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Develop Radiation Hard Beam Monitor and Muon Spectroscopy by using Machine Learning for Intense Neutrino Target System

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CPAD Workshop

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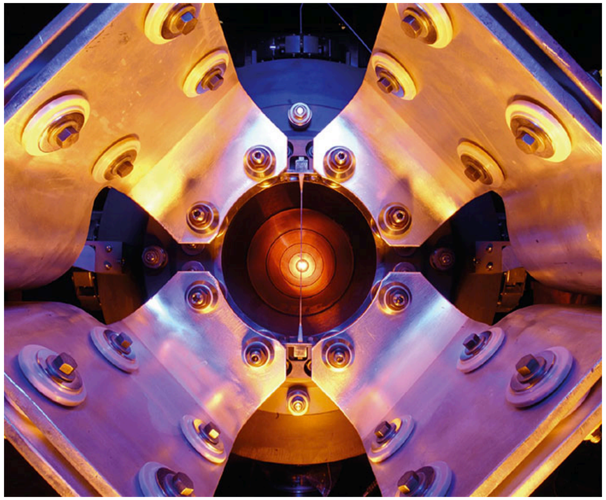
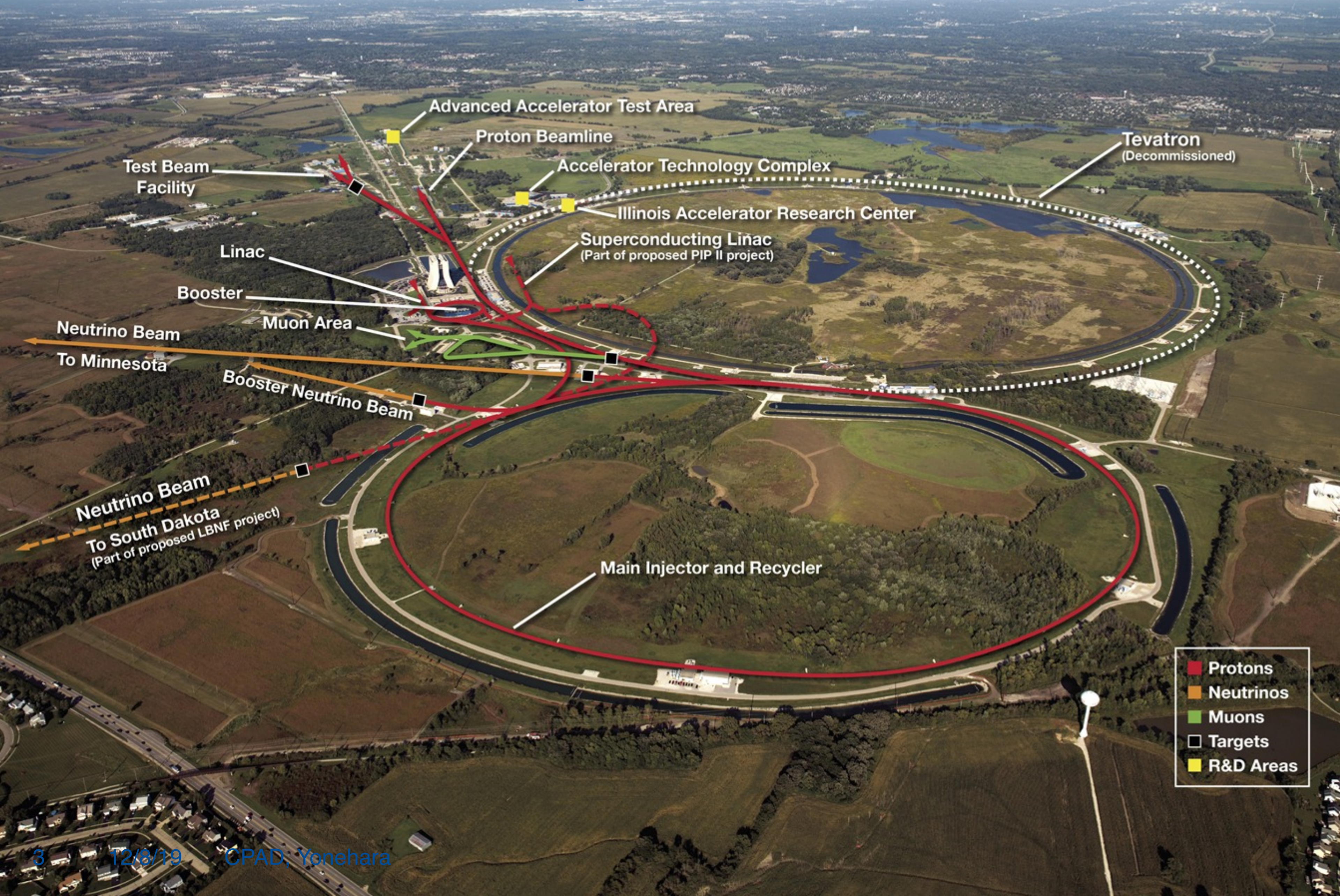


Fermilab Intensity Upgrade Plan

- NuMI-AIP (Neutrinos at the Main Injector – Accelerator Improvement Plan)
  - Upgrade existing Fermilab accelerator complex with the same footprint to increase proton beam intensity on the NuMI target from 780 kW to **> 900 kW**
  - Machine operation starts from **2020**
- LBNF (Long Baseline Neutrino Facility)
  - Apply PIP-II SRF Linear Accelerator to send **1.2 MW** beam to the LBNF target
  - Machine operation will start from **2029**
  - Extend to PIP-III SRF Linac to reach **2.4 MW** beam power
  - Operation year **TBD**

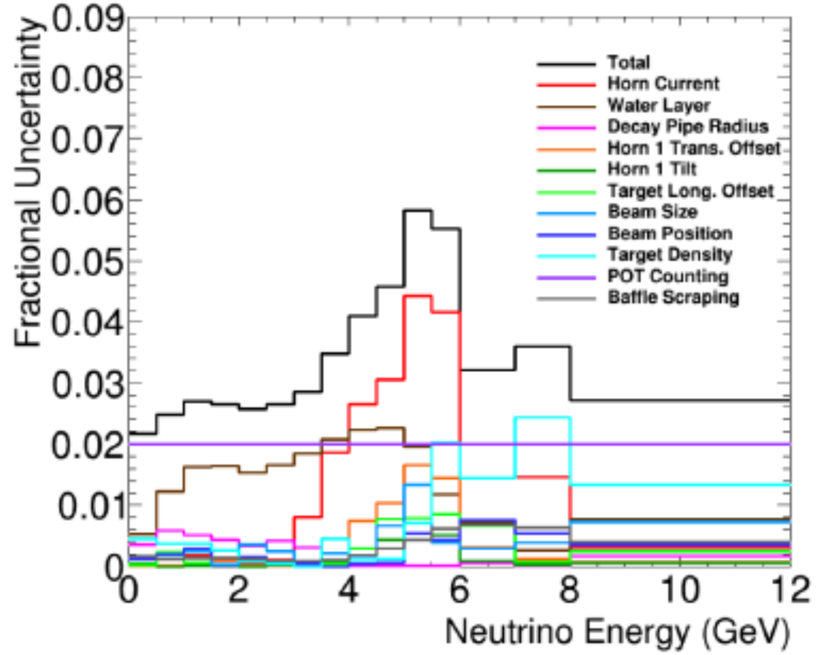
Fermilab Accelerator Complex



Beam Monitor for multi-MW Target System

- Tolerance of the target parameter at LBNF
  - Tighter than NuMI

Parameter	Tolerance
Target Position (each end)	0.5 mm
Horn A Position (each end)	0.5 mm
Horn B Position (each end)	0.5 mm
Horn C Position (each end)	0.5 mm
Decay Pipe Radius	0.1 m
Horn Current	3 kA
Horn water layer thickness	0.5 mm
Beam radius at target	0.1 mm
Baffle Scraping	0.25%
Beam position at target	0.45 mm
Beam angle at target	70 microradians
Target Density	2%
Protons on Target	2%



- **Beam monitor is a real-time (spill-by-spill) detector to check quality of multi-MW target system**
  - High reliability and long lifetime (rad hard) required

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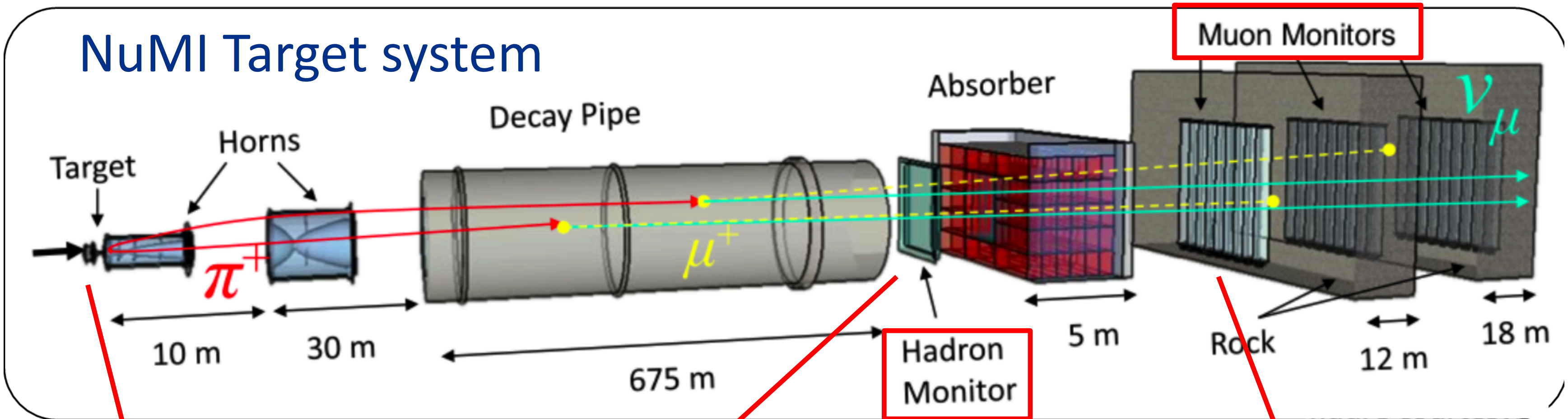
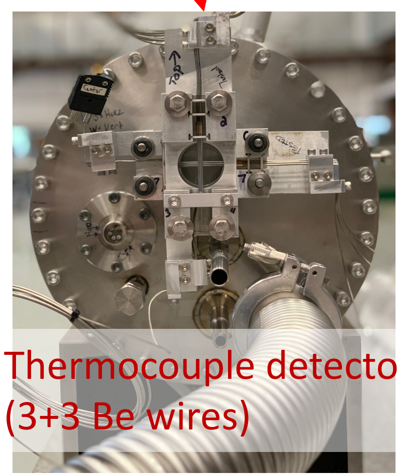
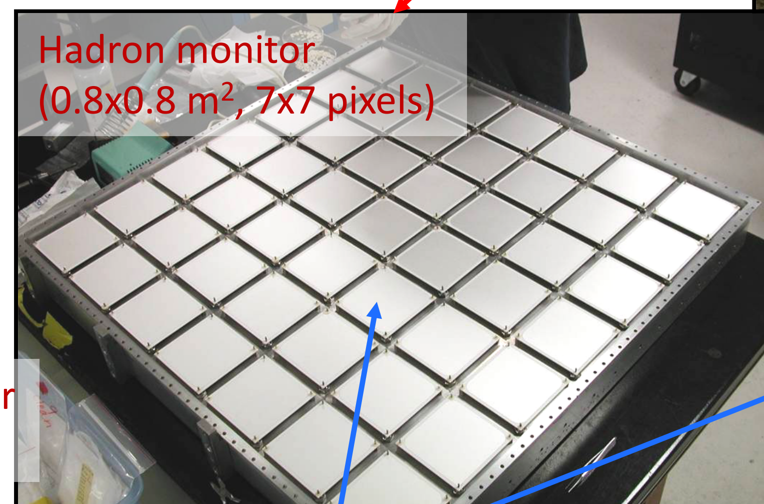
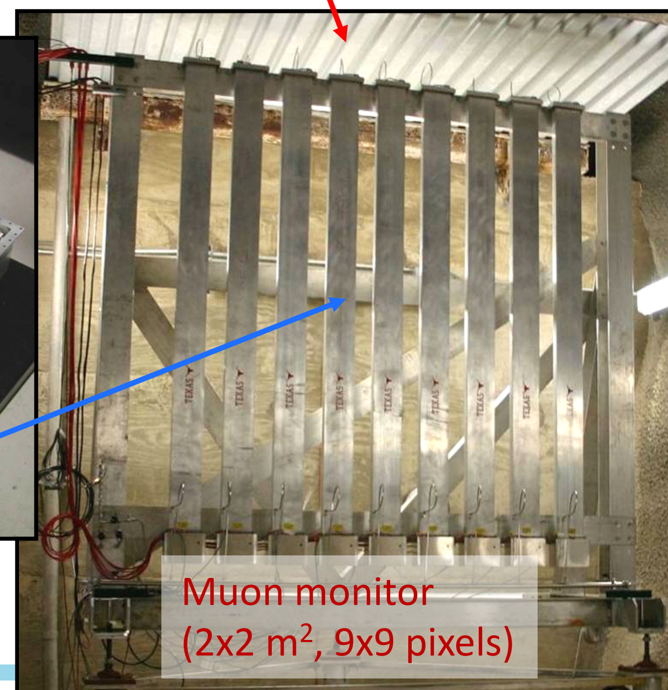
Develop Rad-Hard Beam Monitor System







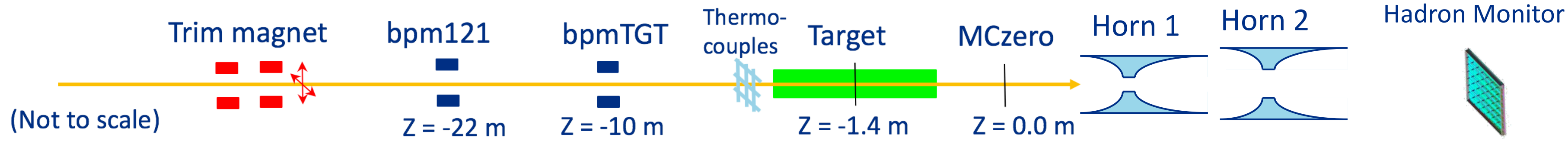


Multi-pixel ionization chamber

Beam Monitor for Beam Based Alignment

- Target beam elements were occasionally displaced or broken by various incidents
  - Radiation damage, thermal expansion, thermal shock, water leak, Helium gas leak, etc
- Beam based alignment permits us to find baffle, target and horn positions w.r.t. the BPM coordinate by using beam monitors
- **<u>Position resolution less than 0.2 mm is achieved</u>**

Layout of beam based alignment

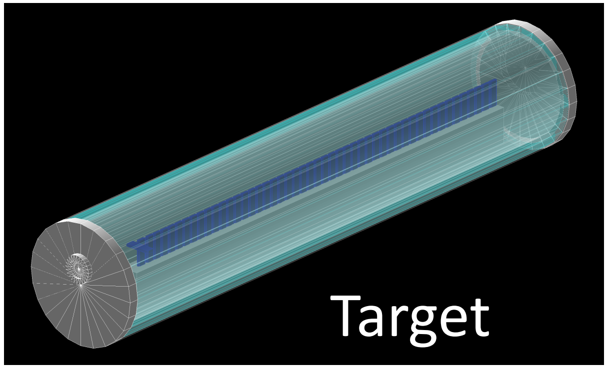


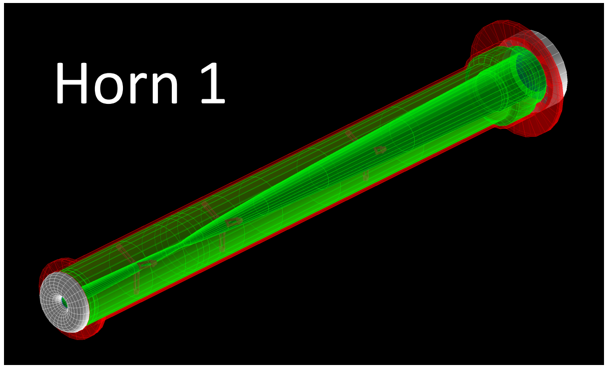
- Beam position and angle are measured by two bpms
- Beam position on target is observed by thermocouple sensor
- Scan requires a special beam condition, but it takes less than hour

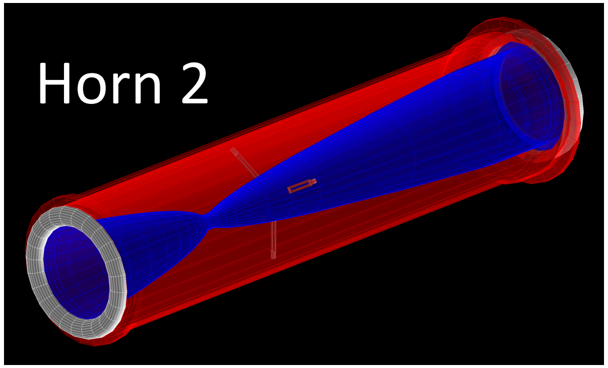
Upgrade Beam Monitor for 1-MW operation

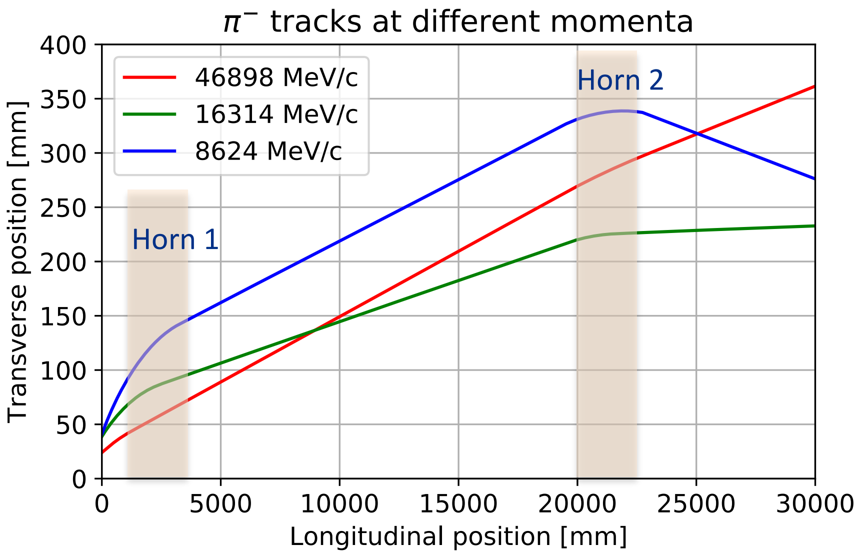
- Develop rad-hard ionization chamber
- Observed signal gain change by varying He gas quality
  - Calibration chamber can calibrate the gain change due to gas quality, but this is not the perfect solution
  - Apply a new gas system
    - Density flow control by using PLC
    - Add bubbler on the outlet of HM to avoid backflow
- Use a radiation hard material
  - Apply radiation hard ceramics for insulator and cable
- Optimize the dimension of monitor system
  - Beam profile simulation
  - Space charge simulation

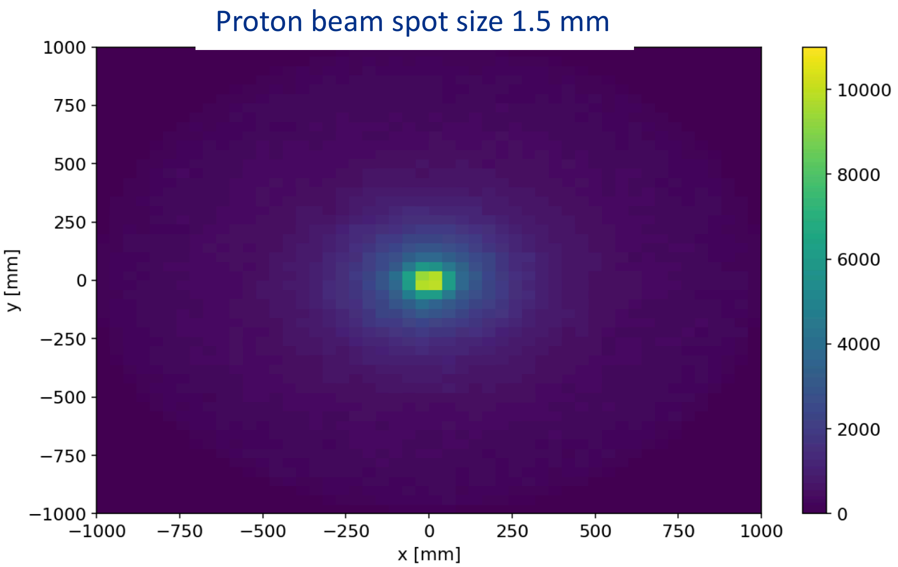
Particle Tracking in Simulation







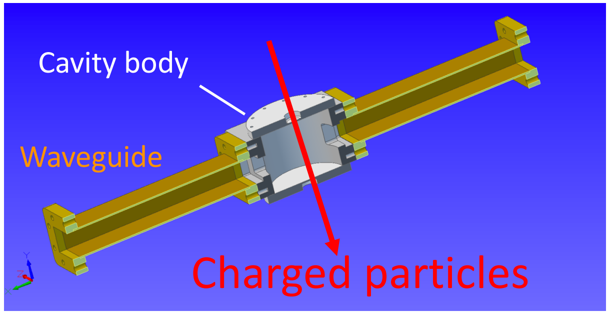




Shows Aberration of horns

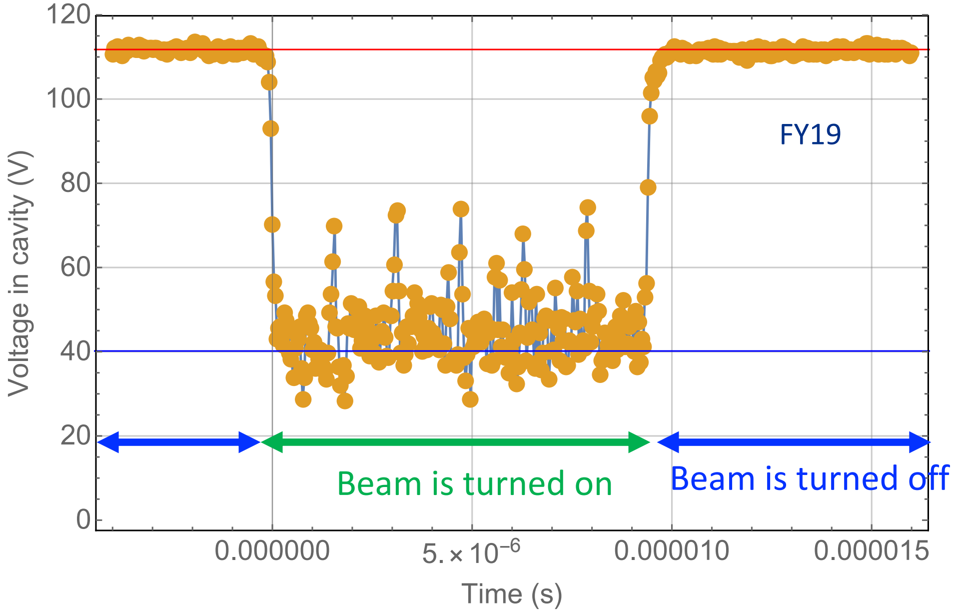
Beam profile on hadron monitor

Alternate Hadron Monitor



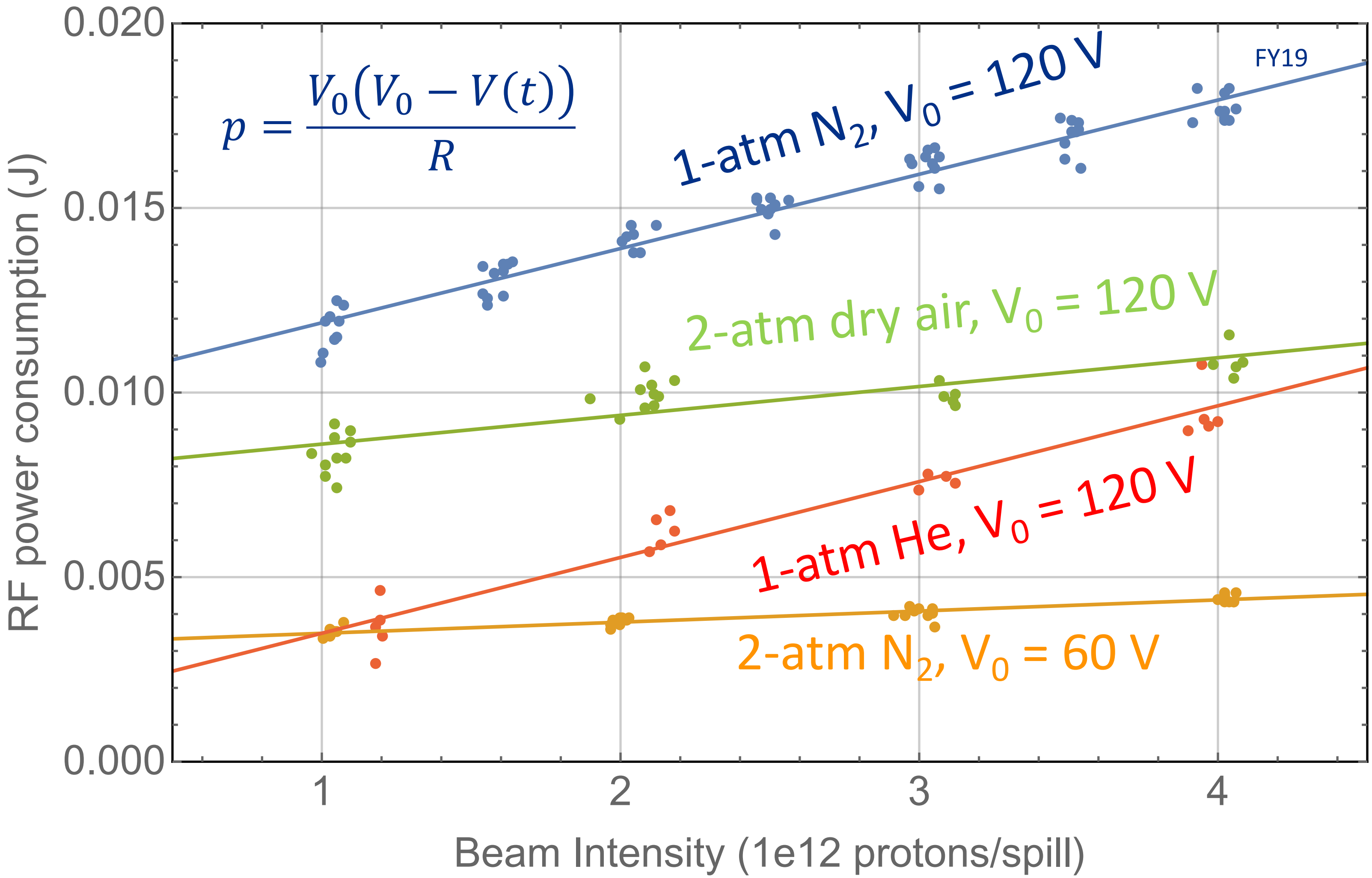
- RF beam detector
- Conceptually new rad-hard beam detector
- Apply RF field to measure the amount of ionization gas plasma which is proportional to the intensity of charged particles passing through a RF cavity by measuring gas permittivity change $\varepsilon = \varepsilon_r + i\varepsilon_i$
- Proof-of-principle test was carried out by using the Main Injector 120 GeV proton beam

- Beam intensity = 1.3e13
- Detector filled with ambient air



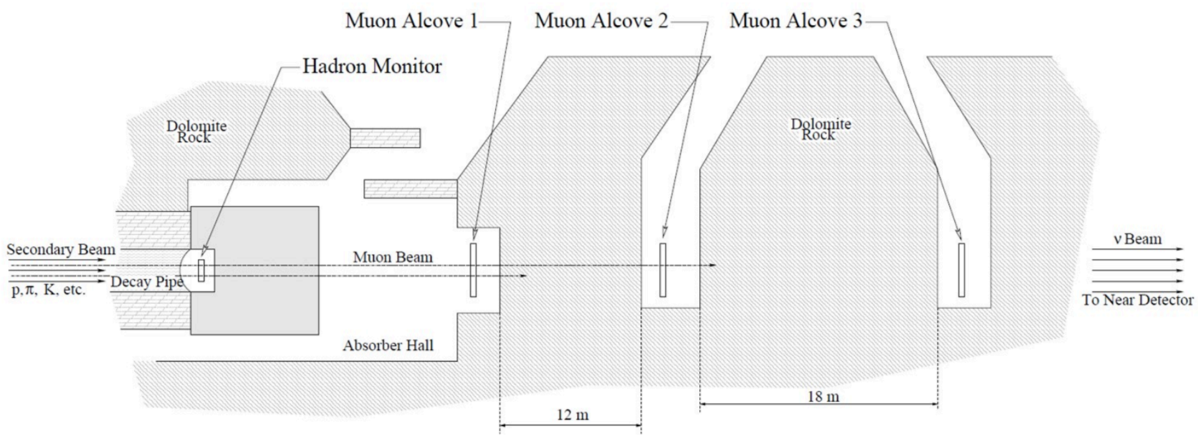
Five peaks during the beam on shows the gap of six MI beam batches

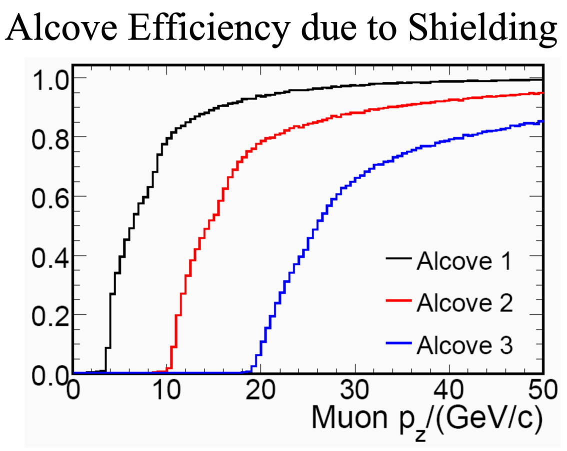
Linearity of RF beam detector



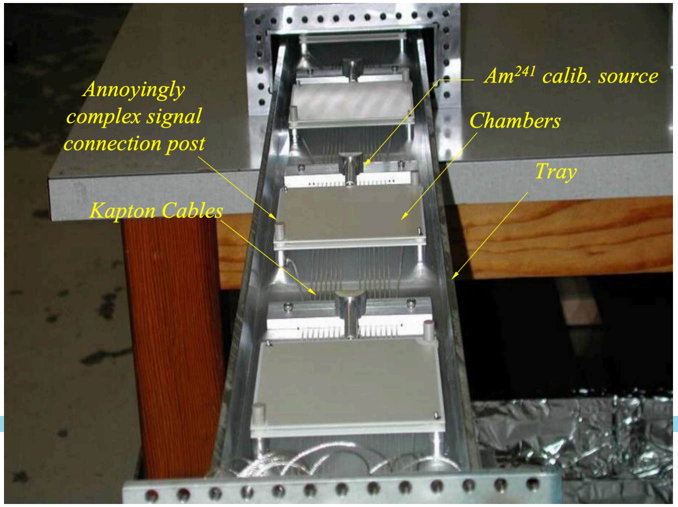
Muon Monitor

- Three monitor receive different energy muons

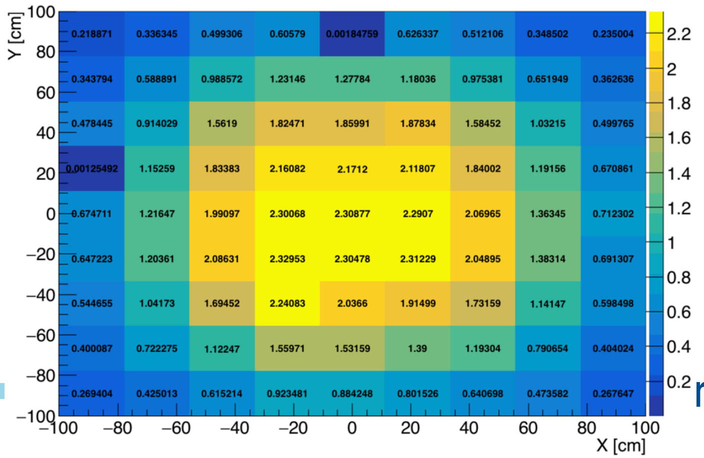




- Similar structure as Hadron monitor



Muon Monitor 1 signal



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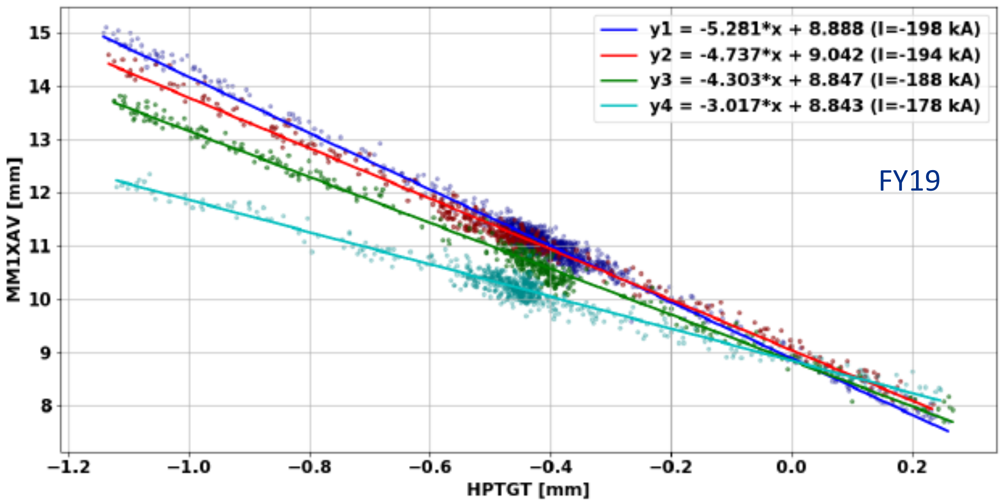
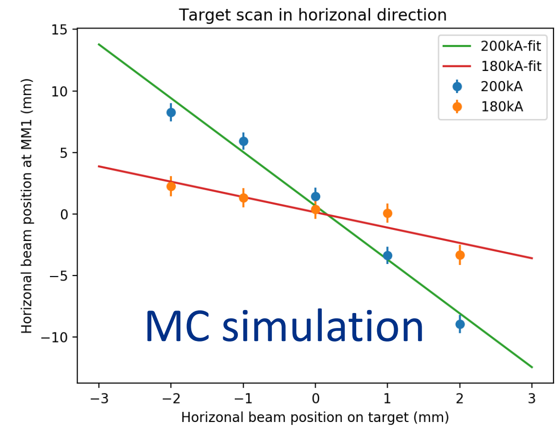
Systematic measurement

Horizontal scan

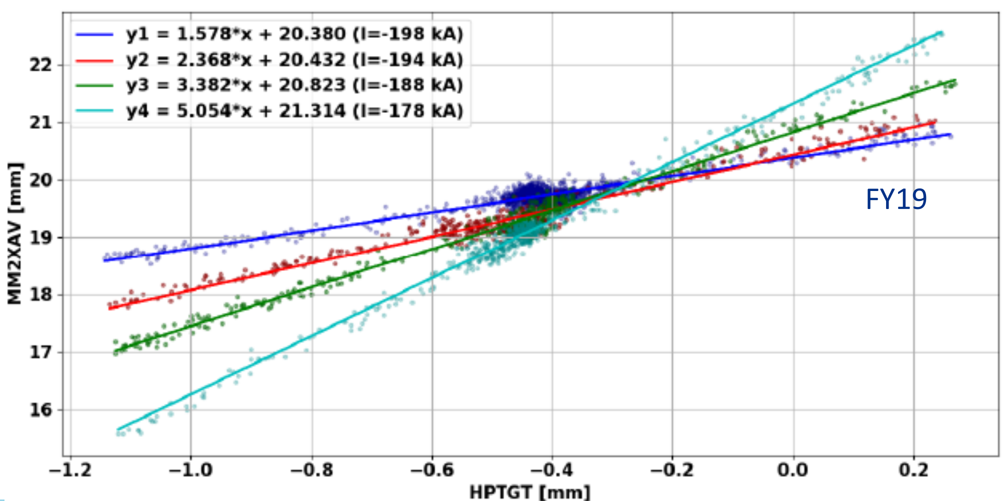
MM1



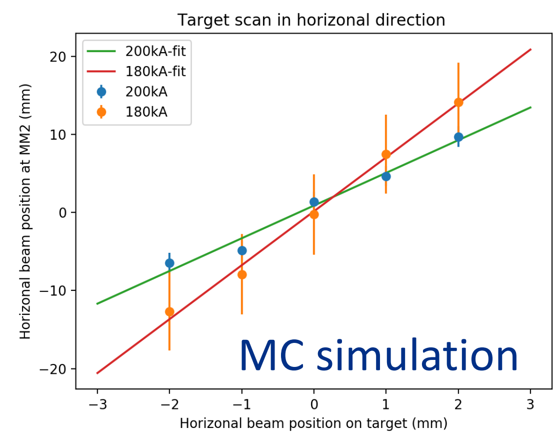
Strong linear correlation between primary proton beam and muon beam centroid on Muon Monitors



MM2



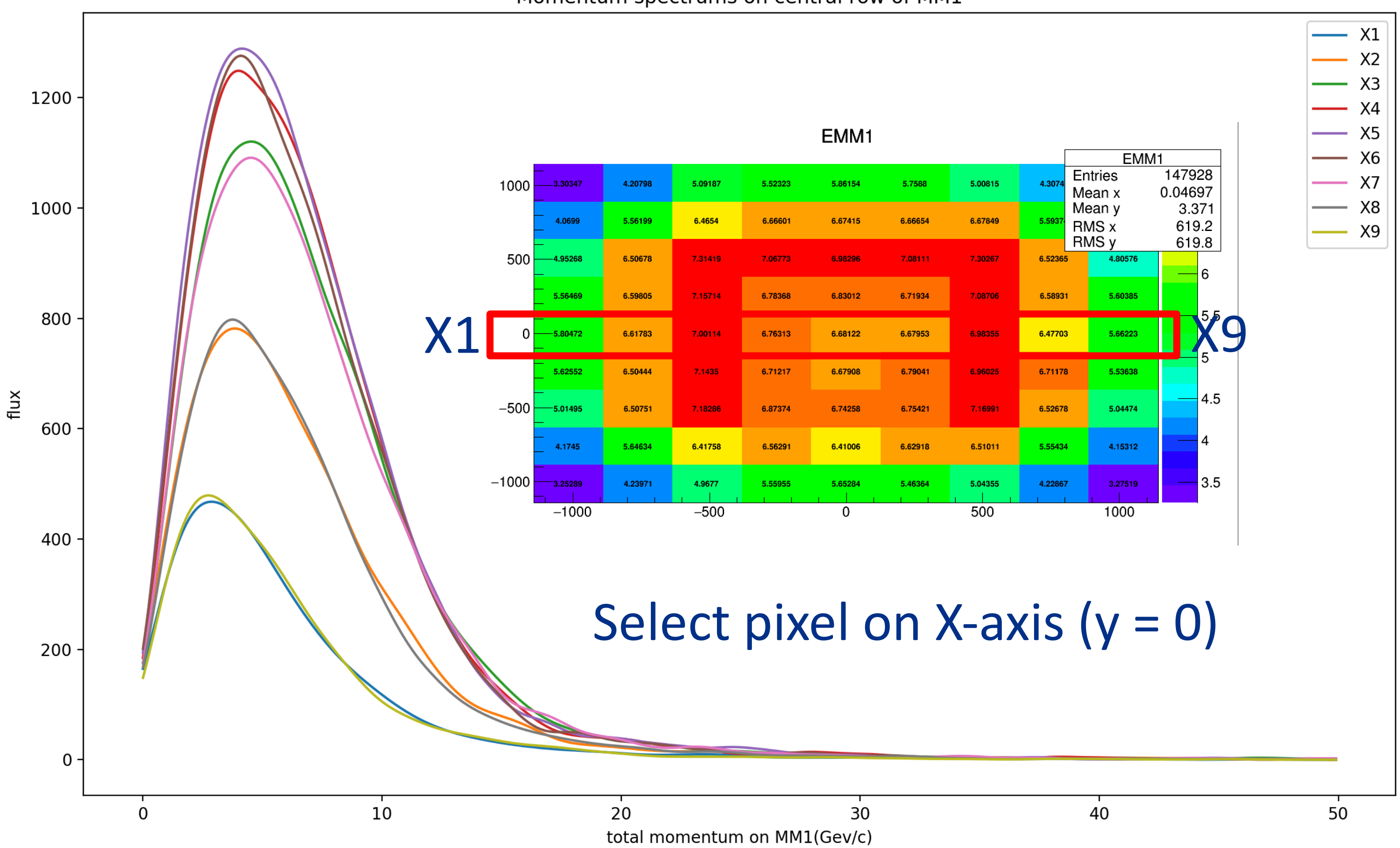
MM2 shows opposite slope from MM1 due to **Aberration of horns**



Pion/Muon Spectroscopy

Magnetic horns have an analyzing power

MC simulation



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

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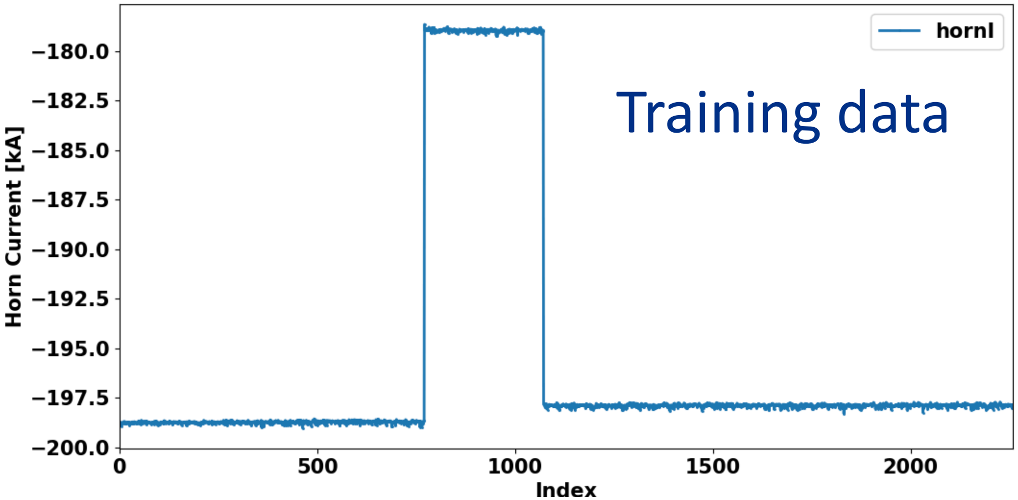
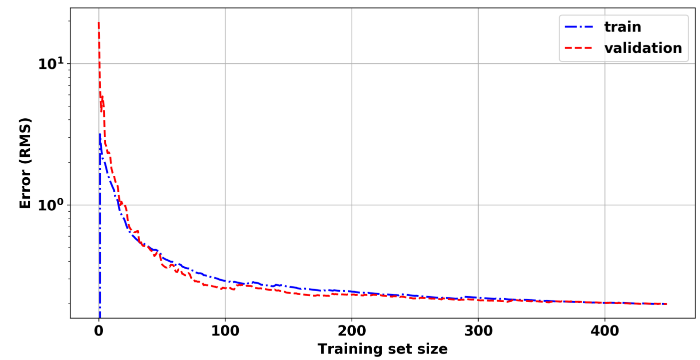
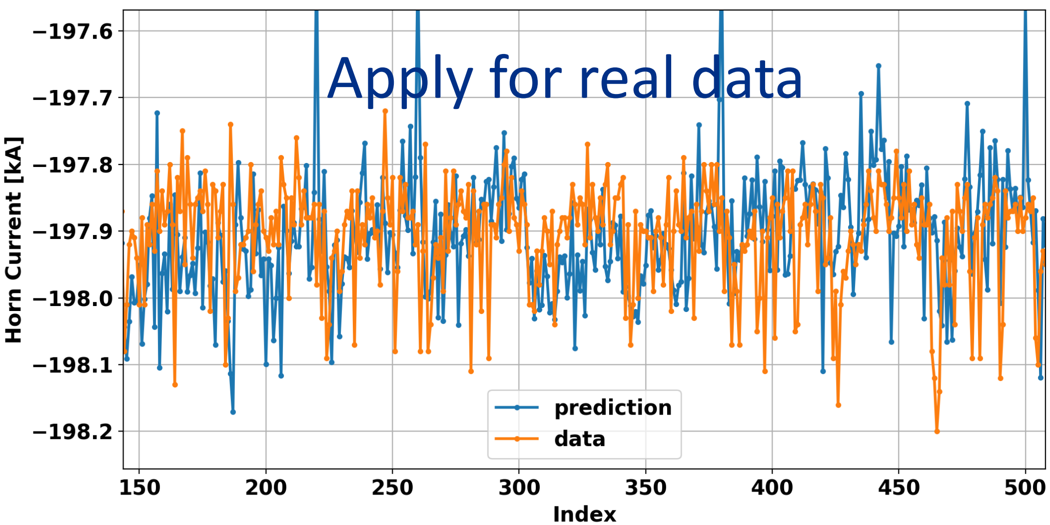
Predicted Horn Current by using Machine Leaning

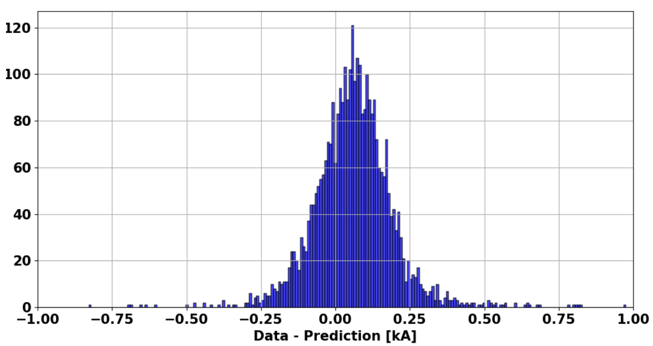
$$\vec{R}_{MM} = f\left(\vec{r}_{beam}, \vec{\sigma}_{r_{beam}}, I_{Horn}, gas\ parameter\right)$$







Horn Current Error RMS = 0.152 kA



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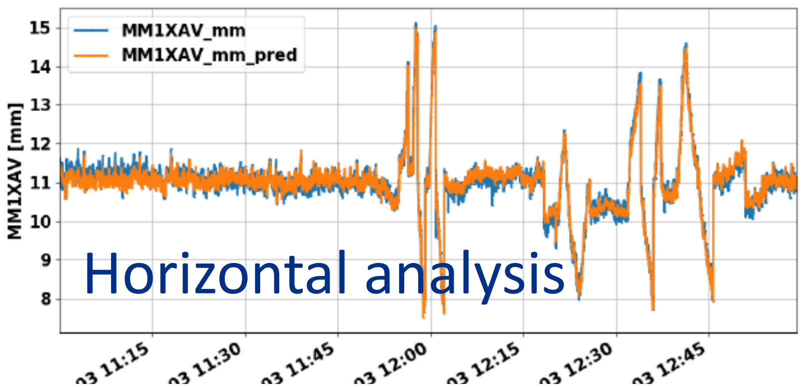
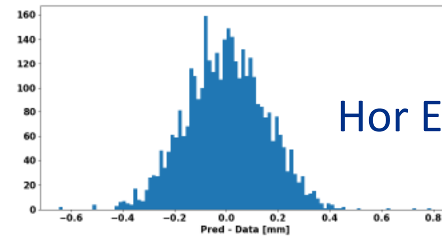
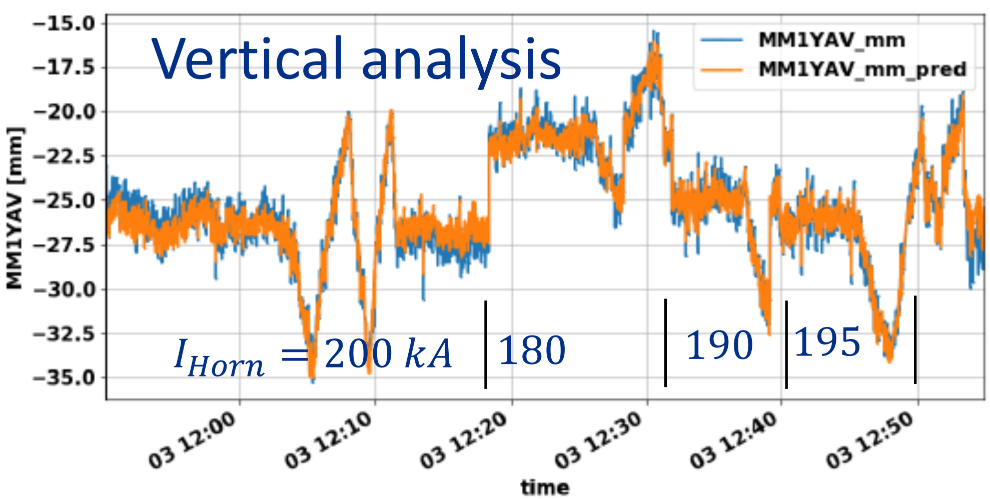
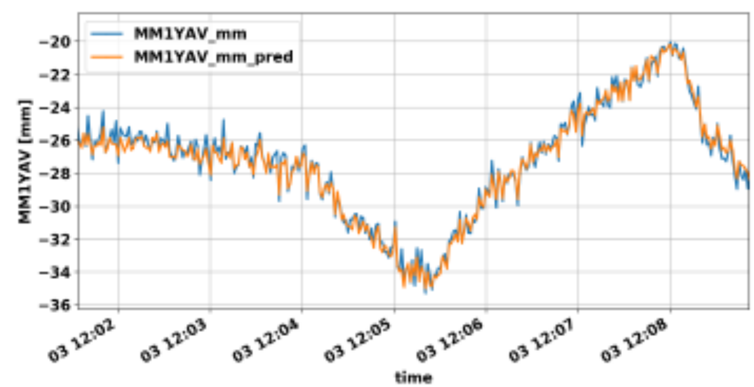
Predicted Beam centroid on Muon Monitor with ML

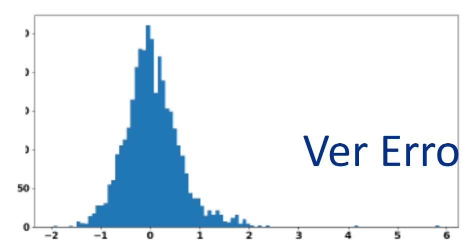
$$\vec{R}_{MM} = f(\vec{r}_{beam}, \vec{\sigma}_{r_{beam}}, I_{Horn}, gas\ parameter)$$











Summary

- Study three beam monitors
  - Demonstrate that beam monitors is capable to operate the target system within the design tolerance
  - Introduce Machine Learning to make an automatic monitor system
  - **Study Pion/Muon spectroscopy by using aberration of horns**
- Develop rad hard ion chamber for multi-MW target
  - New gas system to prevent gas contamination
  - Plan to simulation study to minimize space charge effect
  - Develop RF beam detector
    - Plan more R&D to make a practical detector

Acknowledgement

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  - Karol Lang, Marek Proga from U of Texas Austin
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