Progress of Displacement Per Atom experiment at Fermilab and Study of Horn Focusing Mechanism

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What is DPA?

- Displacement Per Atom (DPA) is a degree of radiation damage on the material
- Various simulation codes have been made to estimate DPA, especially for the radiation shielding design
- Each has pros and cons
- Japanese group has developed a code (PHITS) which predicts the damage in very wide energy range
- We tested the model by using a 120 GeV/c proton beam at Fermilab

Measurements of displacement cross sections of Al, Cu, Nb, and W with 120-GeV protons

Preliminary results

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and other collaborators.

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Background

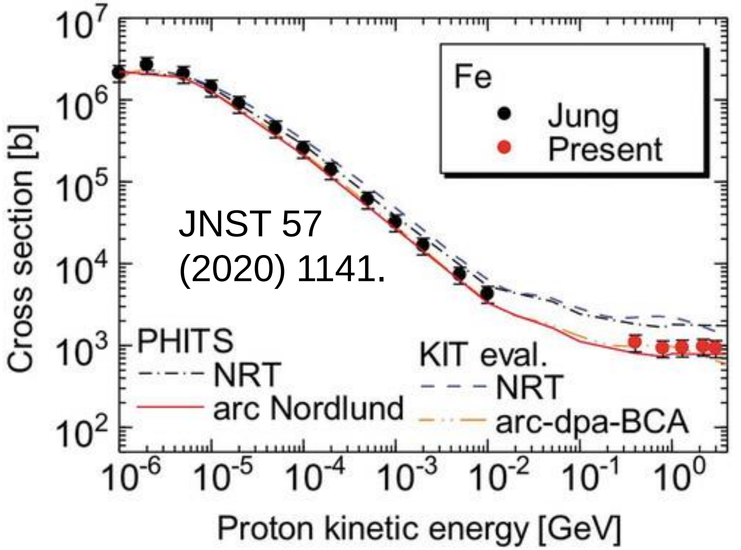
Radiation damage is evaluated with Displacement Per Atom.

$$\text{DPA} = \sigma_d \phi$$

σ_d : displacement cross-section (m^2)
ϕ: irradiation fluence (particles/m^2)

Models in FLUKA, MASR, and PHITS codes have not been validated due to lack of experimental data above 30 GeV.

Goal: Measurements of displacement cross-section for metals with 120-GeV protons.



Displacement cross section for Fe

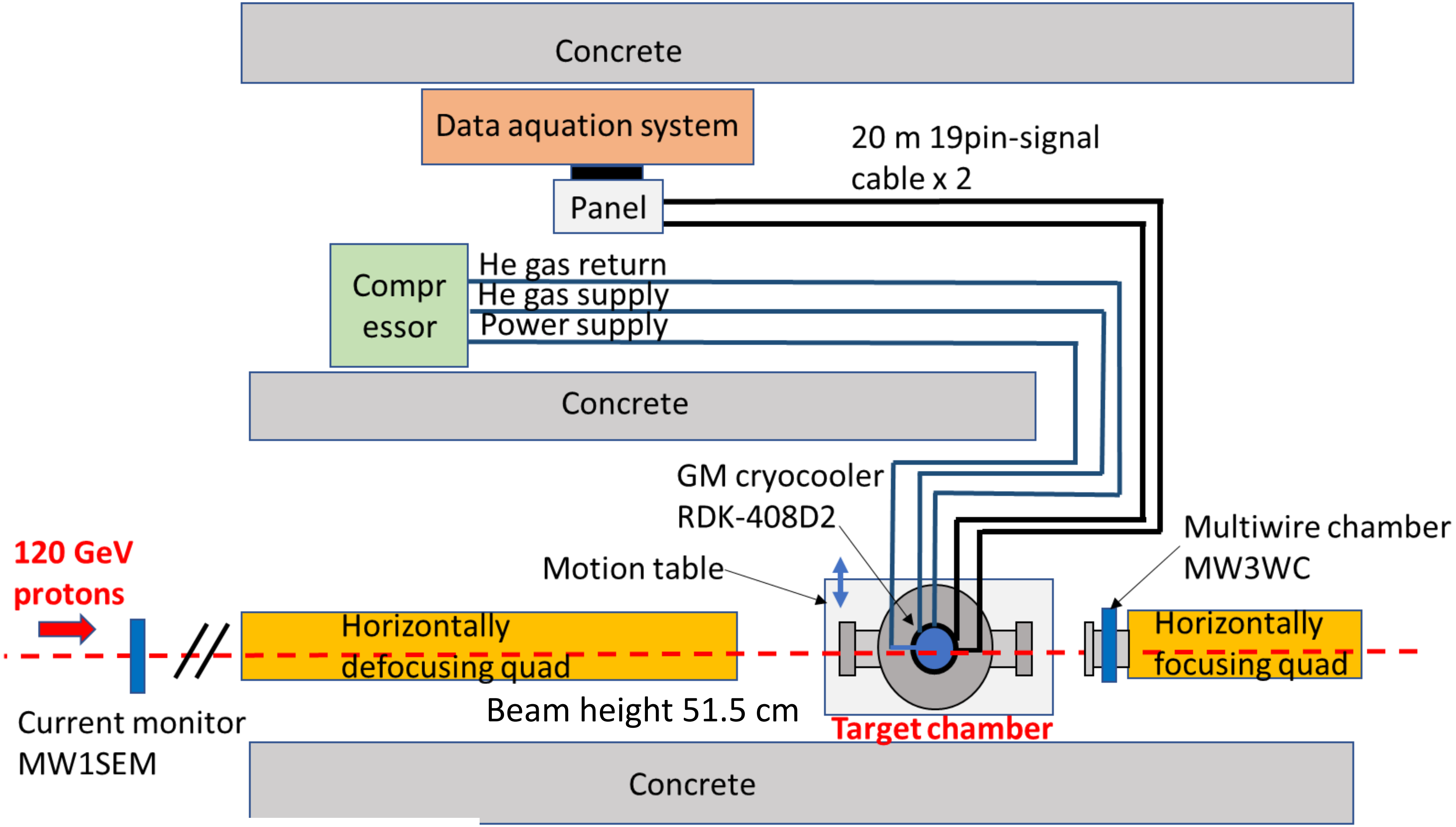
Experimental data: **Damage rate** at cryogenic temperature.

$$\sigma_{exp} = \frac{1}{\rho_{FP}} \frac{\Delta\rho_{metal}}{\phi}$$

$\Delta\rho_{metal}$: Resistivity increase due to defect (Ωm)
Φ: Beam fluence (1/m^2)
ρ_{FP}: Electrical resistivity per Frenkel-pair (Ωm)

Equipment layout in the Fermilab Test Beam Facility (FTBF) tunnel (M03)

The experiment was conducted from January 4 to January 27.

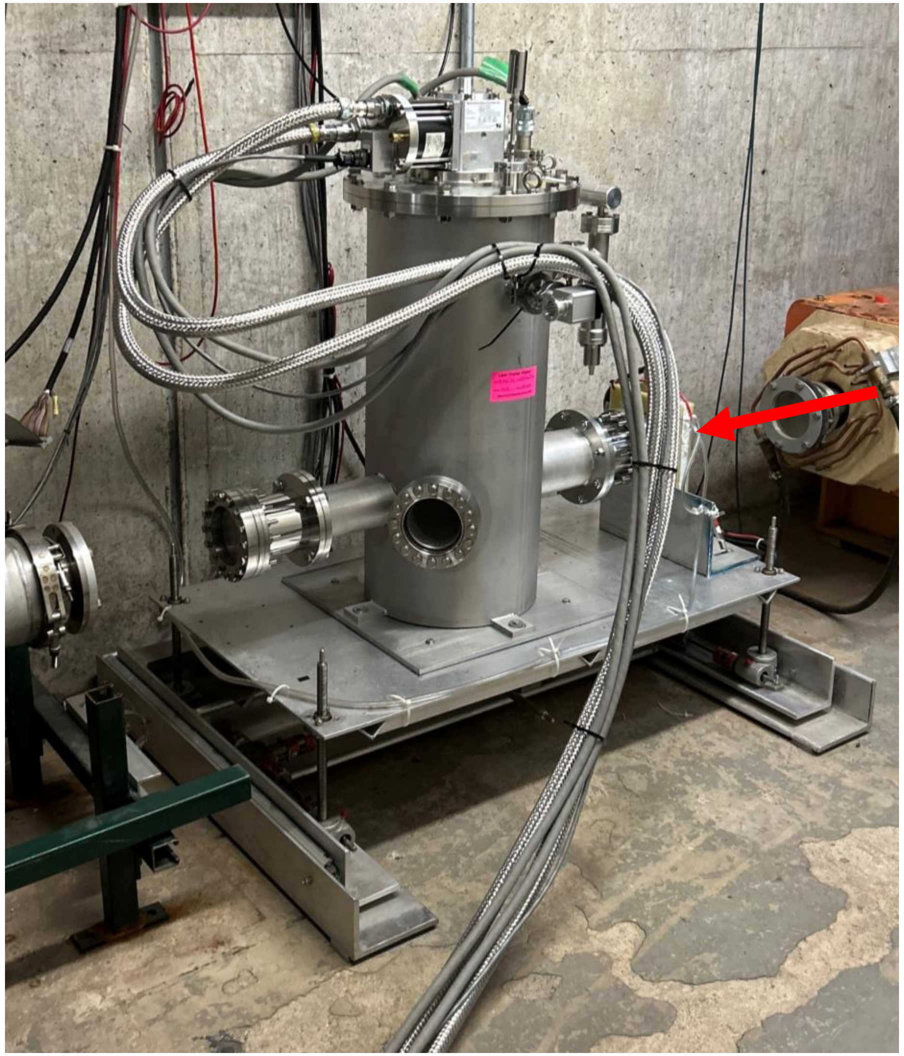


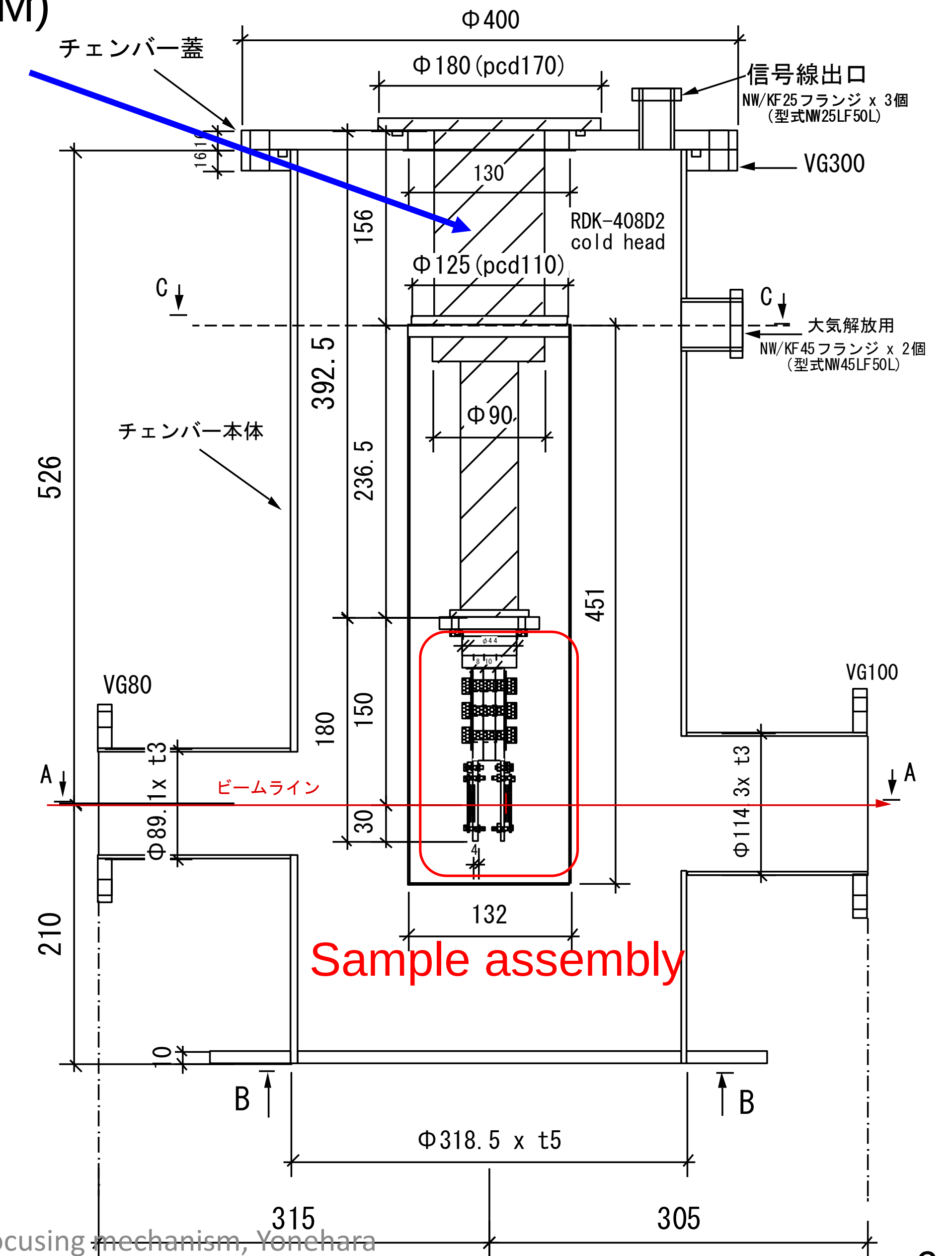
About 1.8 x 10^{11} protons per minute

Top view of layout

Target chamber with a cryocooler

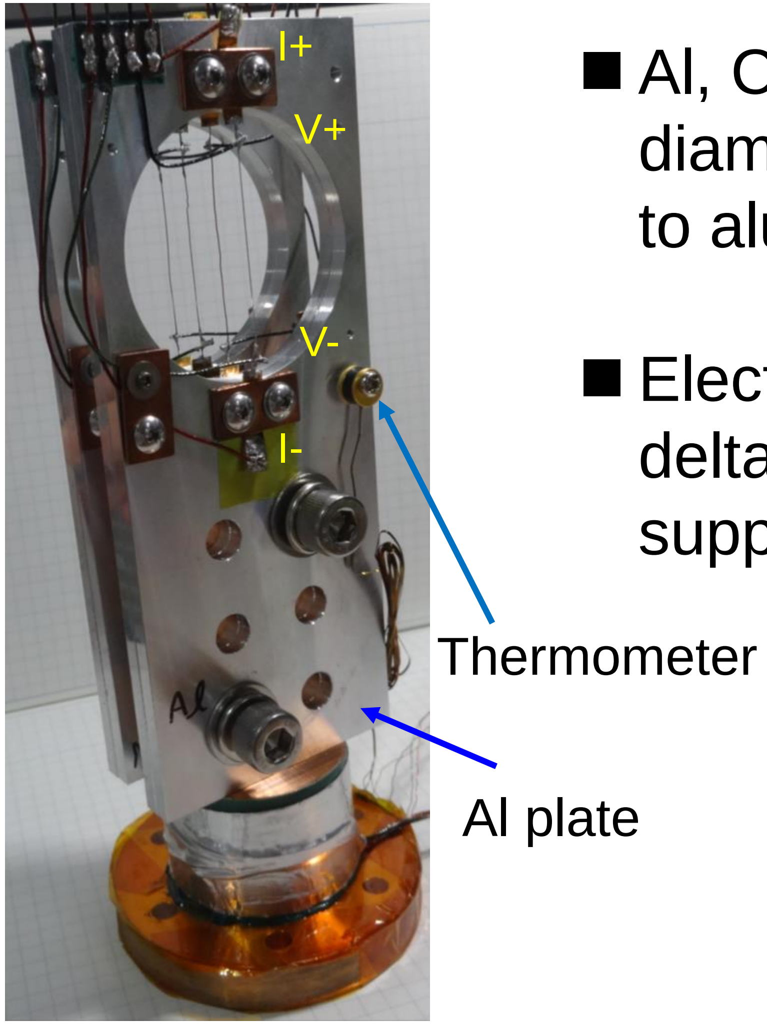
Gifford-McMahon (GM) cooler RDK-408D2



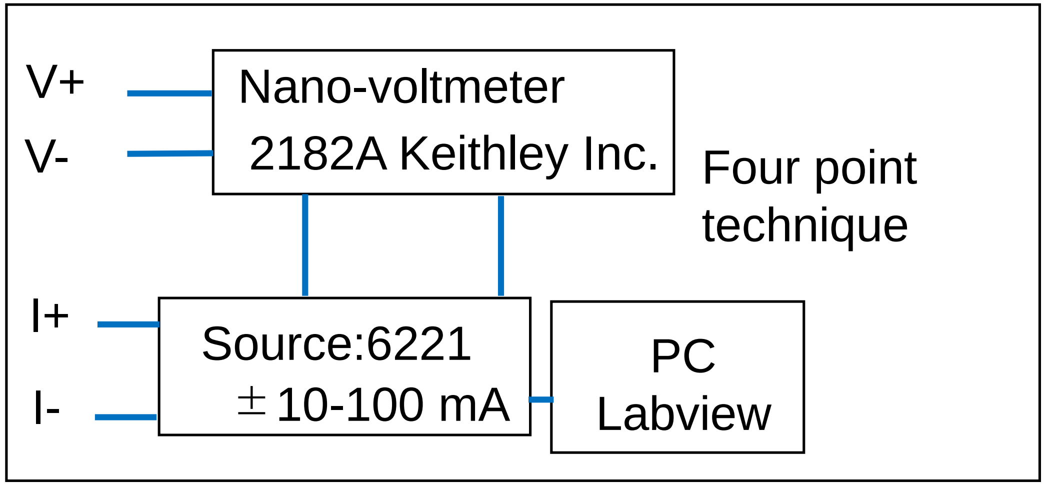


Sample assembly

- Al, Cu, Nb, and W wires with 0.25 mm diameter and 40 mm length were fixed to aluminum plate.
- Electrical resistance measurement using delta-mode 4-terminal method with suppressed thermoelectromotive force.

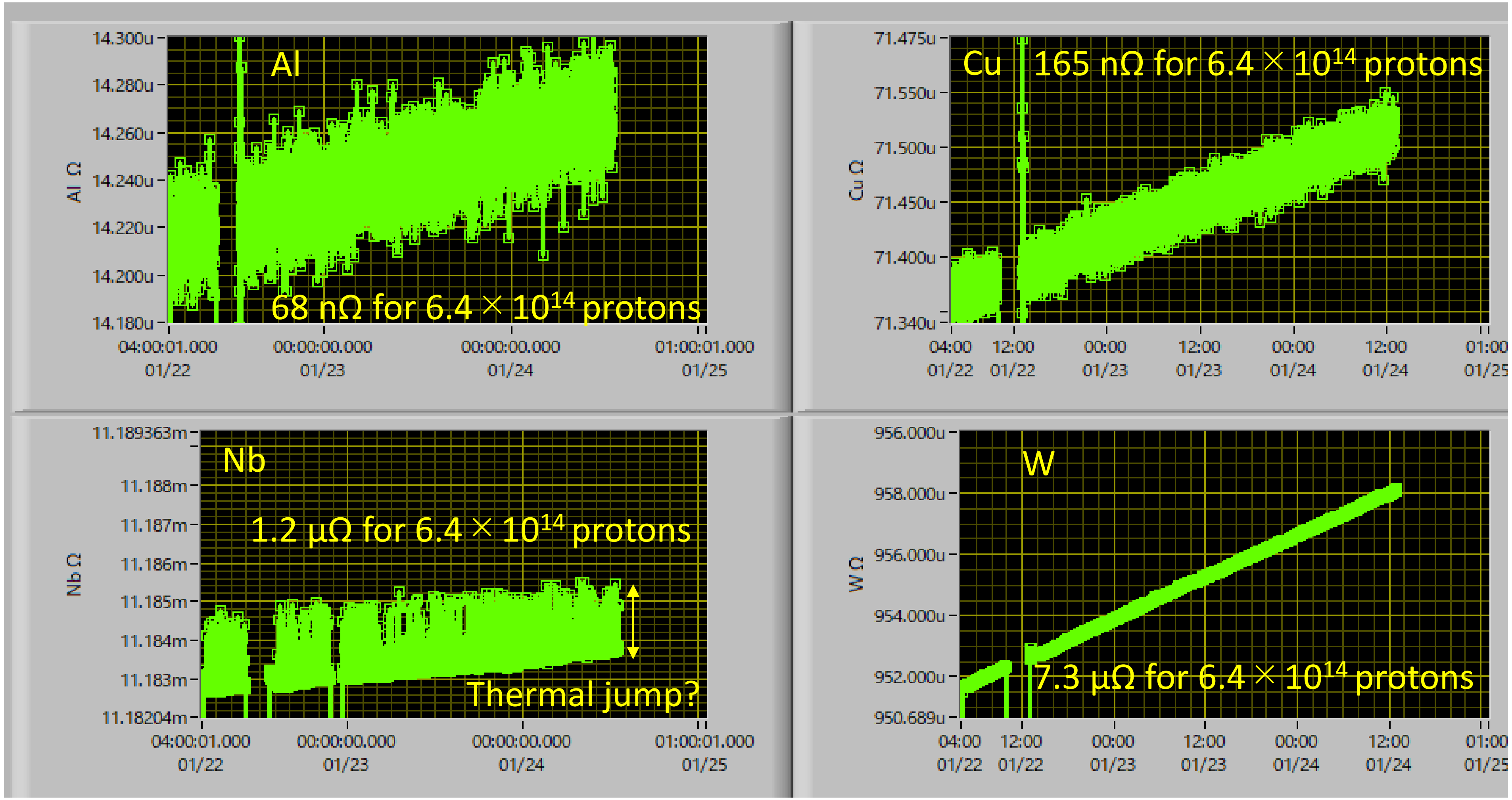


Sample assembly



Data taking system

Preliminary results



Electrical resistance changes of metals at 8 K under 120 GeV proton irradiation

arc-dpa/ experimental data: Al: 1.27, Cu: 1.28, Nb: 1.71, W: 0.94

Summary

We successfully measured displacement cross-section for Al, Cu, Nb, and W with 120-GeV protons at the M03 in the FTBF.

At 8K, the increase in electrical resistance was 68 nΩ to 7.3 μΩ when irradiated with 6.4 x 10^{14} protons.

The ratio of displacement cross sections calculated by PHITS to experimental data is 0.9 -1.3 for Al, Cu, and W and 1.7 for Nb.

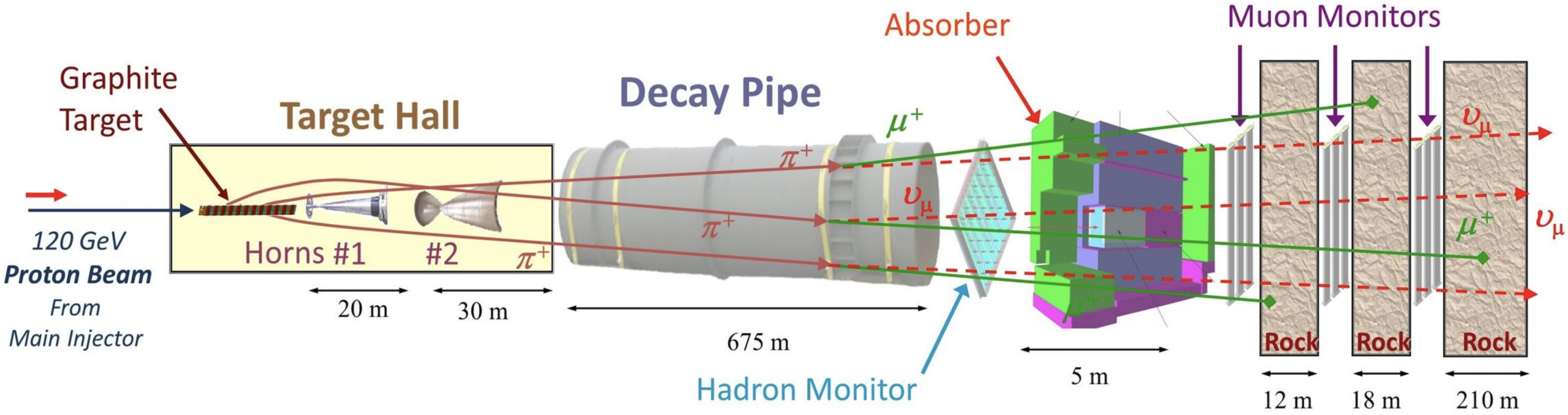
We plan to submit the paper of this work this April.

In the future, we plan to measure data for other metals, such as Ti and alloys; data for Nb will be measured with less thermal effects.

Study of Horn Focusing Mechanism

- Horn magnet is widely used for accelerator-produced neutrino beam experiment
- It is an interesting to apply the horn magnet for muon accelerators
  - Well known engineering technology
  - It will be demonstrated with multi-MW beams
- **Design of a modern neutrino horn system is optimized by using a numerical simulation to maximize the sensitivity to neutrino oscillation and CP violation measurements**
- I apply a reverse engineering technique to understand the mechanism

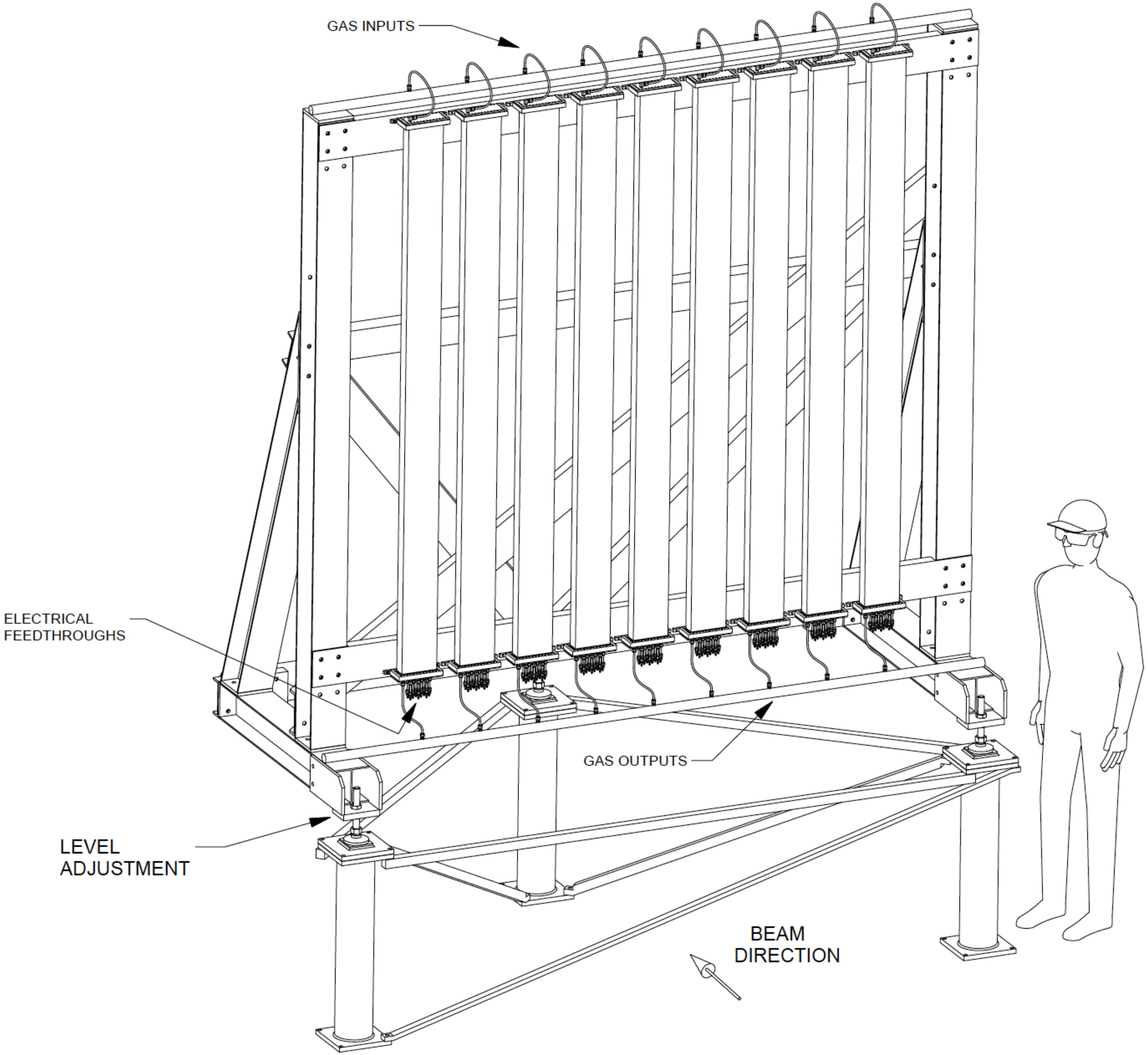
NuMI Horn System



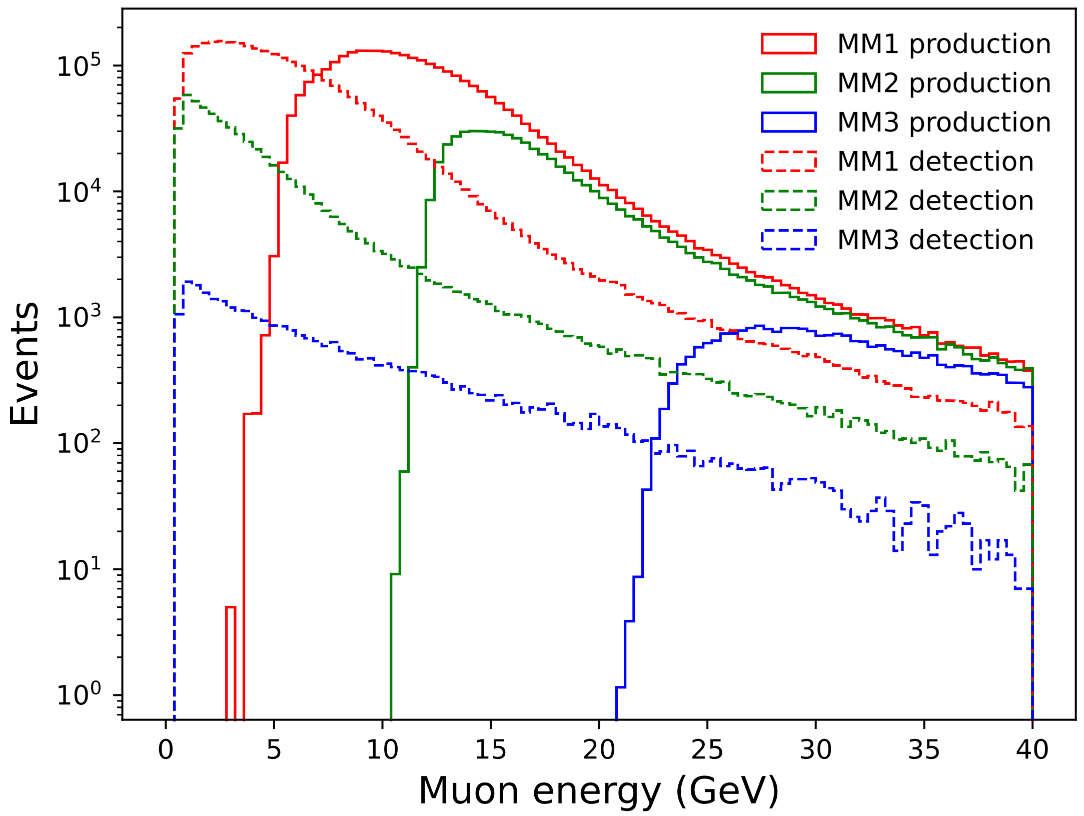
- 1.2-m-long Carbon graphite target to accept 0.9-MW proton beam power
- 120 GeV/c proton beam is arrived from Main Injector to the target every 1.2 sec
- 5.6e13 protons per spill and spill length is 9.6 μsec
- There are two horn magnets to collect right charged pions with 1-20 GeV energy range
- Using muon monitors to study the horn focusing mechanism

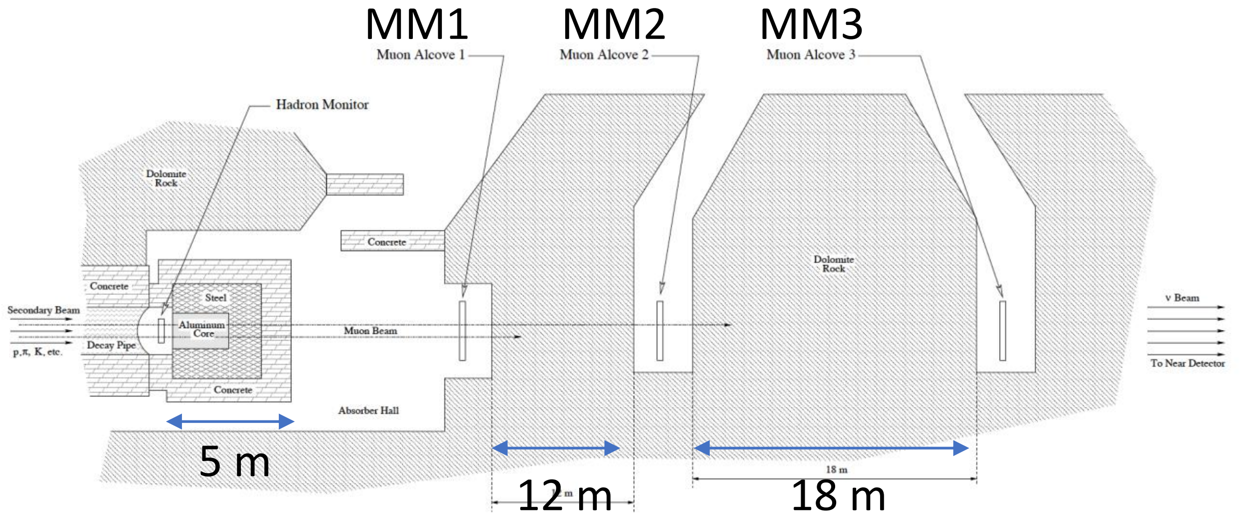
Muon monitor

- It is located downstream of the absorber and rocks
- Most charged particles are ranged out in these materials
- Only muons reach to the monitors
- It consists of 9x9 grid ion chambers
- It covers 2.1 x 2.1 m^2



Simulated muon spectrum

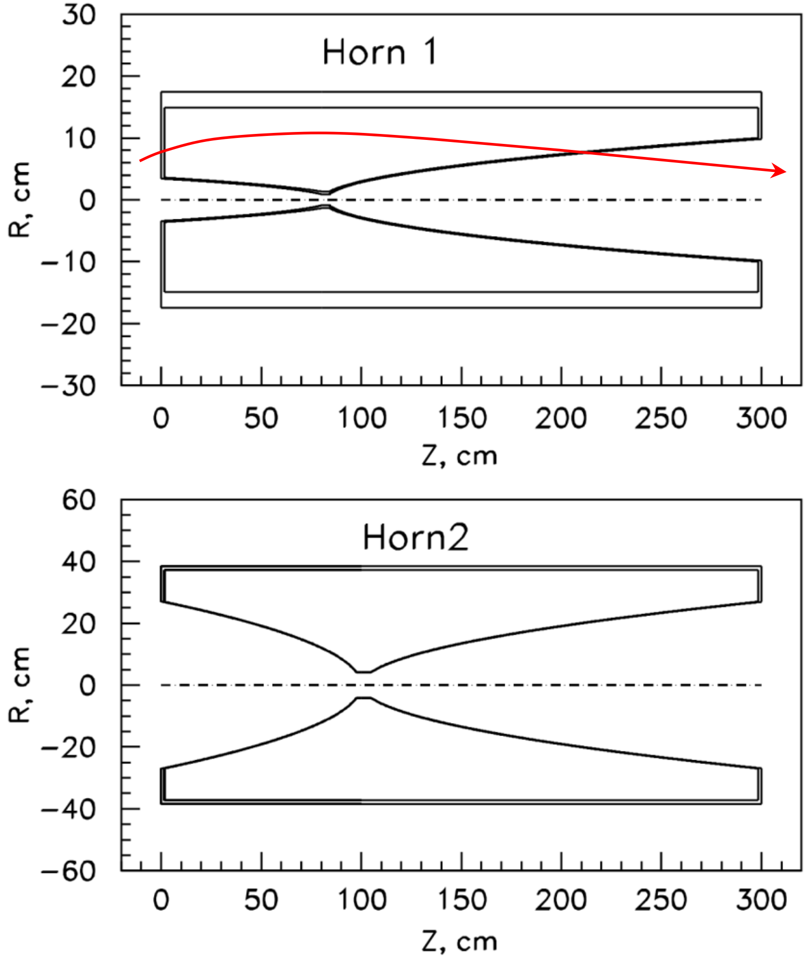




- Top Right: Schematic drawing of beam absorber, muon monitor (MM) 1, 2, and 3
- Left: Simulated muon spectrum

Principle of horn focusing mechanism

Cross-sectional view of NuMI horns



- Horn produces a toroidal field by current flow in the inner conductor

$$b_{\phi} = \frac{\mu_0 I}{2\pi r}$$

- Transverse kick is formulated

$$\theta(p_z, dz, r) = \theta_0 + \frac{q\mu_0 I}{2\pi}\frac{dz}{p_z r}$$

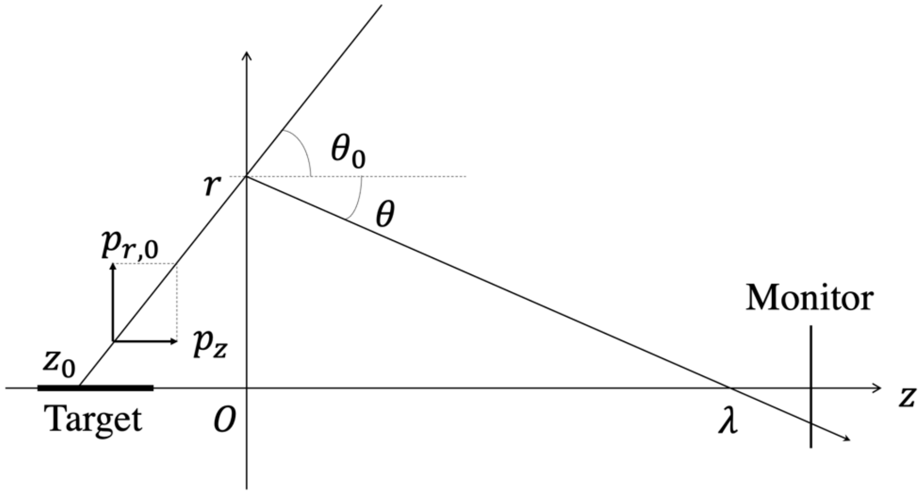
- Because the shape of inner conductor is parabola, the path length can be a quadratic formula. We use a general polynomial function

$$dz \equiv a_0 + a_1 r + a_2 r^2 + a_3 r^3 + O(r^4)$$

- The general transverse kick angle is given

$$\theta(p_z, r, \theta_0) = \theta_0 + \frac{q\mu_0 I}{2\pi p_z}\left(a_1 + a_2 r + a_3 r^2\right)$$

Test linearity of horns with analytical and numerical simulations (I)



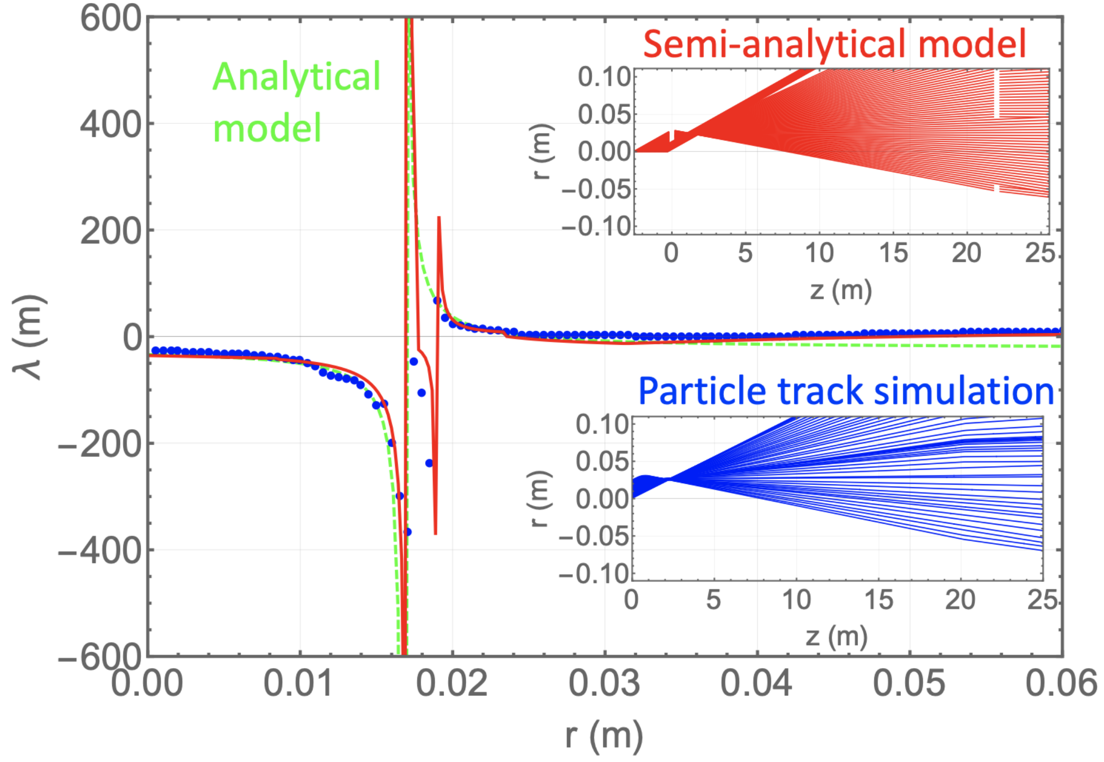
$$\lambda(p_z, r, \theta_0) = \frac{r}{\tan\theta} \sim \frac{r}{\theta} = \frac{r}{\theta_0 + \frac{q\mu_0 I}{2\pi p_z}\left(a_1 + a_2 r + a_3 r^2\right)}$$

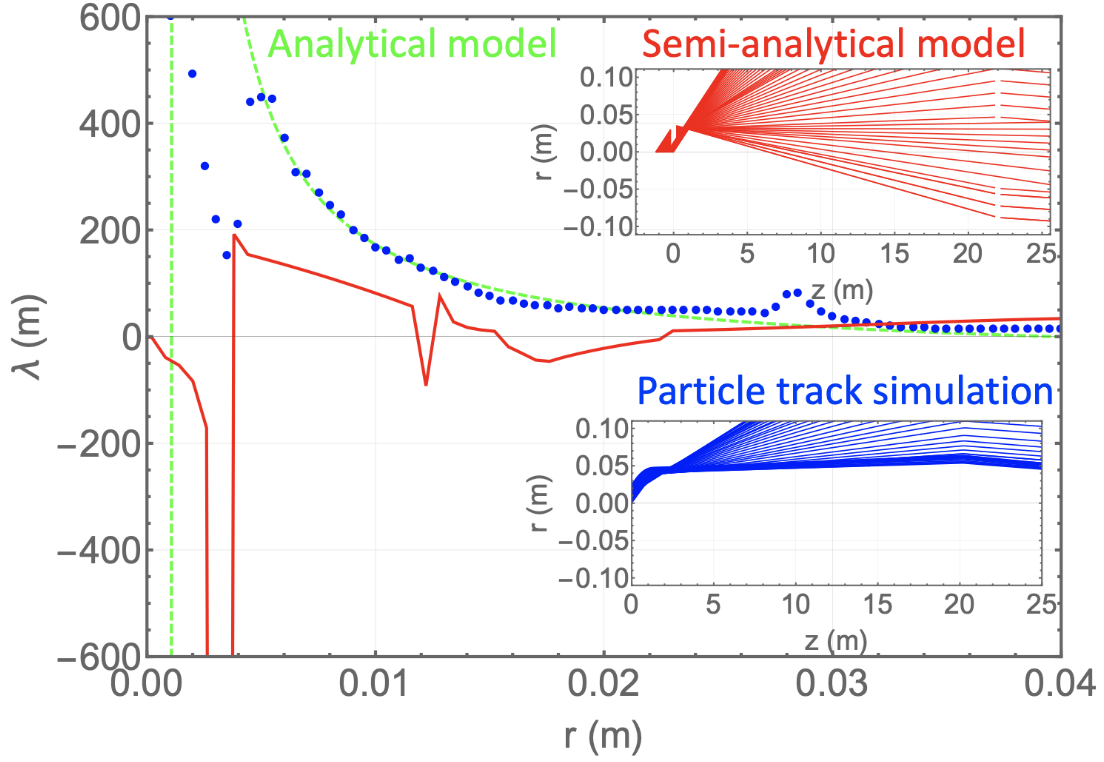
λ shows where the beam is crossing the beam axis

Analytical model: Formulated horn focusing with polynomial
Numerical model: Particle trace simulation by using g4beamline

We also introduce a semi-analytical model:
Trace test particle with two analytical horns

Test linearity of horns with analytical and numerical simulations (II)





p_z = 18 GeV/c, $p_{r,0}$ = 0.2 GeV/c
a_1 = 0.0066 (dipole), a_2 = 0.096 (quadrupole),
a_3 = 5e-6 (sextupole)

p_z = 10 GeV/c, $p_{r,0}$ = 0.3 GeV/c
a_1 = 0.0061 (dipole), a_2 = 0.048 (quadrupole),
a_3 = 2.4e-6 (sextupole)

Summary

- Analysis suggests that the NuMI horn magnet is a linear optics
  - The study will be published in near future
- The model works quite well in higher momentum region
- However, the model does not work well in lower momentum region
  - Need to adjust the horn dimension to reproduce the trace of low momentum particles
  - Energy loss will be dominant for particles at $p < 1$ GeV/c, which should be involved in the model