Radiation Hardened Beam Instrumentations for Multi-Mega-Watt Beam Facilities

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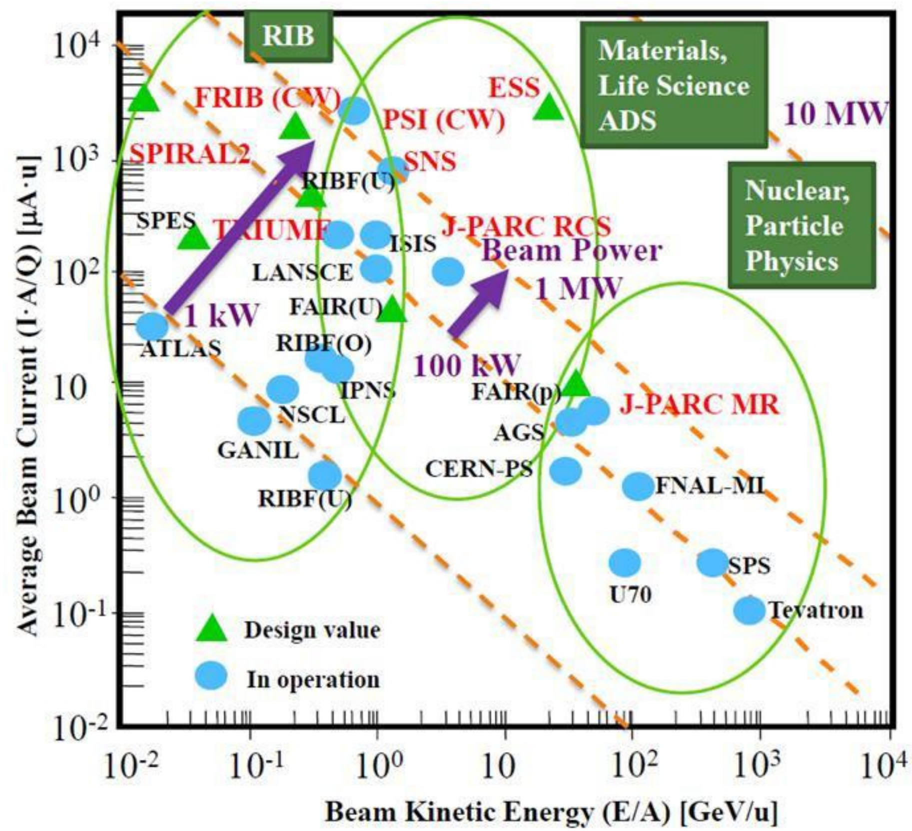
Present/Future Intense Beam Facility

- Intense beam Nuclear and High Energy Particle Physics facilities
  - Accelerator neutrino beam
  - Spallation neutron & ADS
  - Charge Lepton Flavor Violation
  - Hadron collider
  - Lepton-ion collider
  - RI beam
  - Materials, Life Science
  - Nuclear Particle Physics
- Lepton machine
  - X-FEL
  - Lepton colliders

Map created in 2016



https://www.eurekalert.org/news-releases/470669

Beam instrumentation is key component for successful beam operation

- Tool to measure beam parameter which includes beam position, profile, intensity, energy and/or time structure
- Diagnostics for beam commissioning
  - Beam parameters would be extensively varied to characterize and assess the beam optics and beam transport systems
  - Sometimes wide dynamic range, high sensitivity and high gain sensor are needed to detect the tail of the beam distribution
  - Beam would often be interrupted or halted, so that high reproducibility is needed
- Diagnostics for standard beam operation
  - High reliability needed since fluctuation of beam parameter are expected to be minimal
  - Precise beam characterization would be crucial to control and feedback the beam parameters

Why it is so difficult to build rad hard beam instrumentation?

- Extremely high radiation level in accelerator facilities
  - ~10^{10} mSv/hr, Int. energy dep. ~100 MGy are reported
- Property of building material degraded by radiation
  - Electrical insulator, vacuum sealing, grease, adhesive, semiconductor are very sensitive to radiation
  - Often seen swelling and embrittlement of materials
  - Unexpected chemical reaction
- Electric signal quality degraded by radiation
  - Often seen signal modulation, gain change, increase noise level and/or offset
  - Loss of signal calibration accuracy
  - Often hard to re-calibrate detector
  - Signal is distorted during propagated in a long cable
- Concern radioactivation
  - Safety consideration regarding Deployment, Storage and/or Disposal

Rad Hard Beam Instrumentation Workshop

Feb 3 – 4, 2022
US/Central timezone

Enter your search term

- Overview
- Timetable
- Registration
- Participant List

We are planning a virtual workshop on radiation hardened beam instrumentations in the framework of Snowmass to discuss the different challenges on on-line rad hard diagnose systems necessary to support High Power Targetry and the successful operation of multi-MW target facilities in the future.

The workshop will consist of invited talks from experts in this area and discussion on what should be the long-term strategy for development of radiation hardened beam instrumentations including methods of beam detection in extreme environments, rad hard ASIC electronics for beam detectors, and in-situ target health sensors. This workshop will be used as inputs for the Snowmass effort to provide a scientific vision for the future of particle physics in the U.S. and its international partners, in particular for the high power targetry.

Starts Feb 3, 2022, 6:50 AM
Ends Feb 4, 2022, 12:00 PM
US/Central

- Mini virtual-workshop was held in Feb 3-4, 2022 hosted by Fermilab
- It is subgroup of the Accelerator Frontier Technology R&D @Snowmass'21
- Fortunately, we had 49 participants from universities and national labs
- Whitepaper was published based on the discussion arXiv:2203.06024v1 **and JINST**

Highlight of the workshop

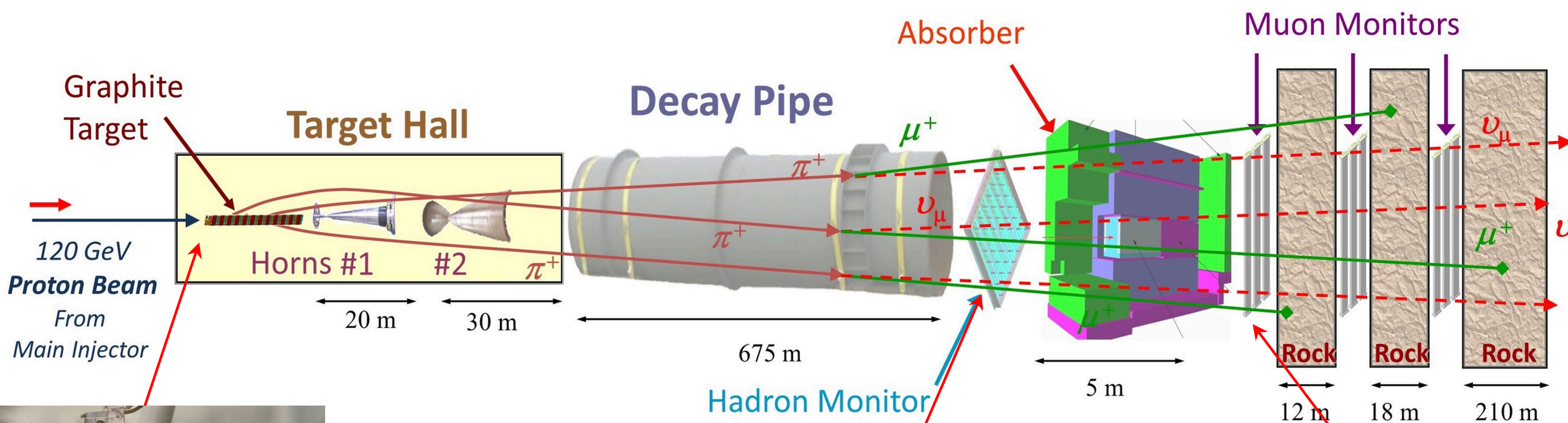
- Identify common issue
  - Many institutions have issue on radiation damage on light optics and photosensors
  - Degradation of transmission efficiency of light guides
    - Various calibration techniques are proposed, e.g. CERN group applied AI/ML to restore beam image
  - Degradation of photosensor
    - Unfortunately, many rad hard cameras were stopped making
    - It is trend to use cheap compact camera instead of expensive one
- Identify non-common issue
  - Nuclear accelerator facilities developed in-situ target health sensor, but not for high energy particle physics experiments
    - Minimize interception of produced particles, which is crucial in cLFV and neutrino experiments
- **Suggested to the DOE to establishment of the technology exchange program in BES/HEP communities**

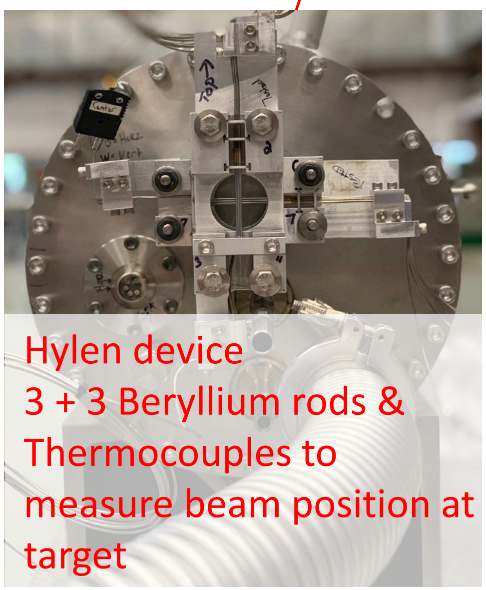
R&D of Rad Hard Beam Instrumentation at NuMI

Beam parameter	Design value	Tolerance	Beam instrument	Accuracy
Horn current	200 kA	±2 kA	Horn CT	0.1%
Horiz. beam position on target	0 mm	±1 mm	BPM	0.02 mm
Vertical beam position on target	0 mm	±1 mm	BPM	0.02 mm
RMS beam spot size	1.3 mm	±0.2 mm	Beam PM	0.1 mm
Beam intensity	50×10^{12} POT	1%	Beam CT	0.5% (stability 0.1%)

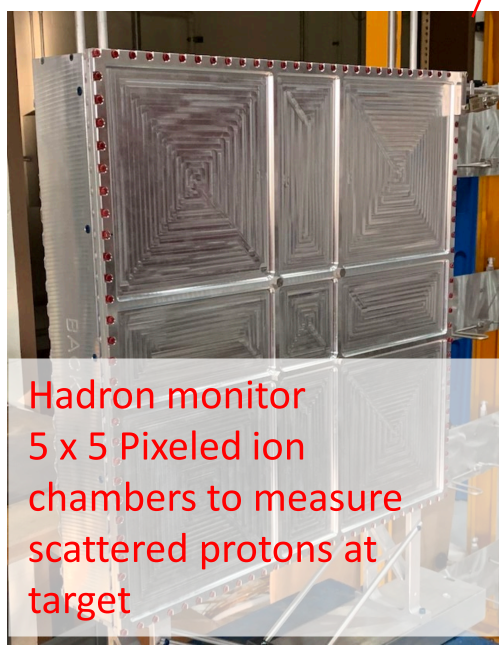
- Table on top shows the estimated physics tolerance of NOvA experiment
- Set of primary beam instrumentation and Accuracy of them are also shown in the table
- Similar set of beam instrumentation will be used for LBNF
- We use beam monitors to find a correlation between the primary proton beam and secondary/tertiary particles so that we can demonstrate the signal fluctuation of primary beam instrumentation is **NOT** noise

Beam Monitor at NuMI beamline





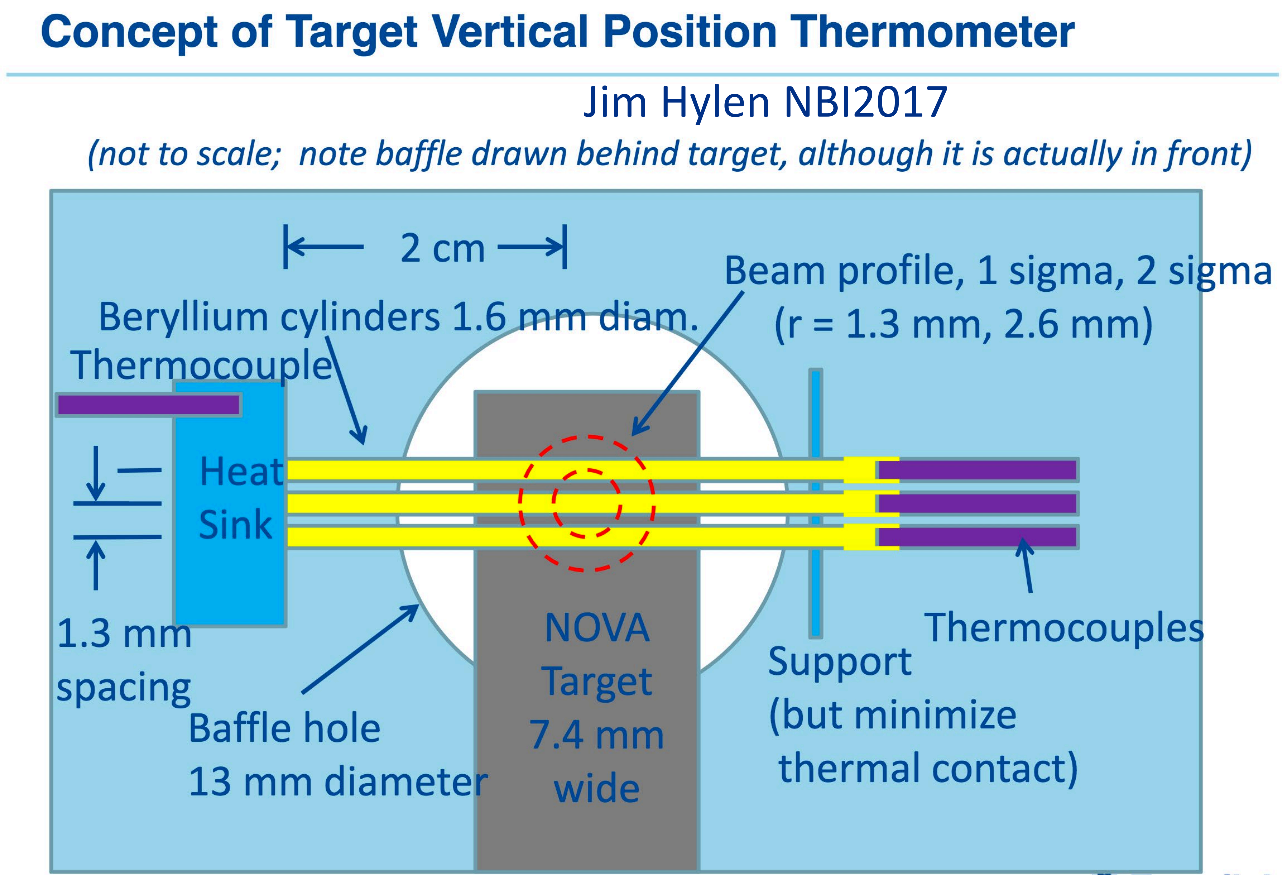
Hylen device
3 + 3 Beryllium rods &
Thermocouples to
measure beam position at
target



Hadron monitor
5 x 5 Pixeled ion
chambers to measure
scattered protons at
target

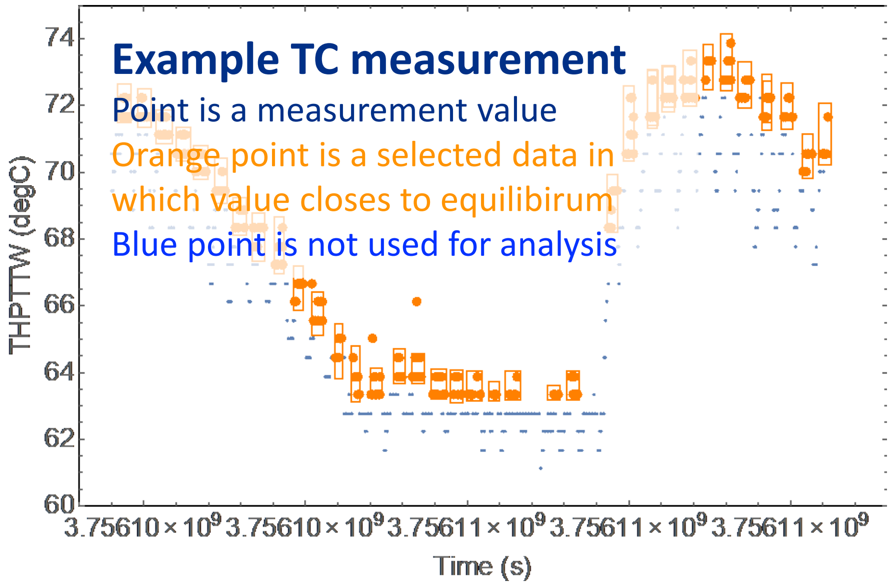
Muon monitor
9 x 9 Pixeled ion chambers to
measure muon flux

Thermocouple Beam Position Sensor (Hylen Device)

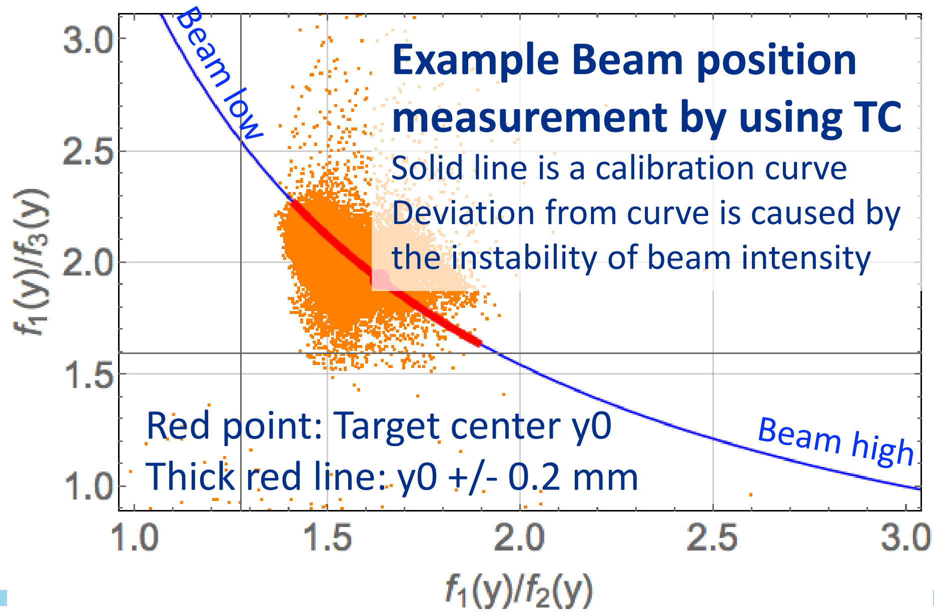


- Beam energy deposition on Beryllium wire
- Measure temperature rise by Thermocouple sensors
- System is very robust; No signal degradation found

Possible issue on Thermocouple sensor

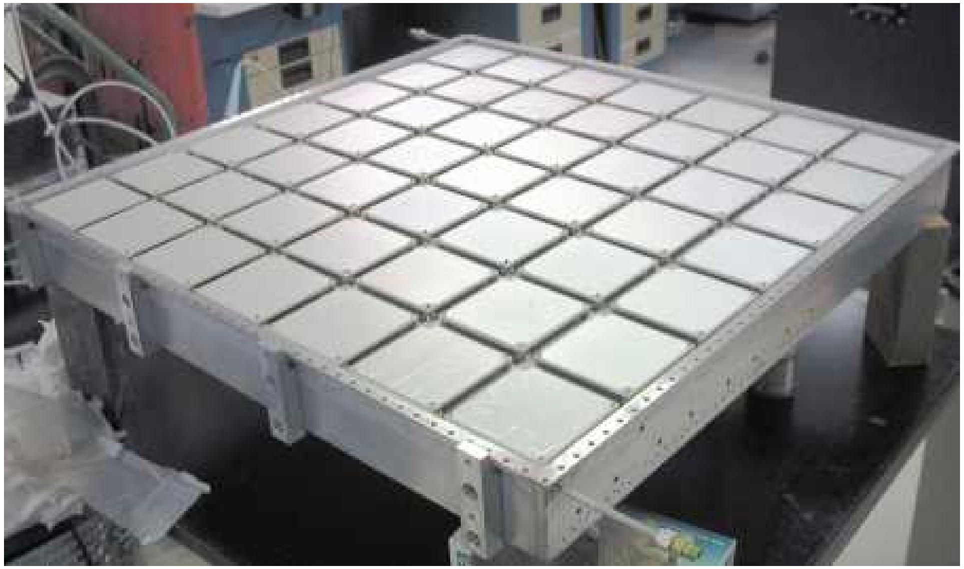


- TC has a relatively long time constant
- Temperature drop each beam gap
- Often a special analysis window needed

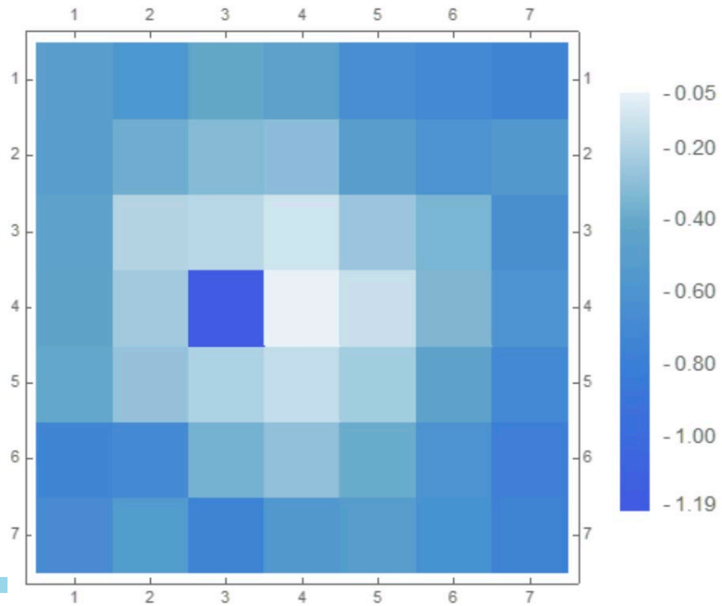


- Determine beam position from TC measurement requires a large set of calibration data
- It also requires a complicate analysis tool

Hadron Monitor

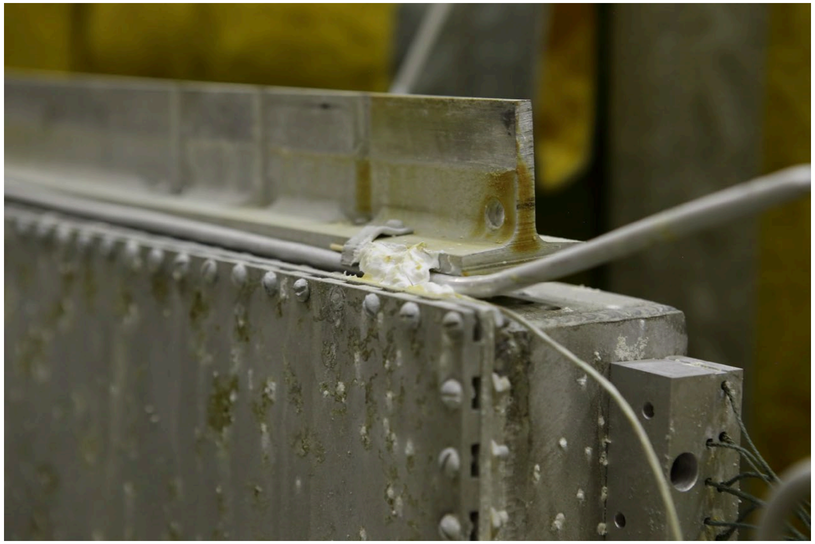


- Hadron Monitor is a pixeled ion chamber
- Picture on left hand side is an old HM which is 7x7 channels
- New HM is 5x5
- Mainly used for beam-based alignment (see NuFACT’23 presentation)

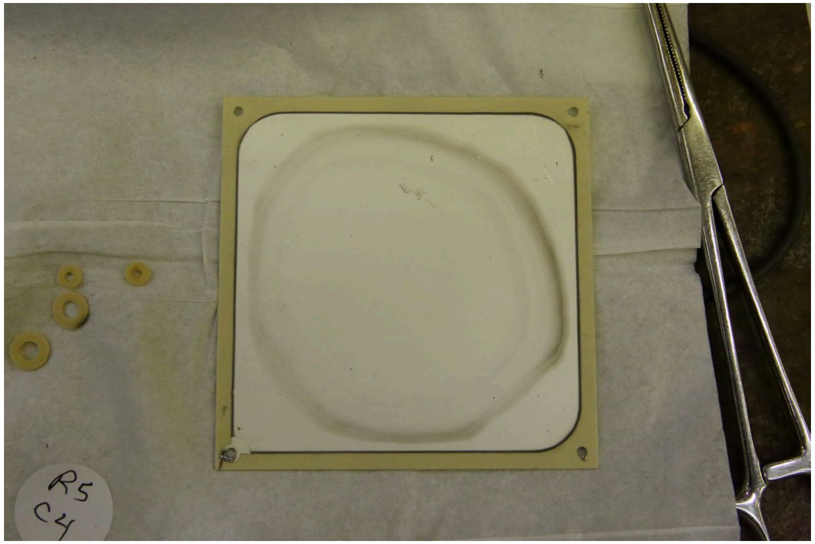


- Example snapshot of the beam profile at HM
- The snapshot was taken a few beam pulses of the 700 kW beam power operation
- One pixel near center shown lower gain than expected due to radiation damage

Inspect Hadron Monitor

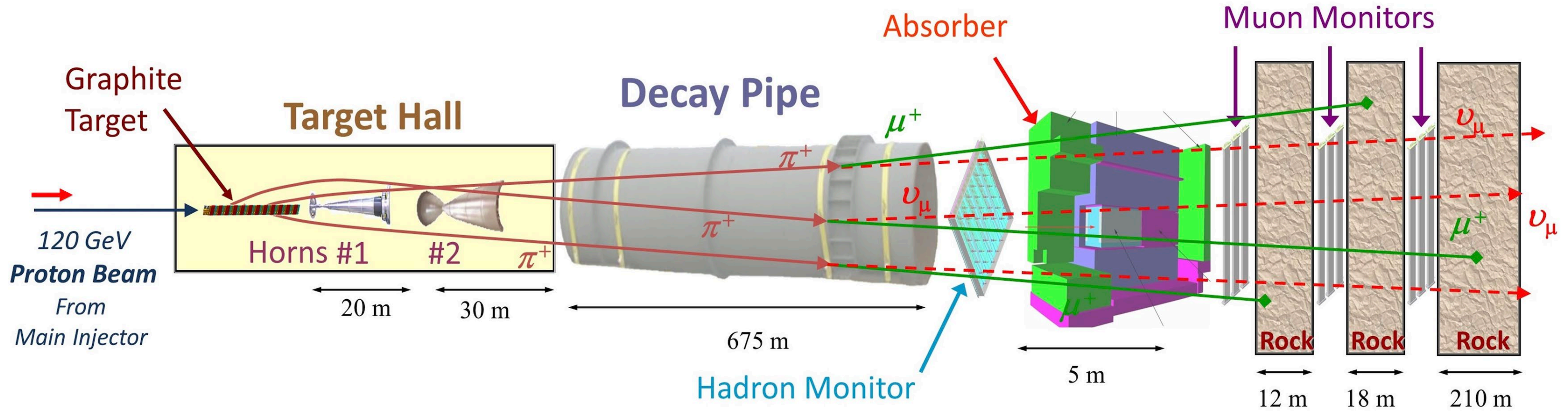


- Picture on top left-hand-side shows top part of second first gen HM (current HM is the seventh gen)
- Glue was discolored (white) and metal surface was heavily corroded



- Picture on bottom left-hand-side shows an electrode of one of pixels
- Au-Pt plate is discolored

Monitor critical beam parameter during operation

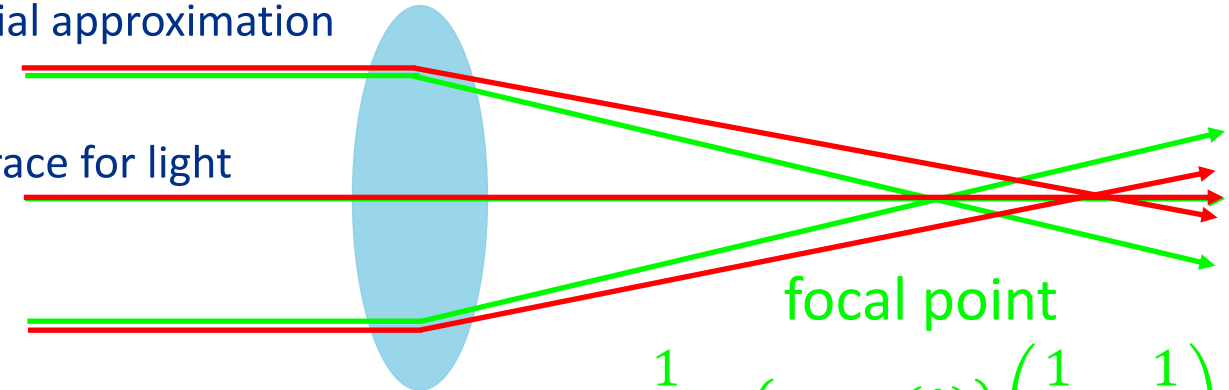


- There is no beam instrumentation near the target
  - Harsh environment
    - High radiation, high temperature, humid, pulsed EM fields
  - Limited space
- Utilize Muon Monitor to monitor target system
  - Demonstrate how the monitor is sensitive to the critical beam parameters

Magnetic Horn Model as Optical Lens

Paraxial approximation

Ray trace for light



Convex light lens

focal point

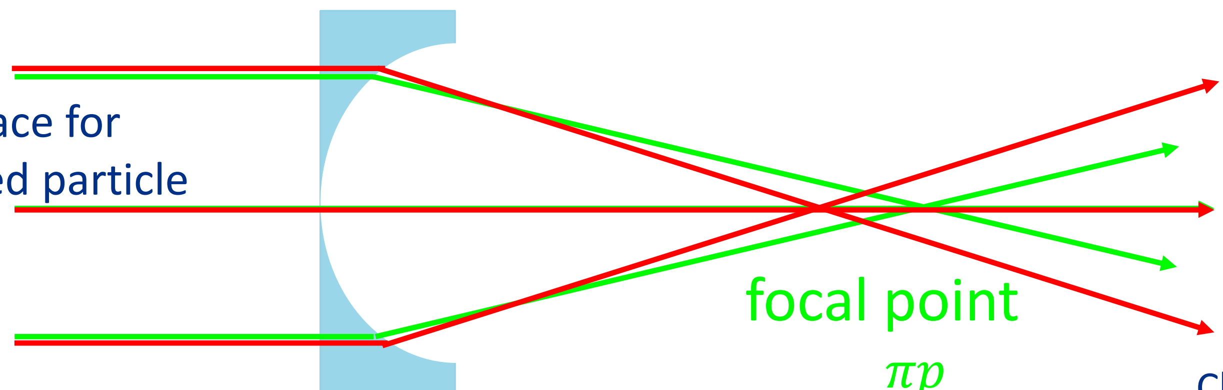
$$\frac{1}{f} = (1 - n(\lambda))\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

Optical lens

$$f_r > f_g$$

Chromaticity aberration because refractive index depends on wavelength

Ray trace for charged particle



Magnetic horn lens

focal point

$$f = \frac{\pi p}{\mu_0 a I}$$

Magnetic horn

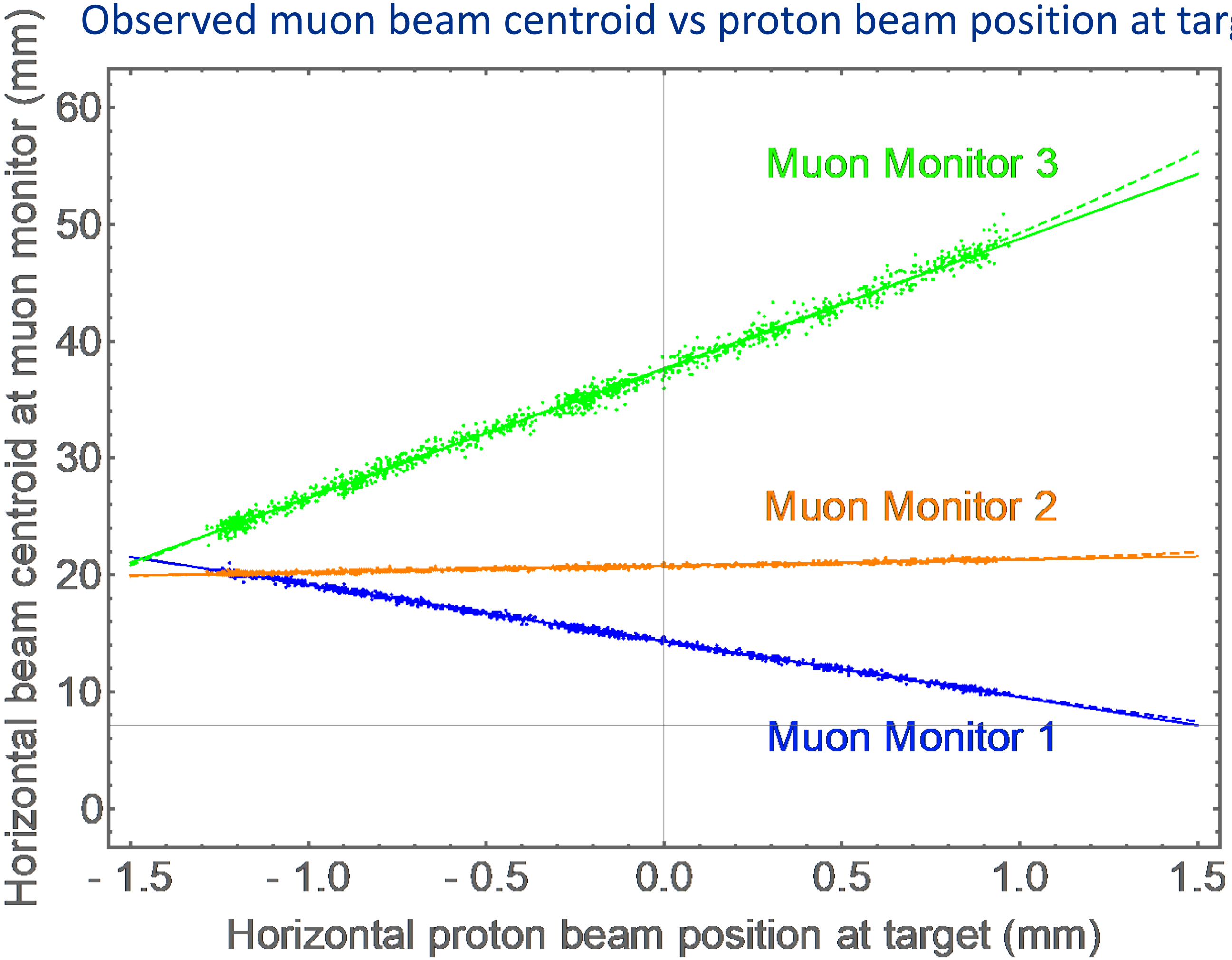
$$f_r < f_g$$

Chromaticity aberration because focal length is proportional to momentum

Magnification of muon image on muon monitors

arXiv:2305.08695

Observed muon beam centroid vs proton beam position at target



Positive slope →
High energy muons shown in muon monitor 3 are underfocused by horns

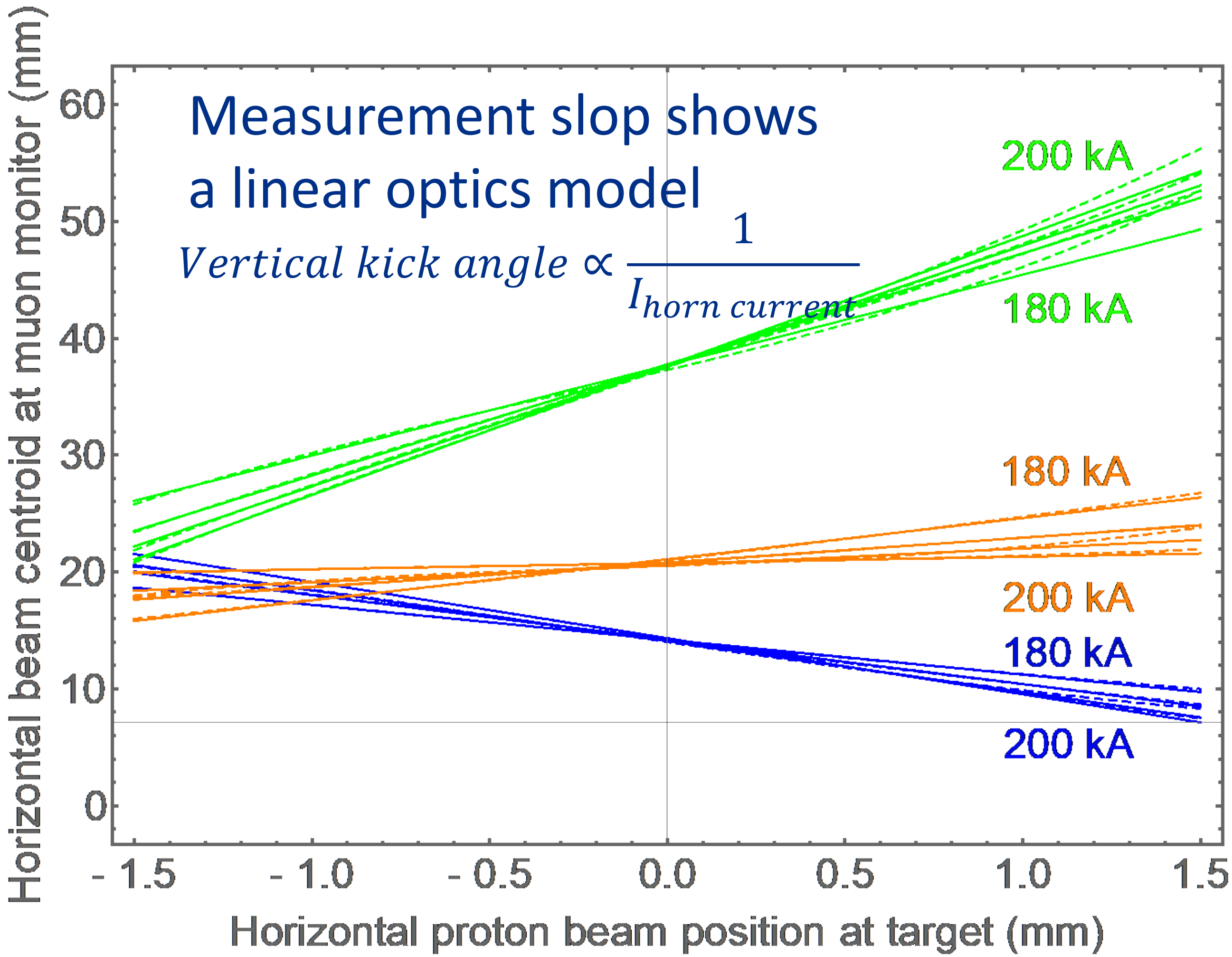
Zero slope →
Medium energy muons shown in muon monitor 2 are on focused by horns

Negative slope →
Low energy muons shown in muon monitor 1 are overfocused by horns

Slope size shows a magnification factor of the lens

Horn current dependence

arXiv:2305.08695

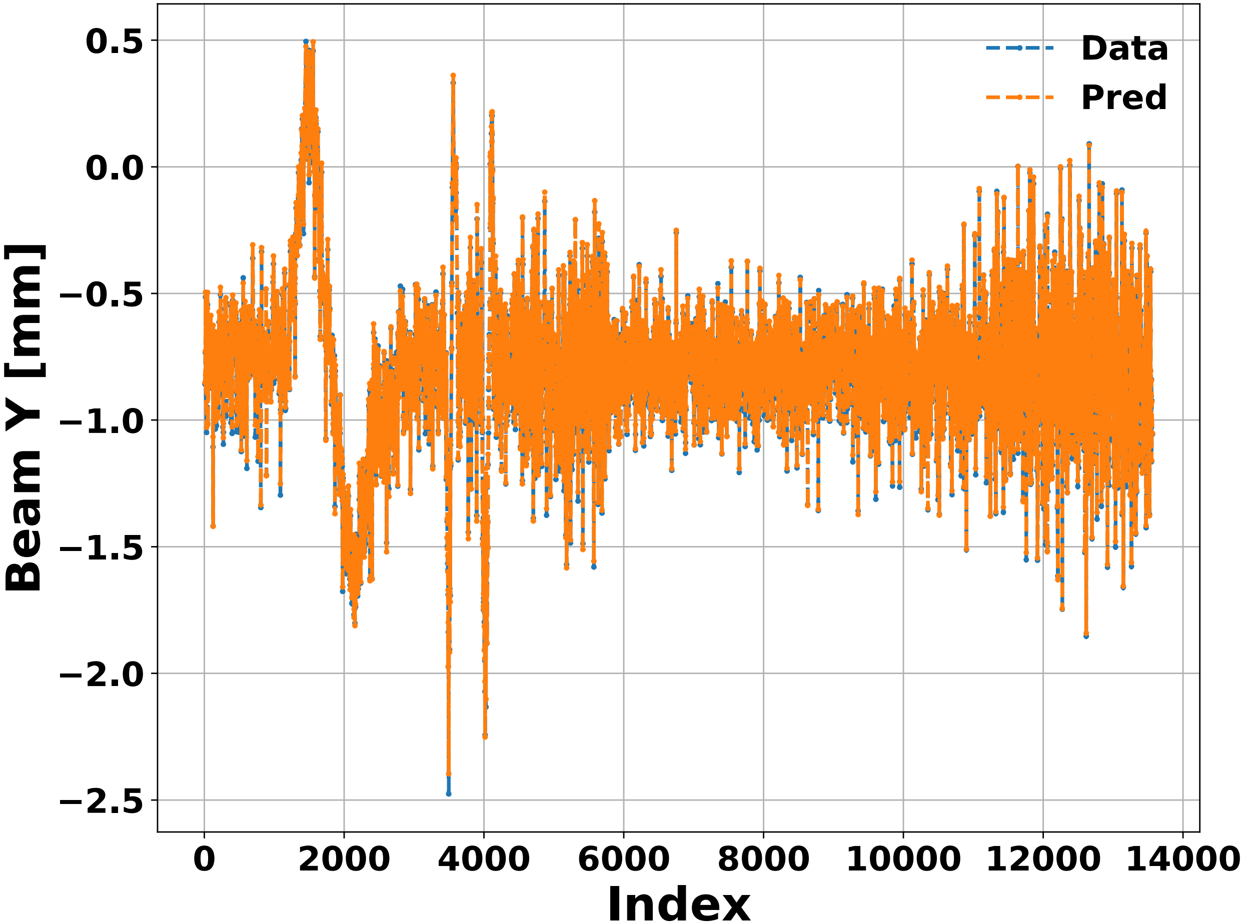


Slope is changed by the horn current and the change is unique for each monitor.
Muon monitor 2 will be the most sensitive monitor for the horn current because the slope is deviated from zero.
Intersection of curves may indicate the effective beam axes of low, medium, and high energy muons (study is on going).

Fermilab

Demonstrate Machine Learning to extract beam parameter from muon monitor signal (I)

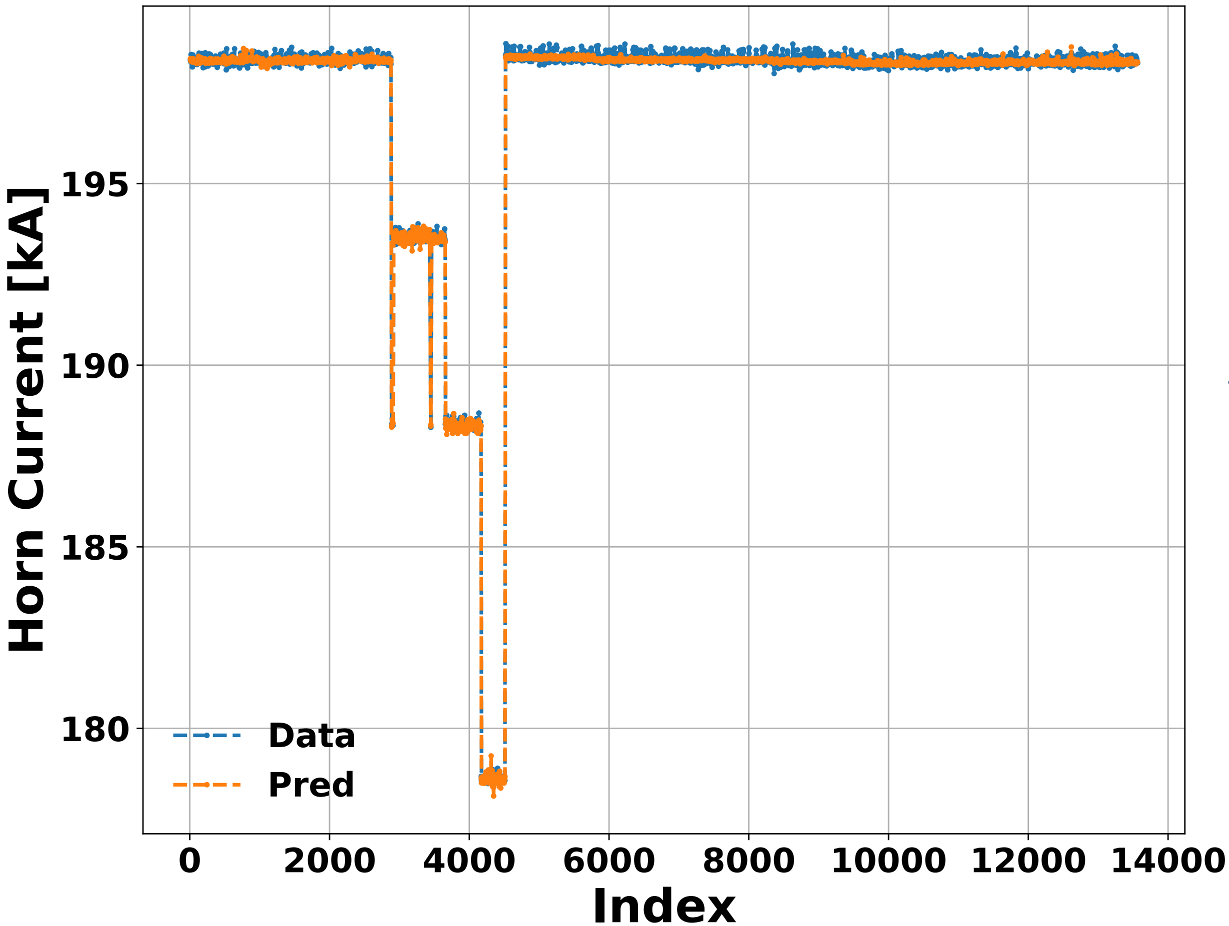
arXiv:2305.08695



Demonstrated ML to predict beam position at the target. The accuracy of training data (= accuracy of bpm) is 0.02 mm. Deviation of ML prediction is 0.02 mm. This suggests that the observed small fluctuation of beam position measurement is a **real** beam motion.

Demonstrate Machine Learning to extract beam parameter from muon monitor signal (II)

arXiv:2305.08695



Demonstrated ML to predict horn current.
Horn current is predicted by ML within the accuracy of +/- 0.05 %.
Beam intensity is predicted by ML within the accuracy of +/- 0.1 %.

Summary

- R&D of Radiation Hardened Beam Instrumentation is crucial for future intense beam and target facilities
  - Proposed R&D plan to DOE for establishment of the exchange program between BES and HEP communities
- Mini virtual workshop for Rad Hard Beam Inst. was held
  - Rad hard light optics and photosensors are highly demanded
- Demonstrate NuMI beam instrumentation
  - Muon monitor is accurate target monitor
  - AI/ML is a very useful tool for analysis; AI/ML predicts proton beam parameters and horn current significantly better than the estimated physics tolerance