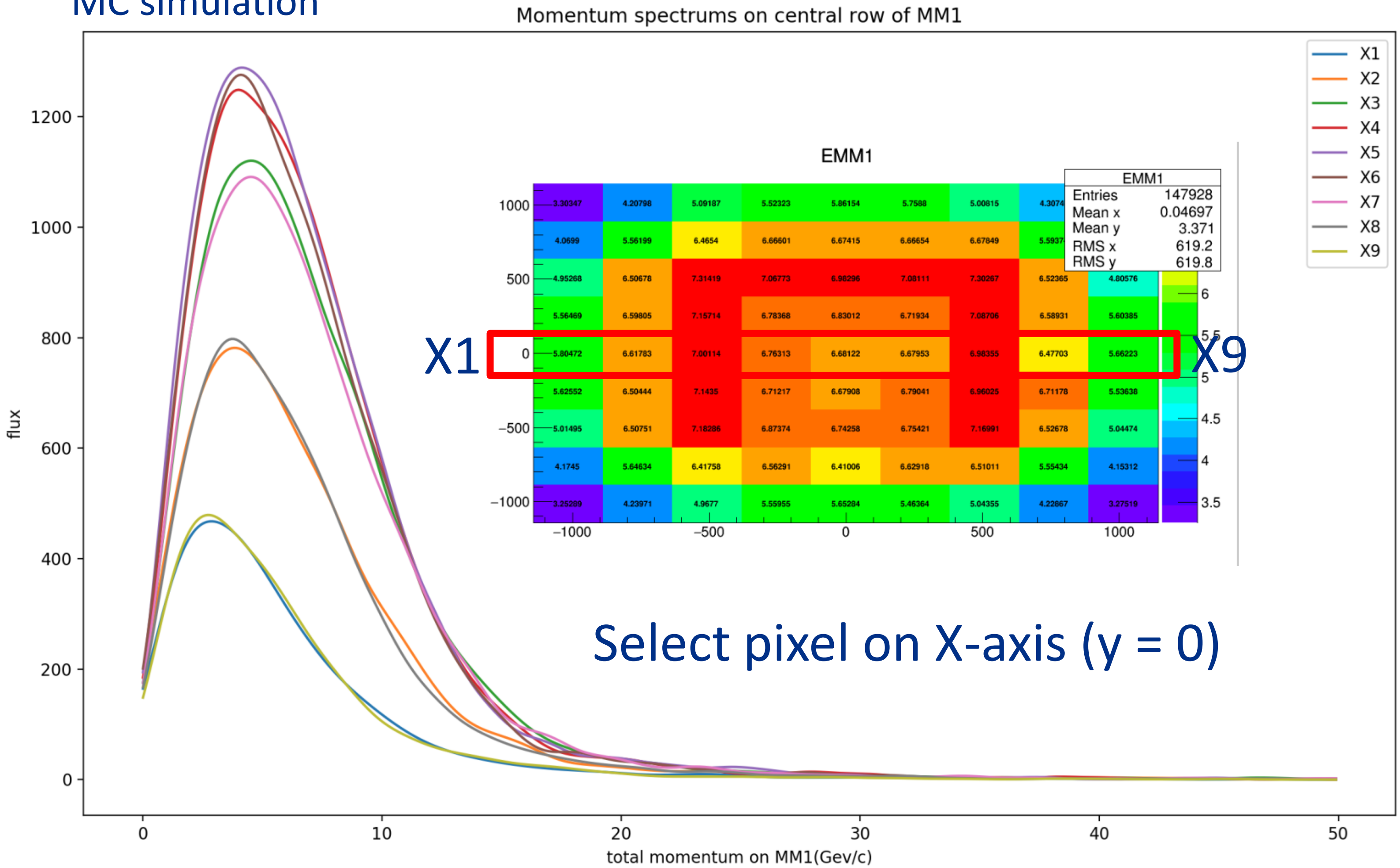
MM2 shows opposite slope from MM1 due to **Aberration of horns**



Pion/Muon Spectroscopy

Use aberration of magnetic horns to observe pion/muon spectroscopy by using muon monitors

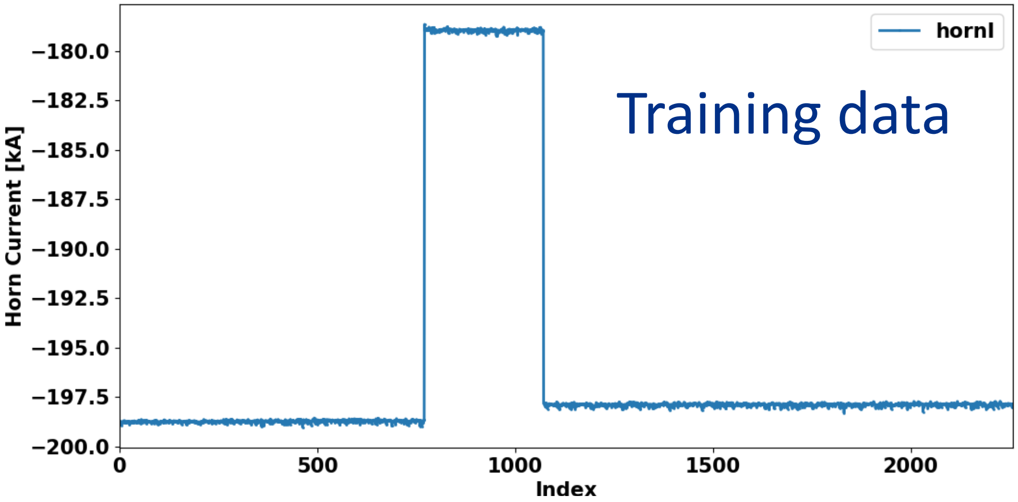
MC simulation

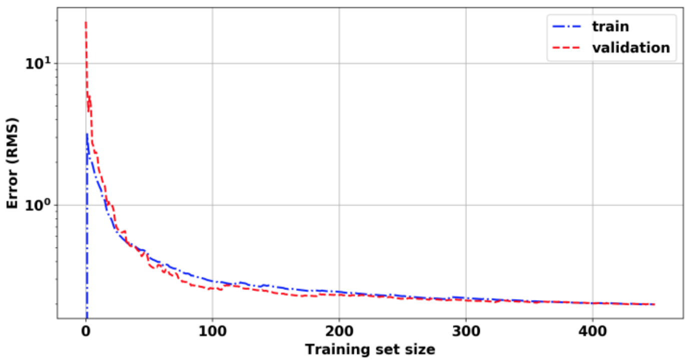


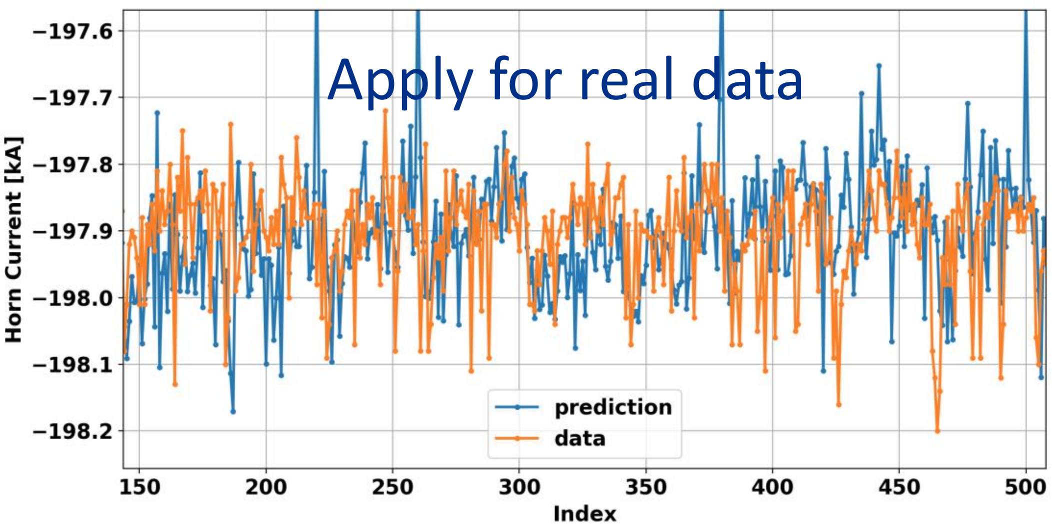
- Individual pixel sees different muon spectrum
- X1 & X9, X2 & X8, X3 & X7, X4 & X6 shows similar shape as expected

Apply Machine Learning to predict target parameter

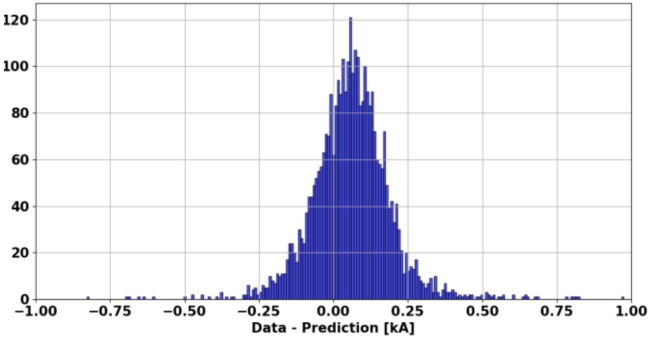
$$\vec{R}_{MM} = f(\vec{r}_{beam}, I_{Horn})$$





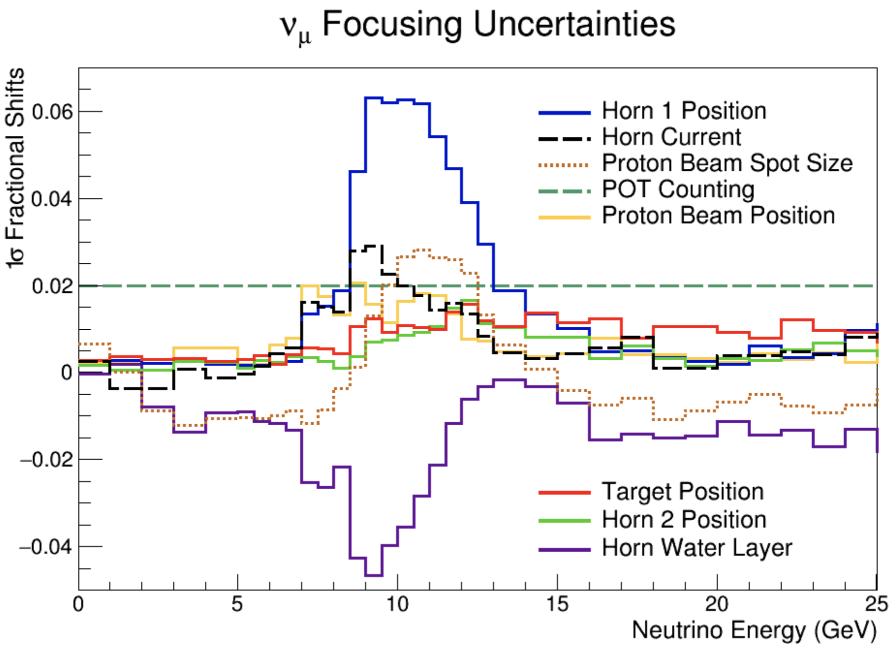


Horn Current Error RMS = 0.152 kA



Goal resolution of ML beam diagnostic

- Prediction accuracy of proton beam position at target $\leq 0.05\ mm$
- Prediction accuracy of proton beam intensity $< 10\ \%$
- Prediction accuracy of horn current $\leq 0.15\ kA$
- **Apply ML to predict Beam-related systematic uncertainty at on-axis neutrino event $\leq 5\ \%$**
- **Apply ML for anomaly detection**



Simulated beam-related systematic uncertainty for on-axis neutrino event in NuMI target system

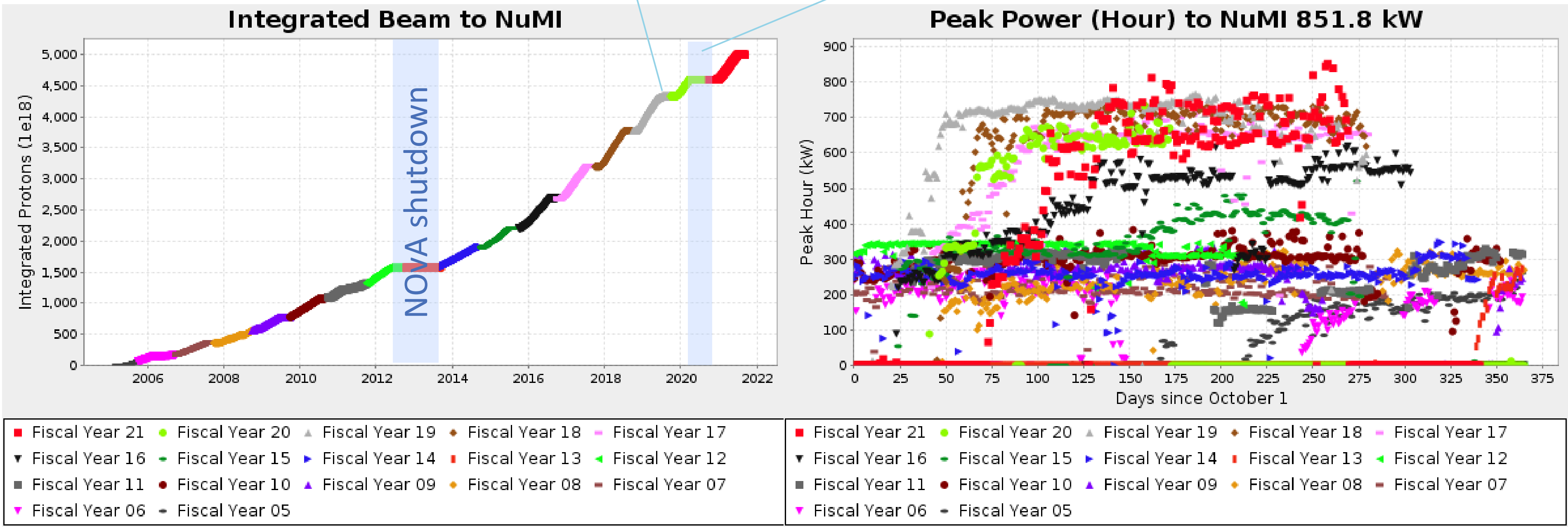
Radiation hardened beam monitor system

- Hadron monitor
  - Ion chamber
    - Install new hadron monitor this summer
  - Gas RF resonator
    - Observe RF signal modulation due to ionization in the resonator
    - First demonstration done
- Muon monitor
  - Ion chamber
  - Microchannel plate (MCP)
  - Developed at JPARC
    - Electron multiplier tube
    - Current transformer

Integrated protons send to NuMI

1-MW target installation

Early shutdown due to COVID + 1-MW horn installation



In 2021 (FY21)

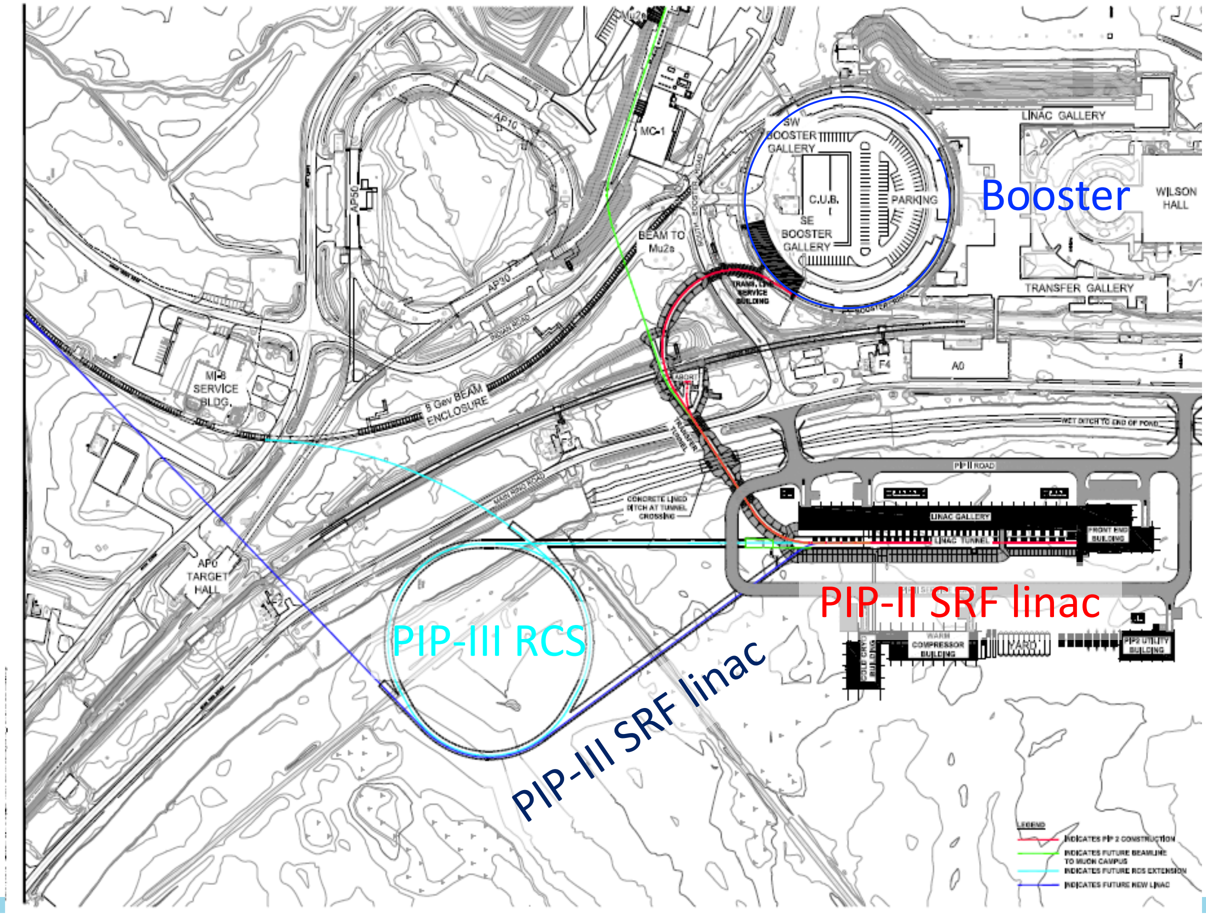
- 852 kW beam successfully operated by hour

In 2022 – 2025 (FY22-25)

- Reoptimize NuMI beam transport optics
- Tune accelerator complex to achieve 900+ kW

Future beam power upgrade plan

- PIP-II SRF Linac + 20 Hz Booster for 1.2 MW (2025 -)
- PIP-II SRF Linac + New accelerator system (SRF Linac or Fast ramp RCS) for 2.4+ MW (203X -)

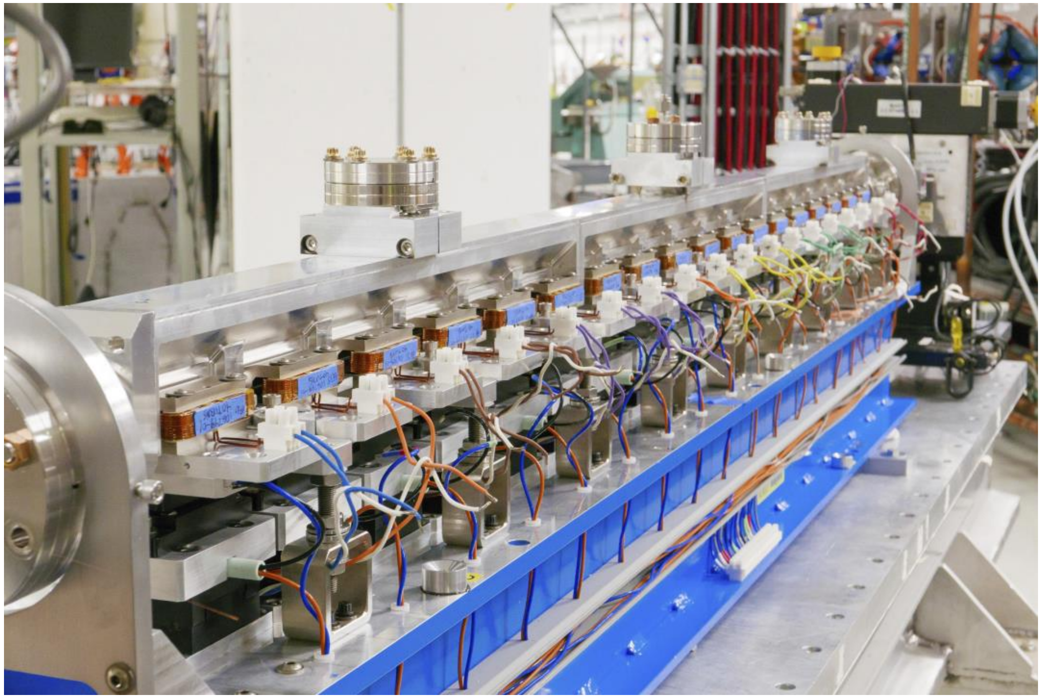


Fermilab

Fast Ramping RCS at Fermilab

- Integrable optics has a potential to compensate a space charge: The concept has been tested at Fermilab Accelerator Science and Technology (FAST)
- If success, we will have a solution to accelerate a 5-MW scale beam in PIP-III RCS

Integrable optics magnet in FAST



IOTA/FAST https://fast.fnal.gov/?p=papers

Demonstrate prototype fast ramp HTS at Fermilab (12 T/s)

H. Piekarz, NIMA 162490 2019

Conclusion

- Proton-Improvement-Plan (PIP) has begun since 2011 and Fermilab accelerator complex has been refurbished to reach 700 kW beam power
- PIP has extended to deliver a 900+ kW beam power to the NuMI target for NOvA
  - NuMI target is 1-MW capable
  - Average beam power 852 kW has been recorded in 2021
- Fermilab proposes to build more intense beam facility
  - PIP-II + 20 Hz Booster for 1.2-MW
  - PIP-III + new accelerator system for 2.4-MW or higher