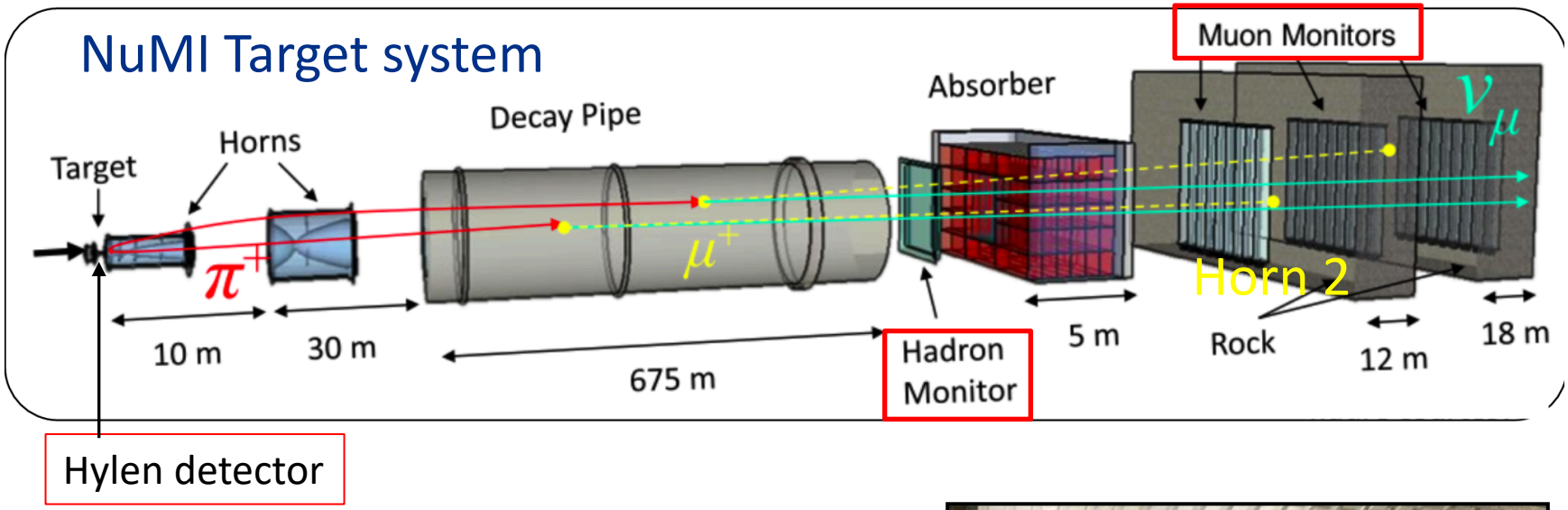
NuMI Beam Monitor System

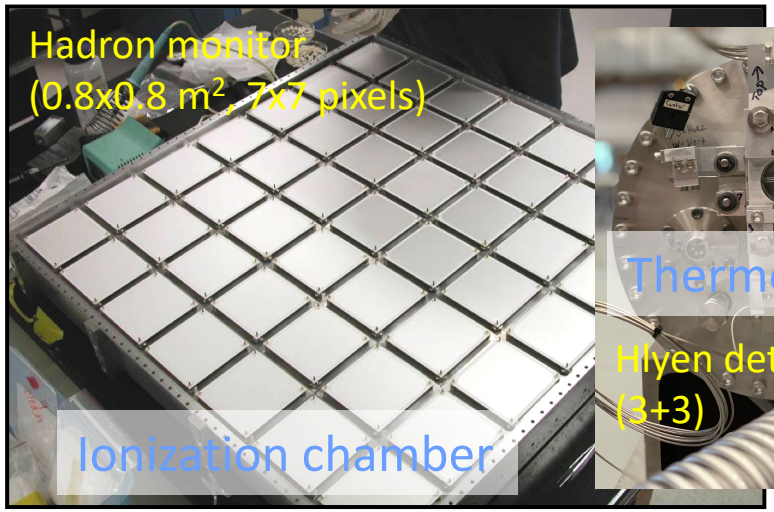
Katsuya Yonehara

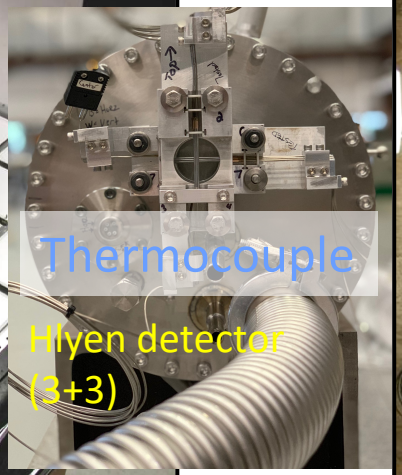
NBI Workshop

10/25/2019

NuMI Beam Monitor System

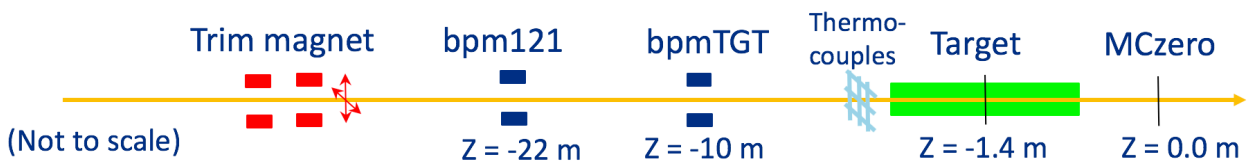






NuMI Hadron Monitor

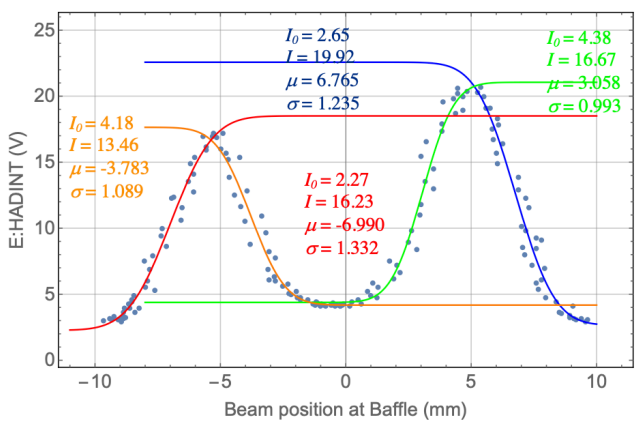
- Originally designed for monitoring target density degradation and for measuring proton beam profile on target spill by spill
- Soon after, we realize that the monitor is also useful for beam-based alignment with proton tomography



- Beam position and angle are measured by two bpms
- Beam position on target is observed by Hylen device (3v+3h Thermocouple Be wires)

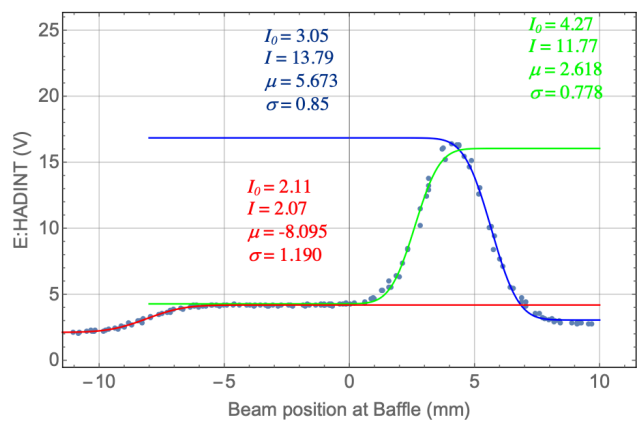
$$g(x,\mu,\sigma,I,I_0) = I_0 + \int \frac{I}{\sqrt{2\pi}\sigma} exp\left[-\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)^2\right] \mathrm{dx} = I_0 + \frac{I}{2}\left(Erf\left[\frac{x-\mu}{\sqrt{2}\sigma}\right]+1\right)$$

Horizontal scan

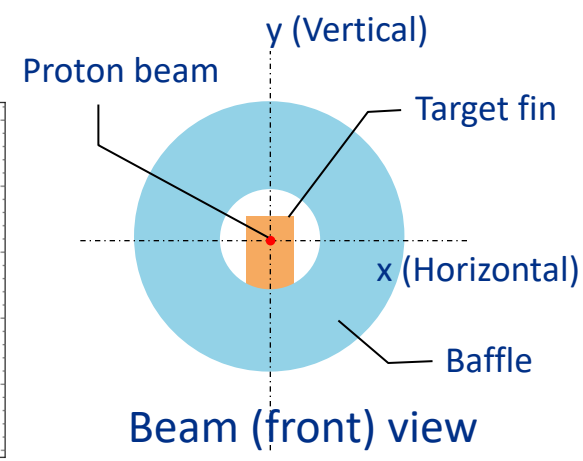


Baffle = -0.113 mm
Target = -0.362 mm

Vertical scan

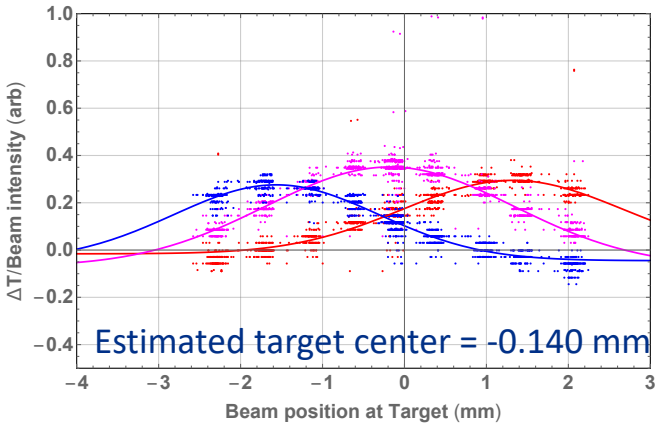


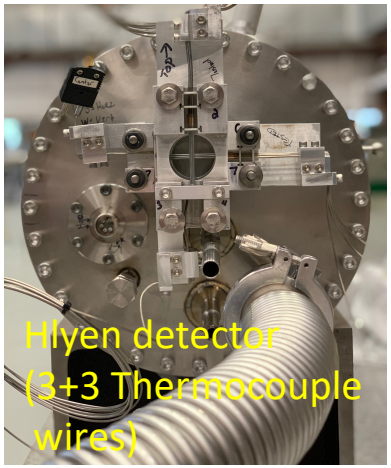
Baffle = -1.211 mm
Target = 2.618 - 3.7 = -1.082 mm



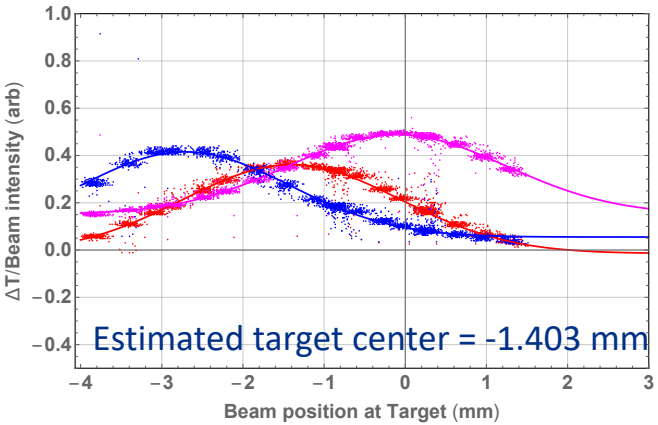
Hylen device and Summary of Beam Scan

Horizontal scan





Vertical scan

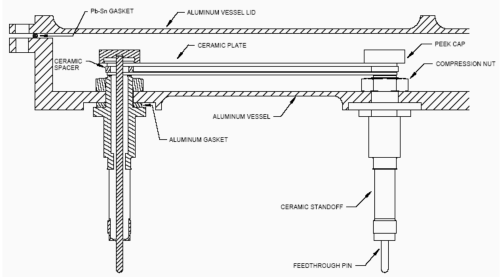


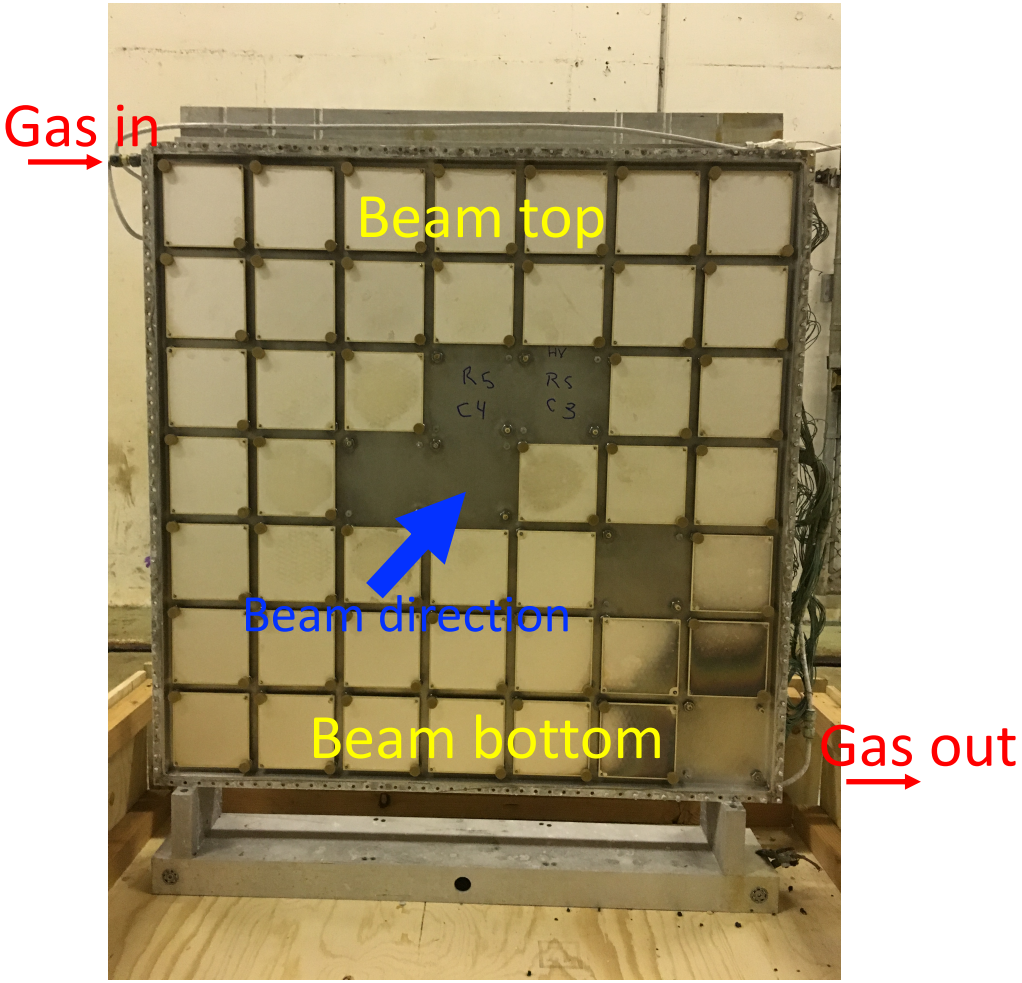
mmin	prev	H bp (mm)		11-Jan-19 3nd target scan station (m)		thpt scan med bear (mm)	hpt scan ligh beam (mm)	average X (mm)	residual (mm)	Wes est (mm)	esid/es	square of resid (R/E)^2
	-0.6	-0.55	set	bpm121	-22							
	-0.5	-0.35	set	bpmtgt	-10							
		-0.223		baffle	-2.4			-0.113	0.11	0.5	0.22	0.04912724
		-0.207		tgt	-1.4	-0.14	-0.295	-0.217	-0.01	0.5	-0.02	0.00046512
		-0.183		MCZERO	0							
		-0.17	extrap	neck	0.82			-0.52	-0.35	0.5	-0.70	0.49092957
		-0.128	extrap	H1 DS fin	3.343			-0.023	0.11	0.7	0.15	0.02250305
		0.146	extrap	H2 US fin	19.76			0.9757	0.83	1	0.83	0.68845519
		0.2127	extrap	H2 DS fin	23.76					1		
		11.633	extrap	HM	709			16.0	4.37	27	0.16	0.02615607
		H										1.27763626
		slope										
		0.2 mm										
		0.0167 mr										

mmin	prev	V bp (mm)		11-Jan-19 3rd beam scan station (m)		tvpt scan Med bear (mm)	tvpt scan ligh beam (mm)	average X (mm)	residual (mm)	Wes est (mm)	esid/est	square of resid (R/E)^2
	-0.55	-1.02	set	bpm121	-22							
	-0.65	-1.17	set	bpmtgt	-10							
		-1.265		baffle	-2.4			-1.211	0.05	0.5	0.11	0.01149184
		-1.278		tgt	-1.4	-1.403	-1.624	-1.514	-0.24	0.5	-0.47	0.22321845
		-1.295		MCZERO	0							
		-1.31	extrap	neck	0.82			-1.544	-0.24	0.5	-0.48	0.22762656
		-1.34	extrap	H1 DS fin	3.343			-0.704	0.63	0.7	0.90	0.81795786
		-1.542	extrap	H2 US fin	19.76			-1.942	-0.40	1	-0.40	0.15984004
		-1.592	extrap	H2 DS fin	23.76					1		
		-10.16	extrap	HM	709			-20.6	-10.44	27	-0.39	0.14958272
		V										1.58971747
		slope										
		-0.150 mm										
		-0.013 mr										

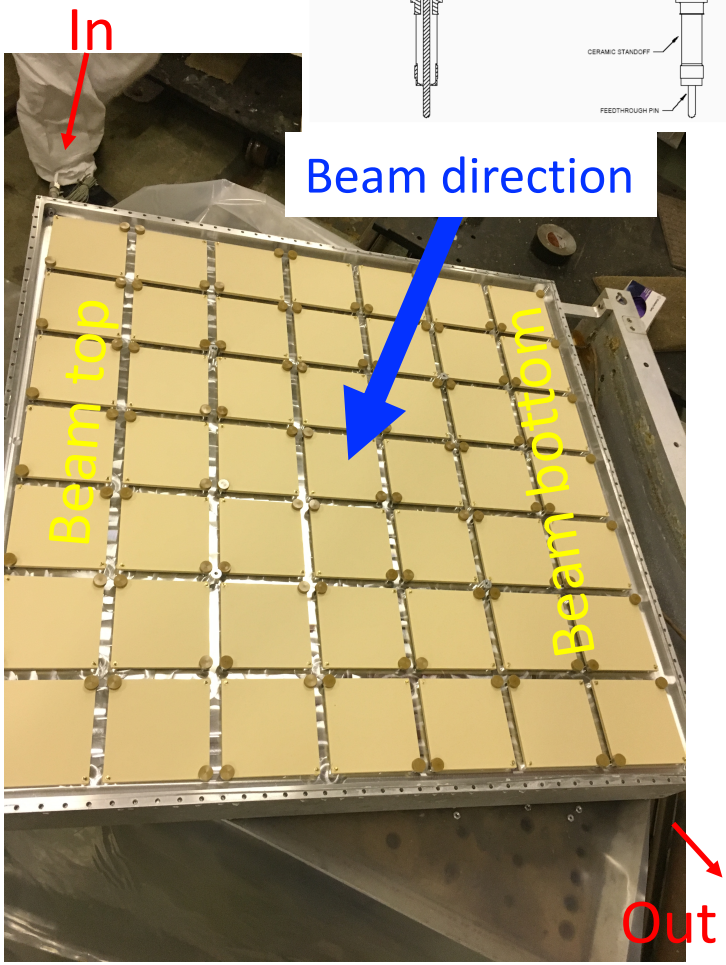
- Comparing observed horn position with the laser survey and the beam scan, we found that **the discrepancy of both measurements is less than 0.2 mm**

Radiation issue on Hadron Monitor





1st gen HM



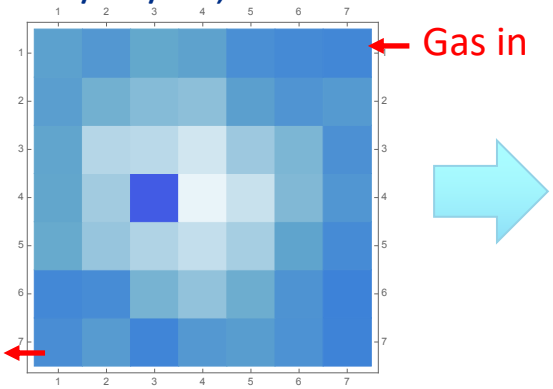
2nd gen HM

- Found discoloration near gas outlet for 1st HM
- Better surface for 2nd HM

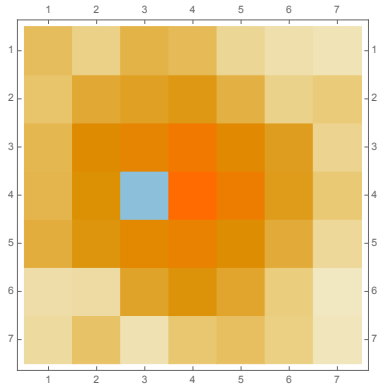
Observed gain change for 3rd gen HM

3rd HM has two ionization layers and narrower electrode gap to accept higher beam intensity

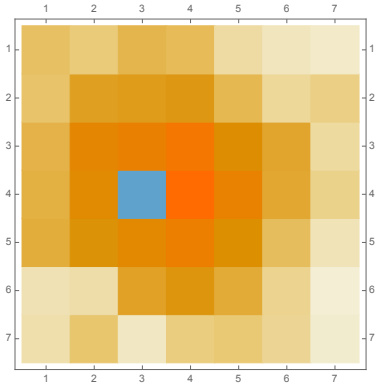
10/16/13, 7.0E12



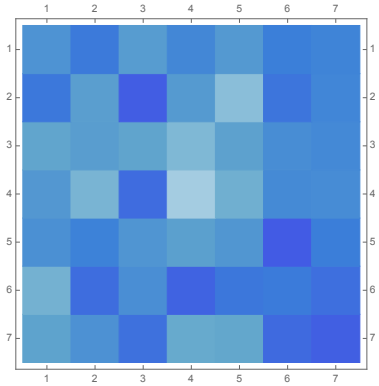
4/16/14, 23.8E12



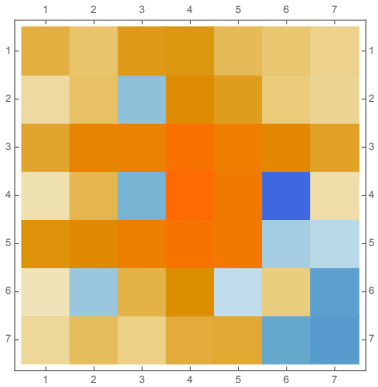
7/16/14, 18.4E12



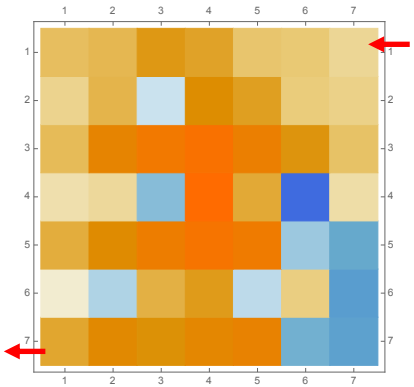
10/22/14, 1.0E12



6/16/18, 49.9E12



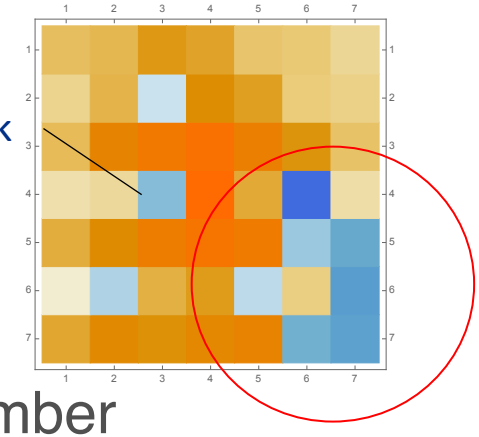
4/16/19, 51.7E12

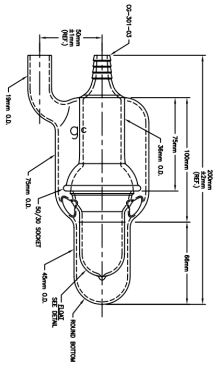


Plan for 1-MW Hadron Monitor

- Use a new gas system
  - Density flow control by using PLC
  - Add bubbler on the outlet of HM
    - Prevent back flow
    - Need to investigate lifetime of oil in rad env
  - Gas quality is calibrated by calibration chamber
- Apply radiation robust material
  - Different grade Al2O3
  - New rad hard cable
- Optimize ionization gap
  - Optimize chamber dimension
  - Gap size
  - Bias voltage
    - A new HVPS which can read a leakage current remotely
  - Analytical investigation of plasma dynamics under way

Present HM signal



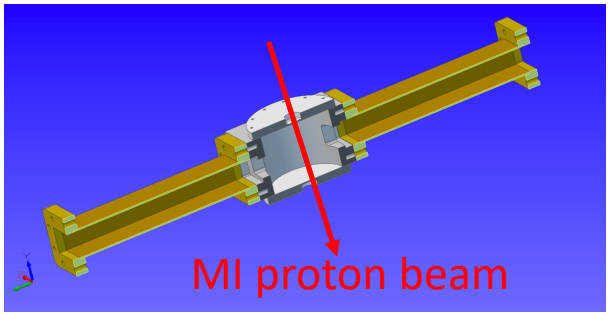


Bubbler

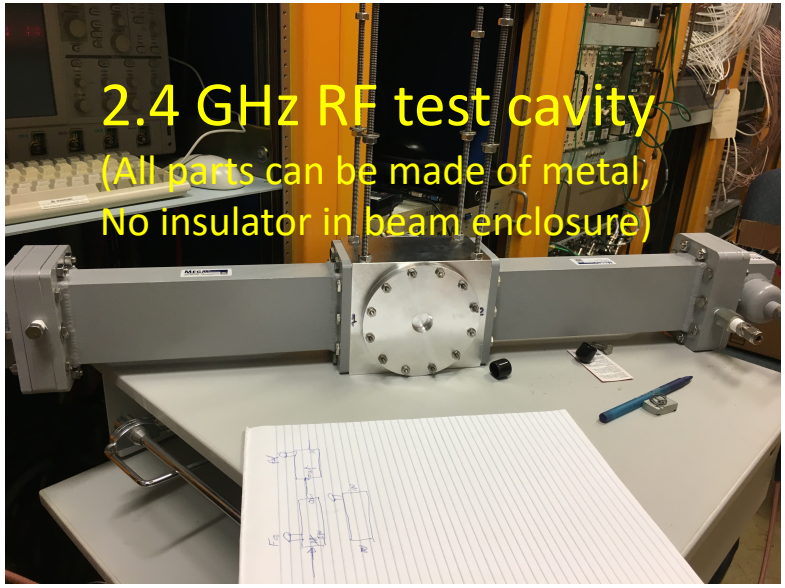
Mitigate Space charge effect

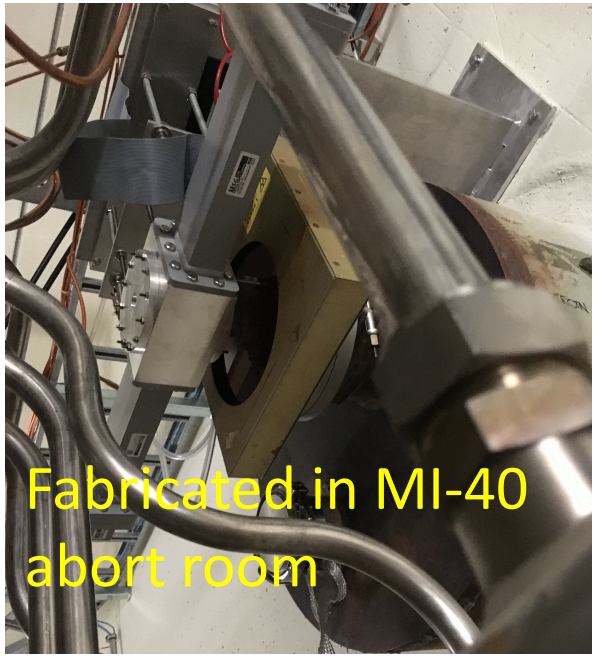
lab

Alternate Hadron Monitor



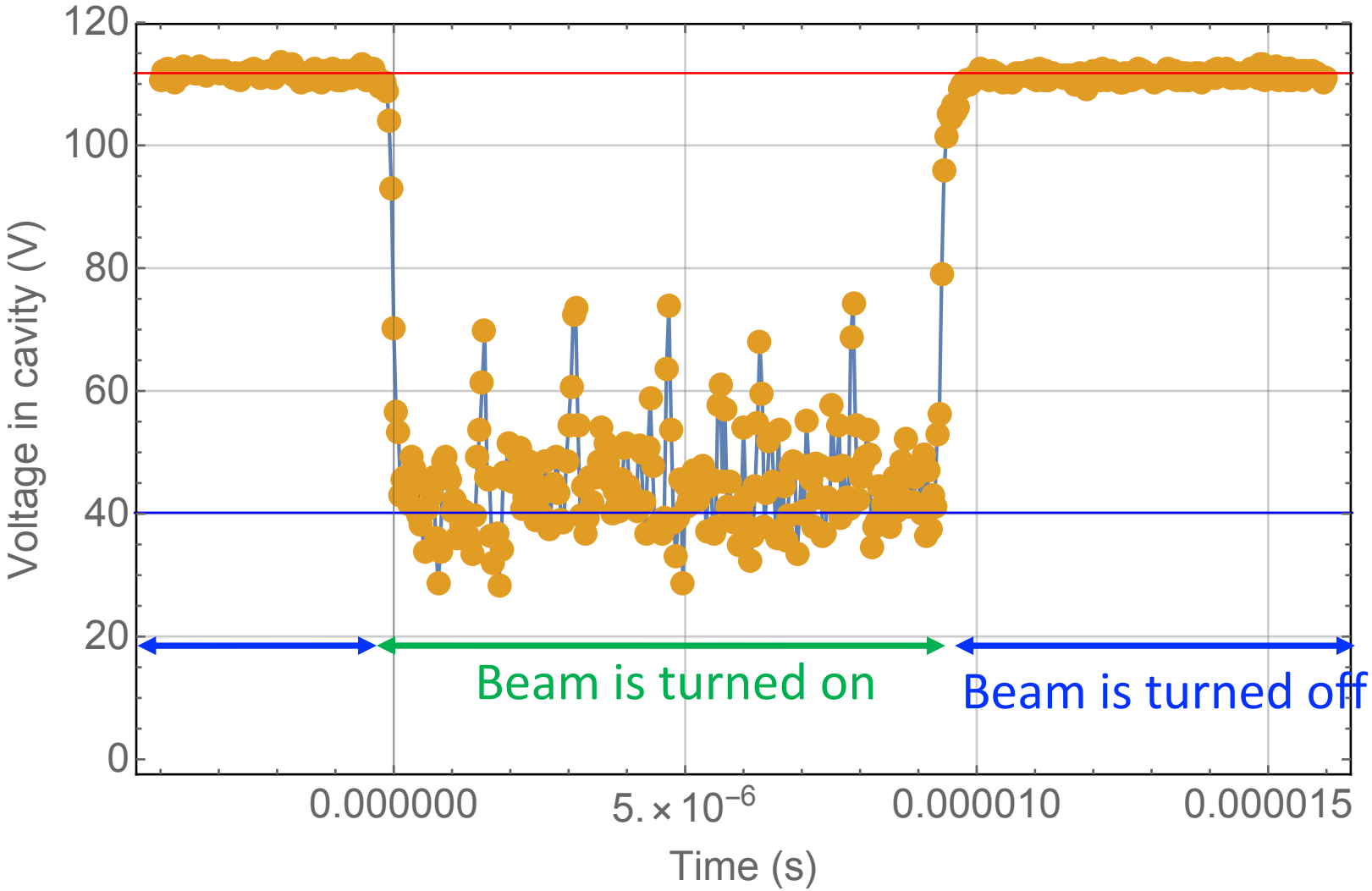
- RF beam detector
- Conceptually new rad-hard beam detector
- Apply RF field to measure the amount of ionization gas plasma which is proportional to the intensity of charged particles passing through a resonator by measuring gas permittivity $\varepsilon = \varepsilon_r + i\varepsilon_i$
- Proof-of-principle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





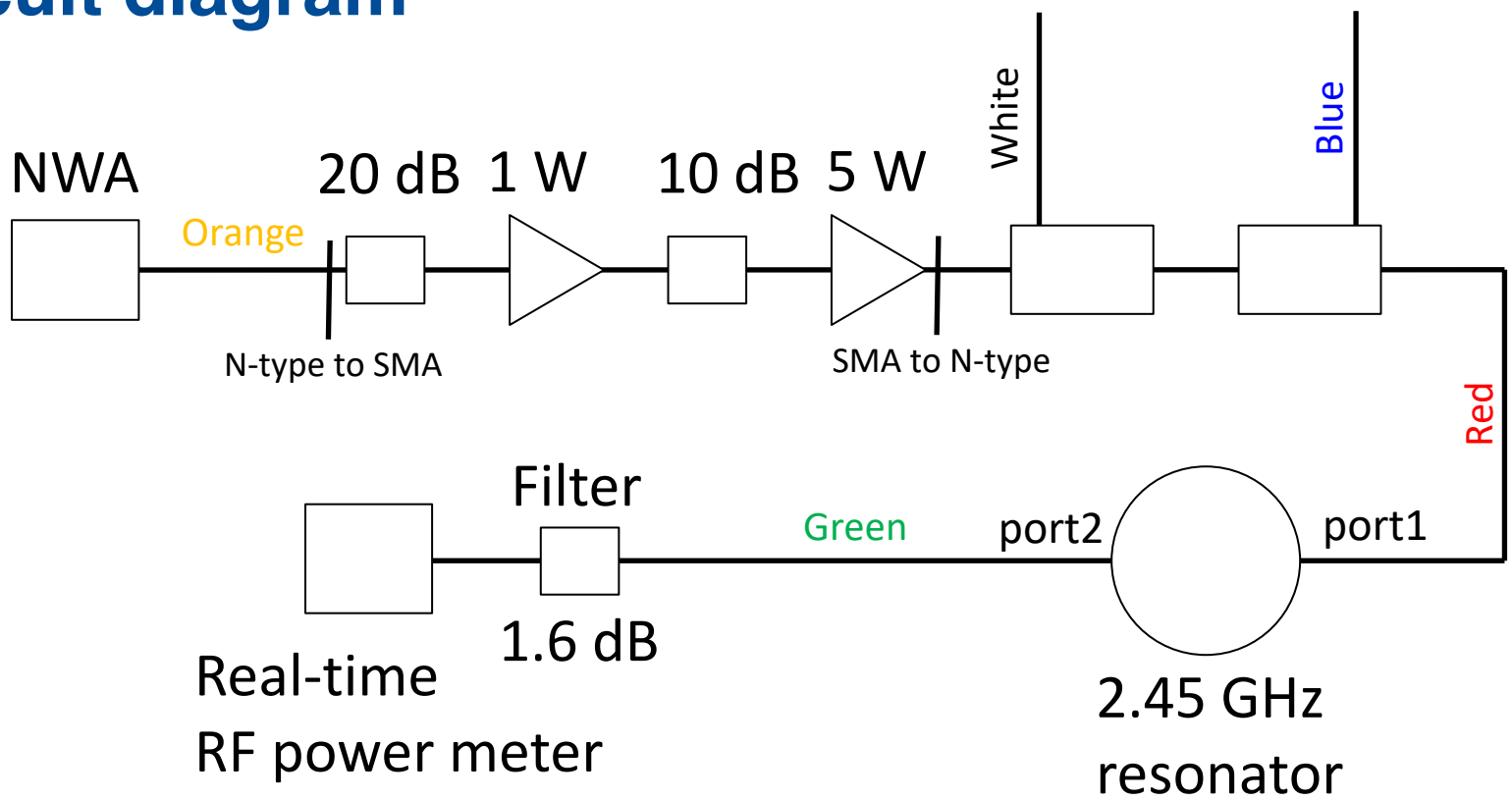
Beam loaded RF signal

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



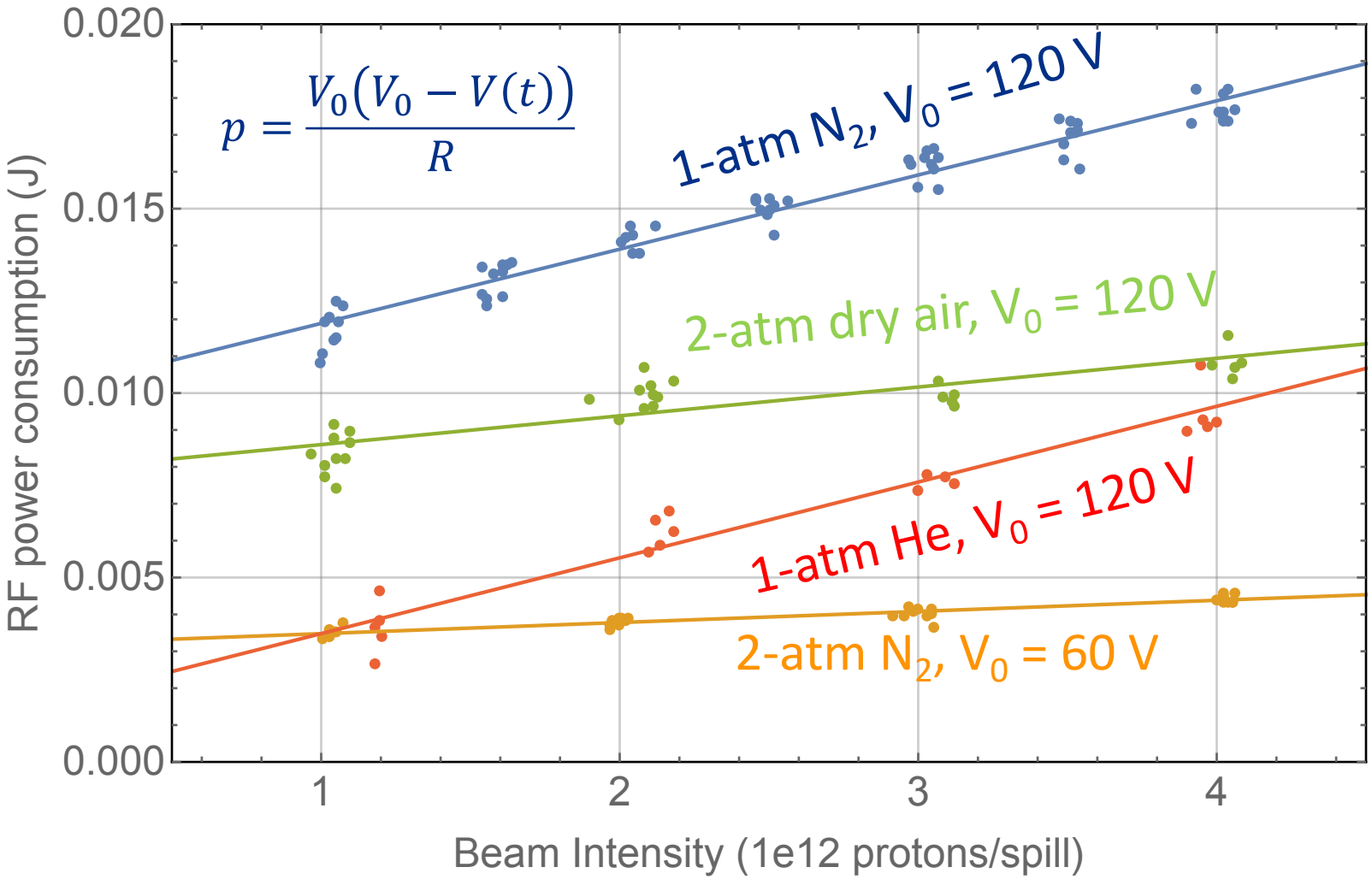
Five peaks during the beam on shows the gap of six MI beam batches

Circuit diagram



- Unique structure of two sets of attenuator and RF amp to make a linear gain and the first RF amp has a narrow band pass to remove RF noise
- Observed RF power consumption by the beam-induced plasma can be absolute value → **It suggests that the absolute beam intensity passing through the RF detector can be reconstructed without beam calibration**

Linearity test



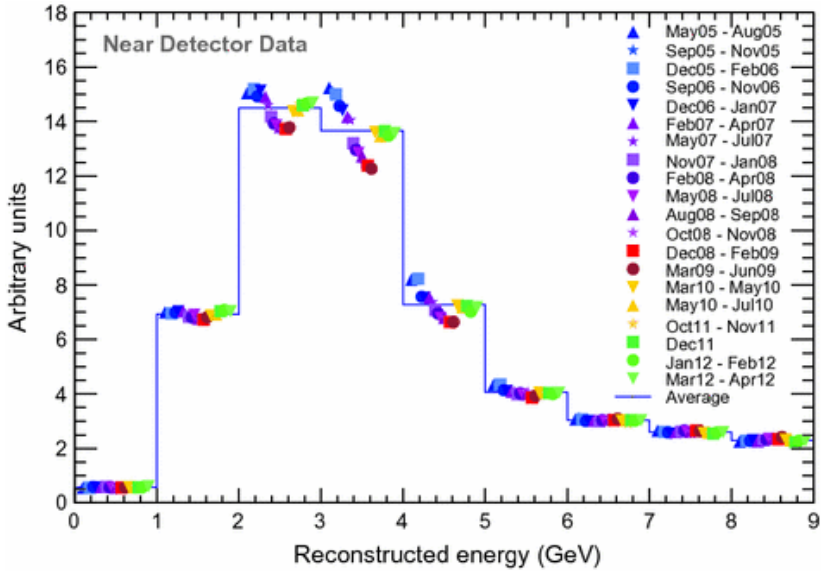
Remaining task for RF beam detector

- Need to study a background signal from waveguide (WG)
  - Ionization takes place on WG
  - Idea is minimize RF power in WG by using high Q RF detector
- Study gas plasma with wider dynamic range
  - Proof-of-principle made just at equilibrium RF power (integrated beam intensity measurement)
  - Time differential beam measurement should be investigated by using more sophisticated analyzer
  - Need to test with low beam intensity (< 1e12 protons/spill)
- Design multi-cell structure
  - WG interferes the position of RF detector
  - Thinner WG needs to be used (high insertion loss though)

Challenge: MINOS ND terminated

- Since MINERvA completed operation in 2019, the MINOS ND operation is terminated
- We lost the most convenient neutrino detector to quickly check the quality of neutrino beam
- We investigate the function of muon monitor to diagnose the condition of NuMI target system

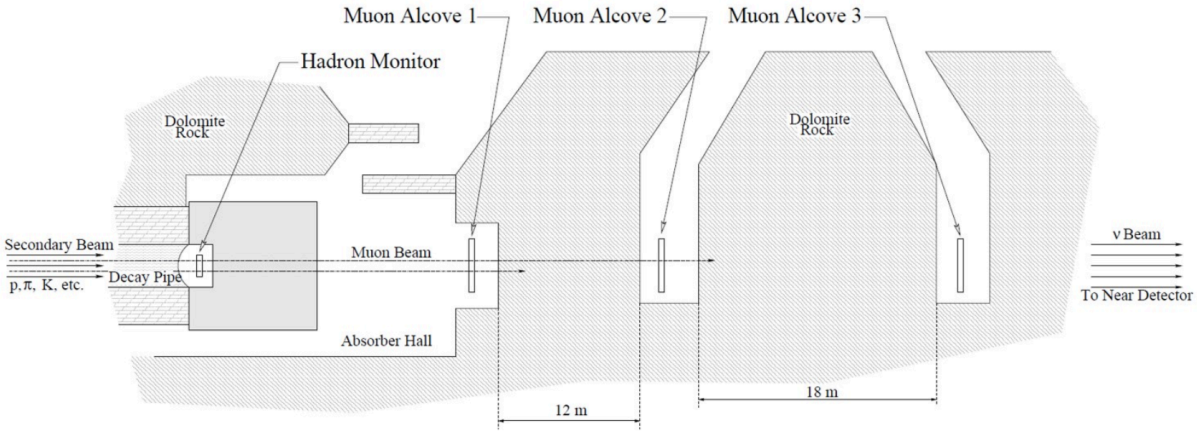
Search for Sterile Neutrinos with the MINOS Long-Baseline Experiment pp 135-152

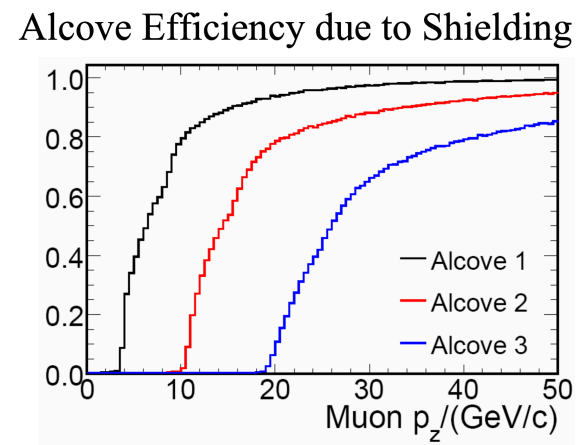


Muon Monitor

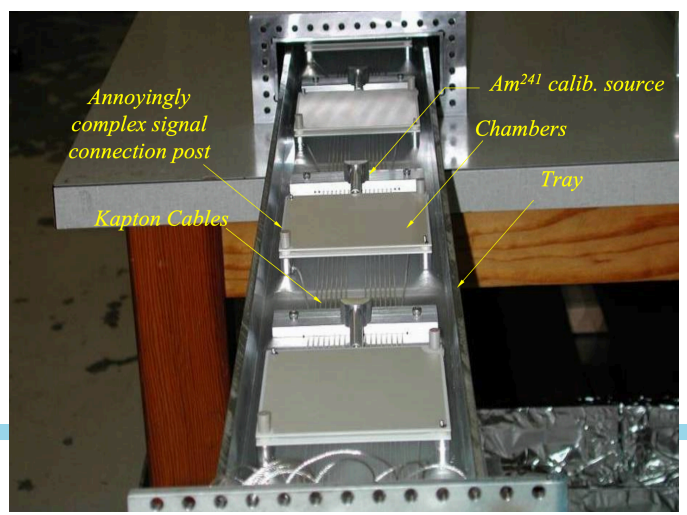
Can we reconstruct the neutrino flux at NOvA ND/FD from beam monitor signal?

- Three monitor receive different energy muons

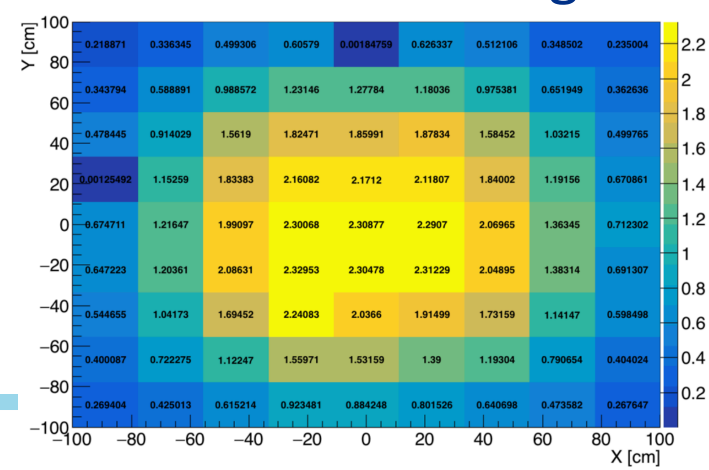




- Similar structure as Hadron monitor



Muon Monitor 1 signal

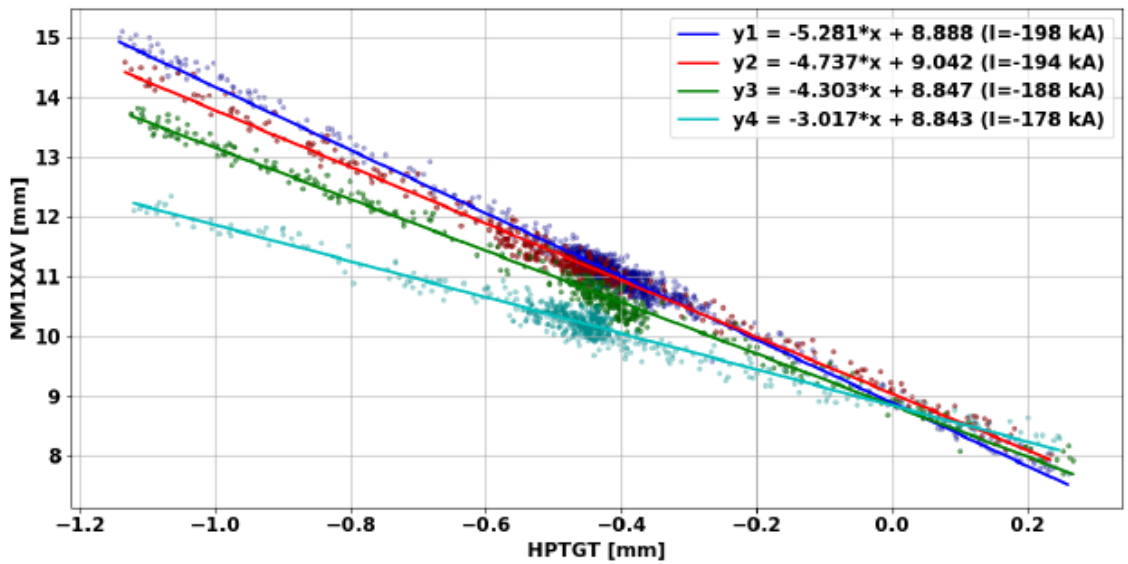


Horn Scan Result (I)

Observed beam centroid on Muon Monitor (MM) 1

Horizontal scan

Note:
Vertical scale is in local coordinate system



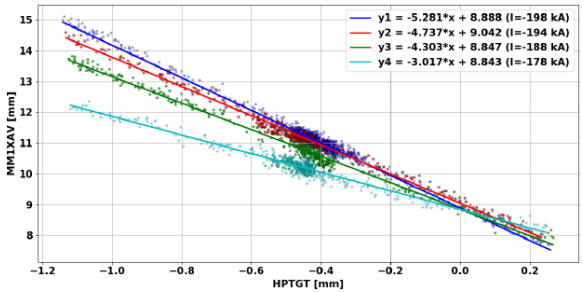
- Measurement shows a strong linear correlation between proton position on target and beam centroid on MM1
- It suggests that we can apply a linear transfer matrix
  - $\overrightarrow{r_{2,\pi}} = \widehat{M} \cdot \overrightarrow{r_{1,p}}$ and $\widehat{M}$ can be a beam transfer matrix
  - Note that Liouville transport theory is not applicable

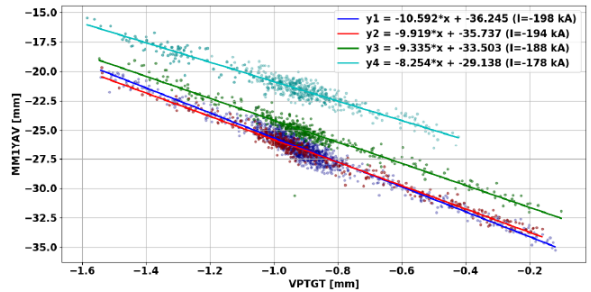
Horn Scan Result (II)

- Determine $\widehat{M}$

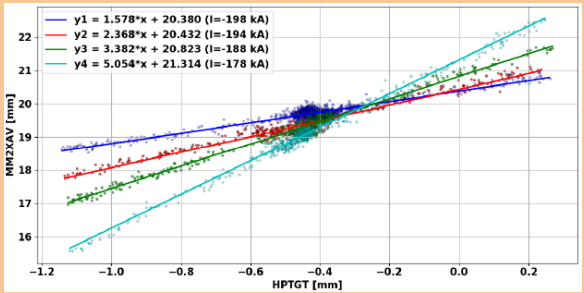
Horizontal scan | Vertical scan

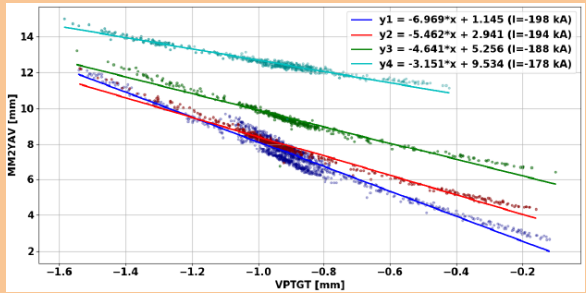
MM1



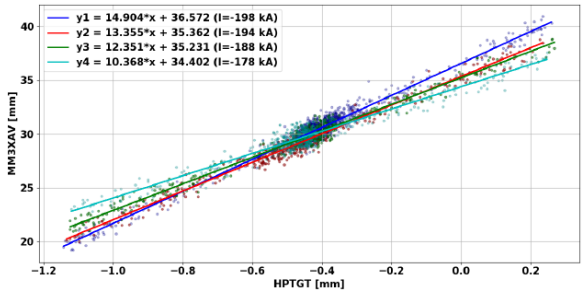


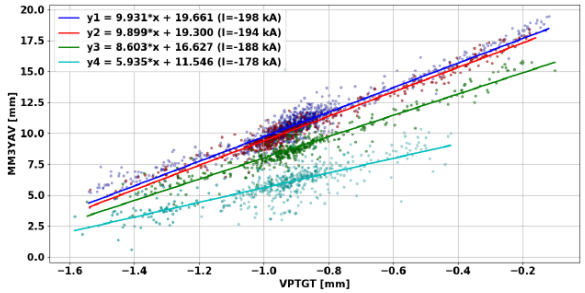
MM2





MM3





MM2 behaves most interesting

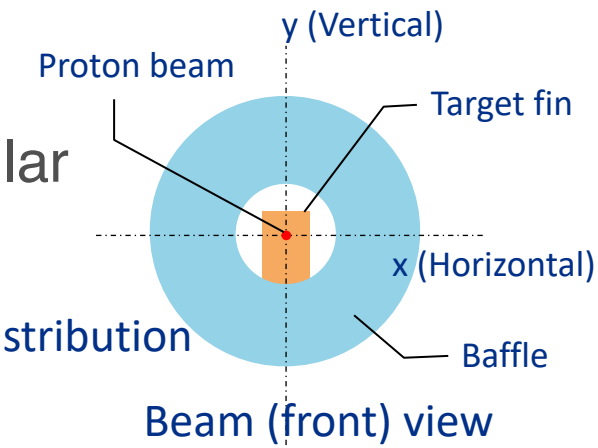
- Slope sign change between horizontal and vertical scans
- Non-linear component in vertical scan

Fermilab

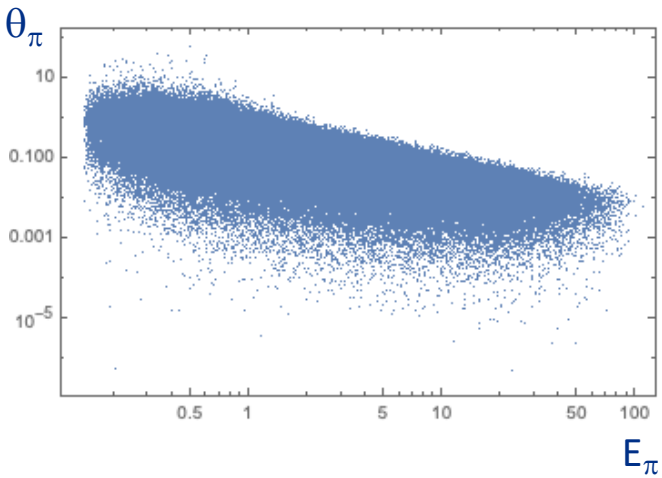
Toy Model

- Apply a simple ray trace model to interpret $\widehat{M}$
  - Use right-hand formula to estimate vertical kick from horn fields
  - Trace pion without decay
  - Initial pion is defined from simulated angular distribution

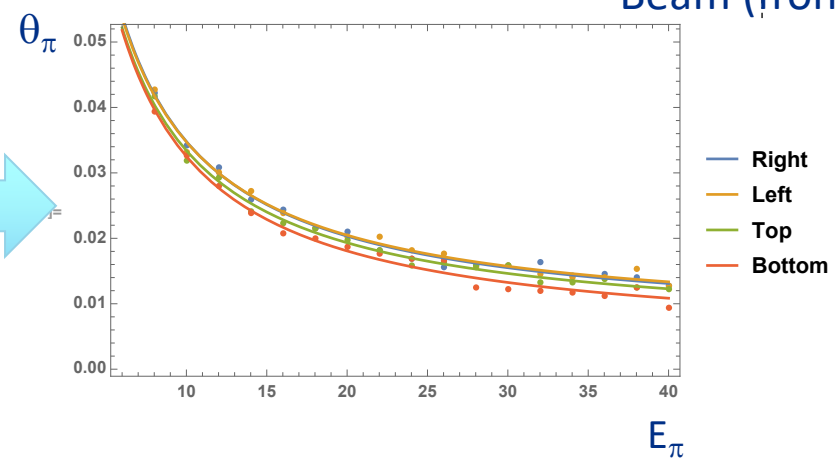
$$\theta = \frac{eBl}{p}$$



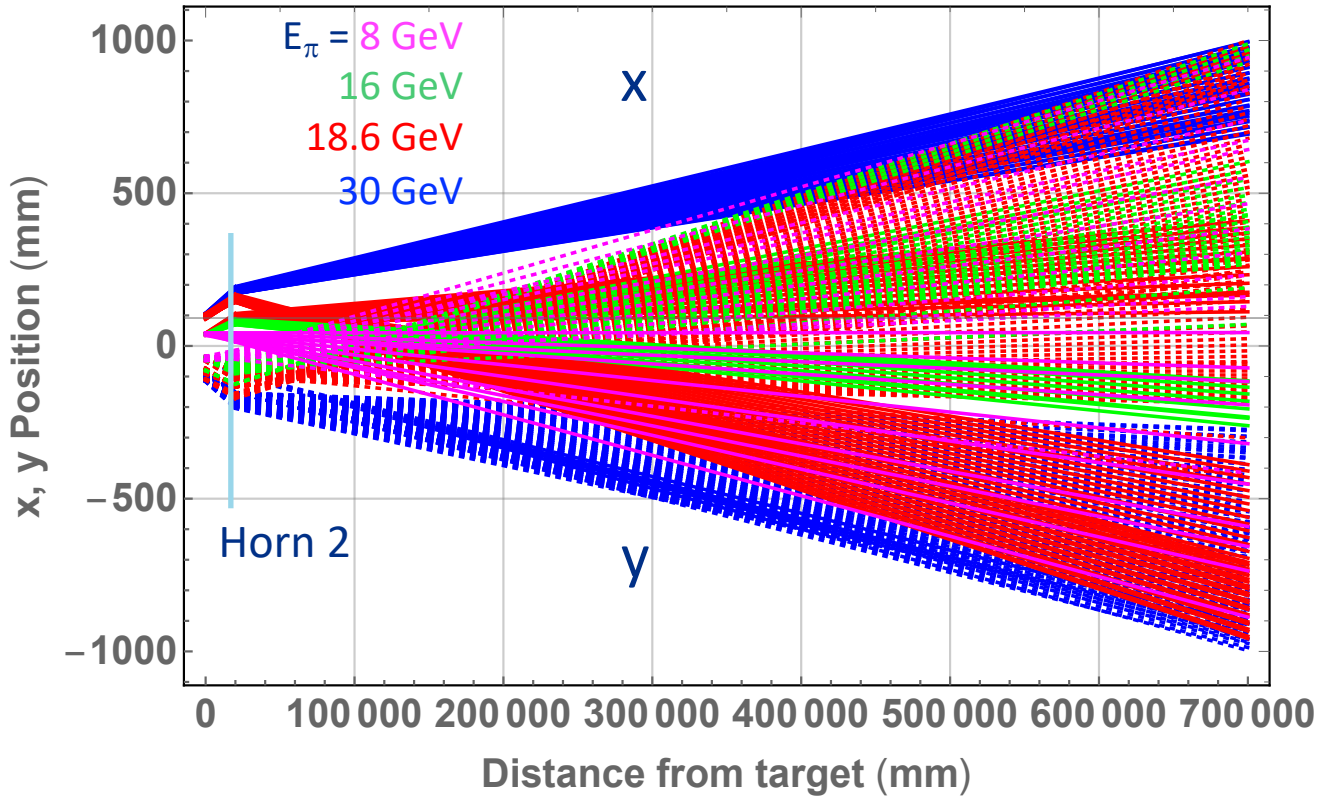
Pion angular distribution in Geant4



Average pion angular distribution as a function of E_π



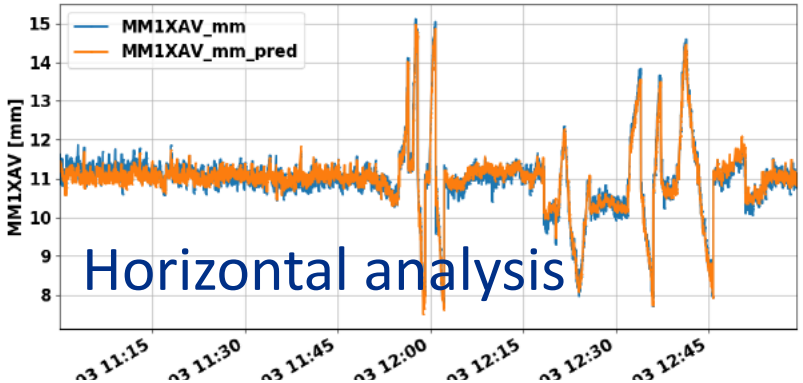
Ray trace

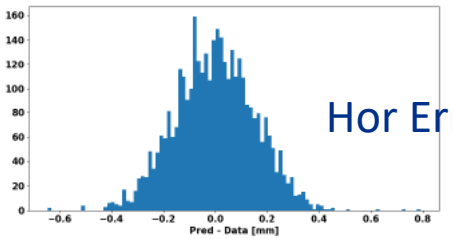


- Horizontal (x) track is symmetry while vertical (y) one is asymmetry due to the NuMI target geometry
- **The model suggests that the horn scan slope and offset should be unique**
- Semi-analytical simulation in G4Beamline to validate the toy model is underway

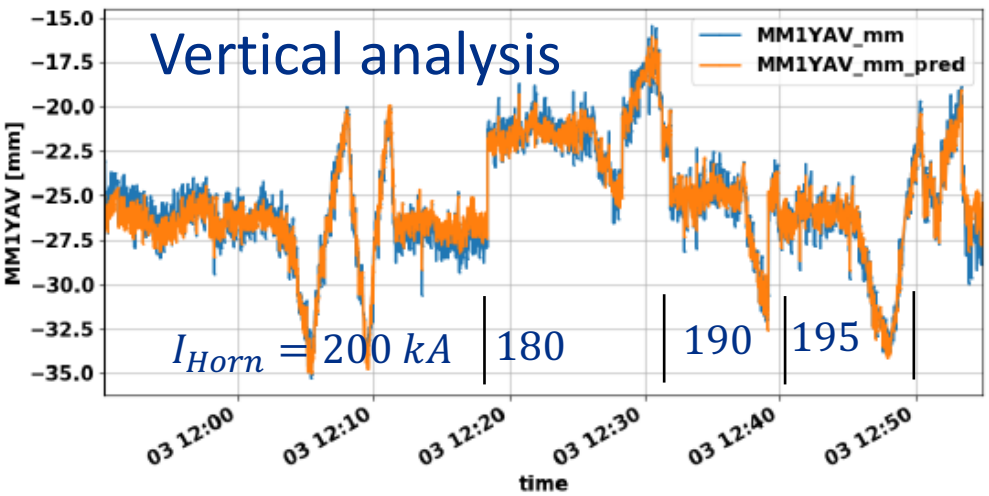
Reproducibility of Beam centroid on Muon Monitor

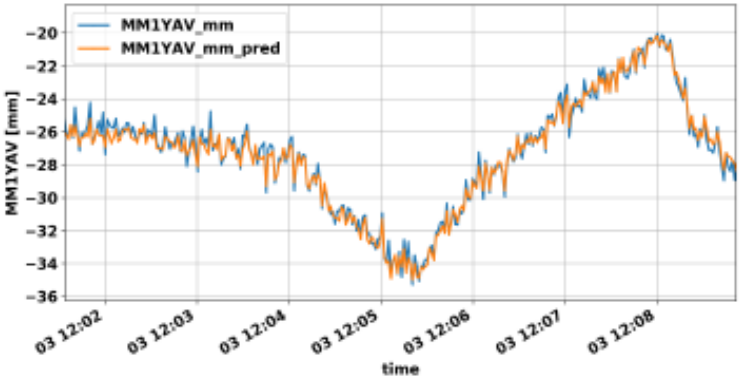
$$\vec{R}_{MM} = f\left(\vec{r}_{beam}, \vec{\sigma}_{r_{beam}}, I_{Horn}, gas\ parameter\right)$$

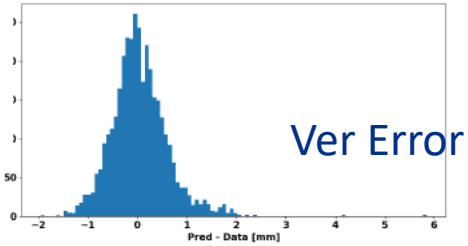




Hor Error RMS = 0.15 mm







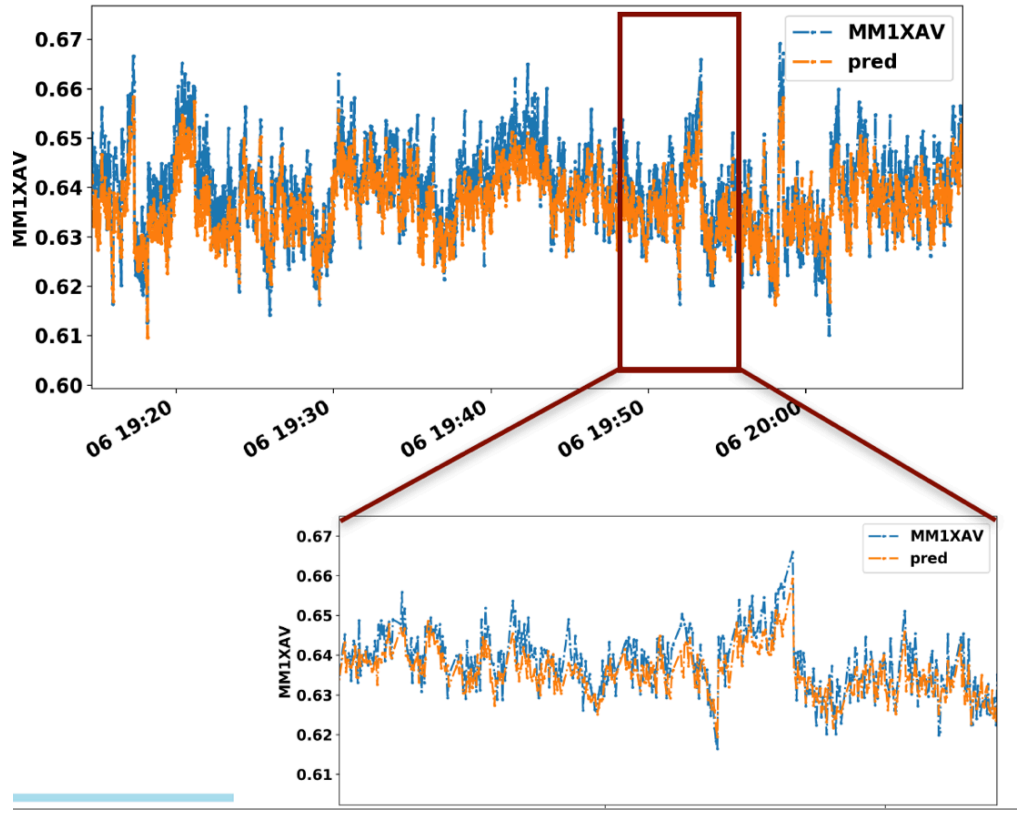
Ver Error RMS = 0.58 mm

Fermilab

Machine Learning in NuMI Target system

- Linear correlation suggests to utilize the Muon Monitor to diagnose the healthiness of target system by using ML system

Prediction of muon monitor1 <X>



- Introduce Machine Learning to daily-base monitor MM signal
- Accuracy +/-0.5 mm

Summary

- Investigate three beam monitor
  - Observe proton beam position on target **spill by spill**
  - Diagnose the target and horn quality **spill by spill**
  - Introduce Machine Learning to make an automatic monitor system
- Develop rad hard ion chamber
  - Build a new gas system to mitigate gas contamination
  - Optimize gas plasma in ion chamber to mitigate a space charge effect
- Study RF beam detector
  - Need more R&D to make a practical detector

Acknowledgement

- Hadron Monitor
  - Karol Lang, Marek Proga from U of Texas Austin
  - Joe Beleski, Jodan Bohn from Fermilab
- RF beam detector
  - Rol Johnson, Mary Anne, Grigory Kazakevic from Muons Inc
  - Al Moretti, Dave Peterson, Adam, Dent, Kyle from Fermilab
- Muon Monitor
  - Pavel Snopok, Yiding Yu from IIT
  - Amit Bashyal from Oregon U
  - Athula Wickremasinghe from Fermilab
- TSD
  - Bob Zwaska, Jim Hylen, Cory Crowley, Yun He, Keith Gollwitzer, Kris Anderson, Patrick Hurh