Pressurized Gas Hadron Monitor for Intense Neutrino Beam Facilities

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Abstract

The alignment of the primary proton beam is critical. Small misalignments in beam angle will result in significant displacement for the neutrino beam once it reaches the far detector 800 miles away. Current deigns for hadron monitors are not fit to withstand the high-intensity beam proposed for a new neutrino beamline facility. A gas-filled RF resonator hadron monitor is proposed to observe this alignment downstream of the target and preceding the beam absorber and detector system.

A preliminary horn electric field map was input to G4Beamline, a particle tracking simulation program, which modelled the position, momentum, global time, and PDGid (Particle Data Group identification number) coordinates for each track. The secondary beam of charged particles produces electron-ion pairs as it ionizes the gas within the resonator. Transverse position and energy dissipation hodoscopes are used to reconstruct these coordinates. Position-dependent electric field is mapped and used to determine the number of electron-ion pairs generated within the resonator. The number of electron-ion pairs generated is integrated over the RF power dissipated by a single electron to give the total RF power dissipation within the resonator.

Problem

The Long Baseline Neutrino Facility (LBNF) will comprise the world's highest-intensity neutrino beam. A primary proton beam provided by the main injector at Fermilab will penetrate a fixed graphite target, generating a beam of secondary particles including pions and kaons. Leptons, namely muons produced from the decay of pions, in this secondary beam decay into neutrinos (Figure 1). These muon neutrinos are directed to a far detector 800 miles away at the Sanford Underground Research Facility (Figure 2).

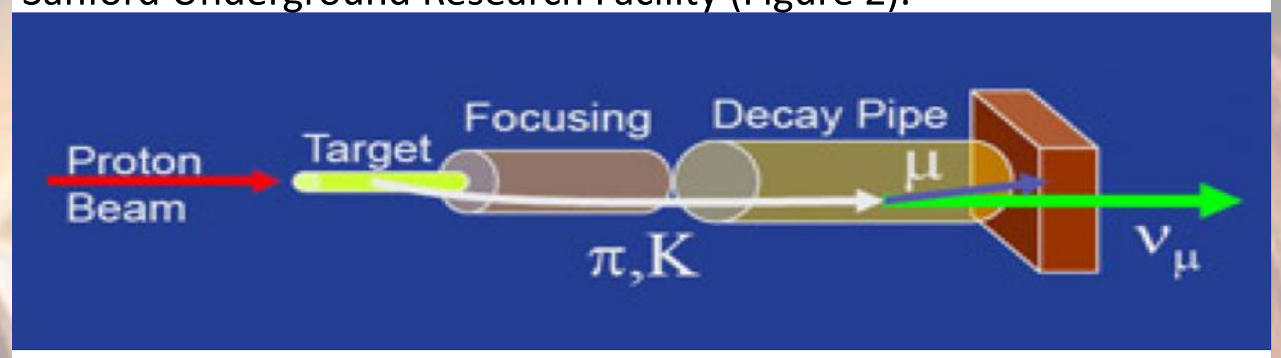

Figure 1: LBNF Beamline Production

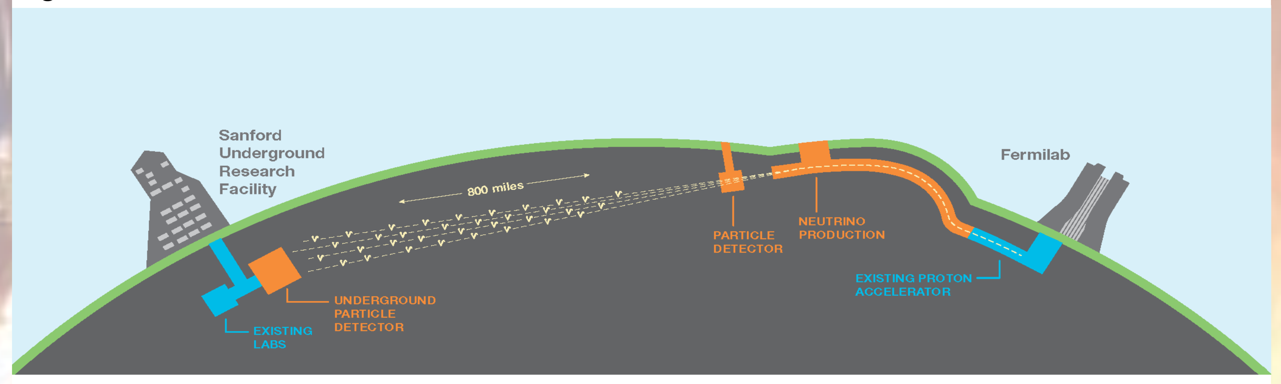

Figure 2: LBNF Facility for a Global Next-Generation Neutrino and Underground Physics Experiment

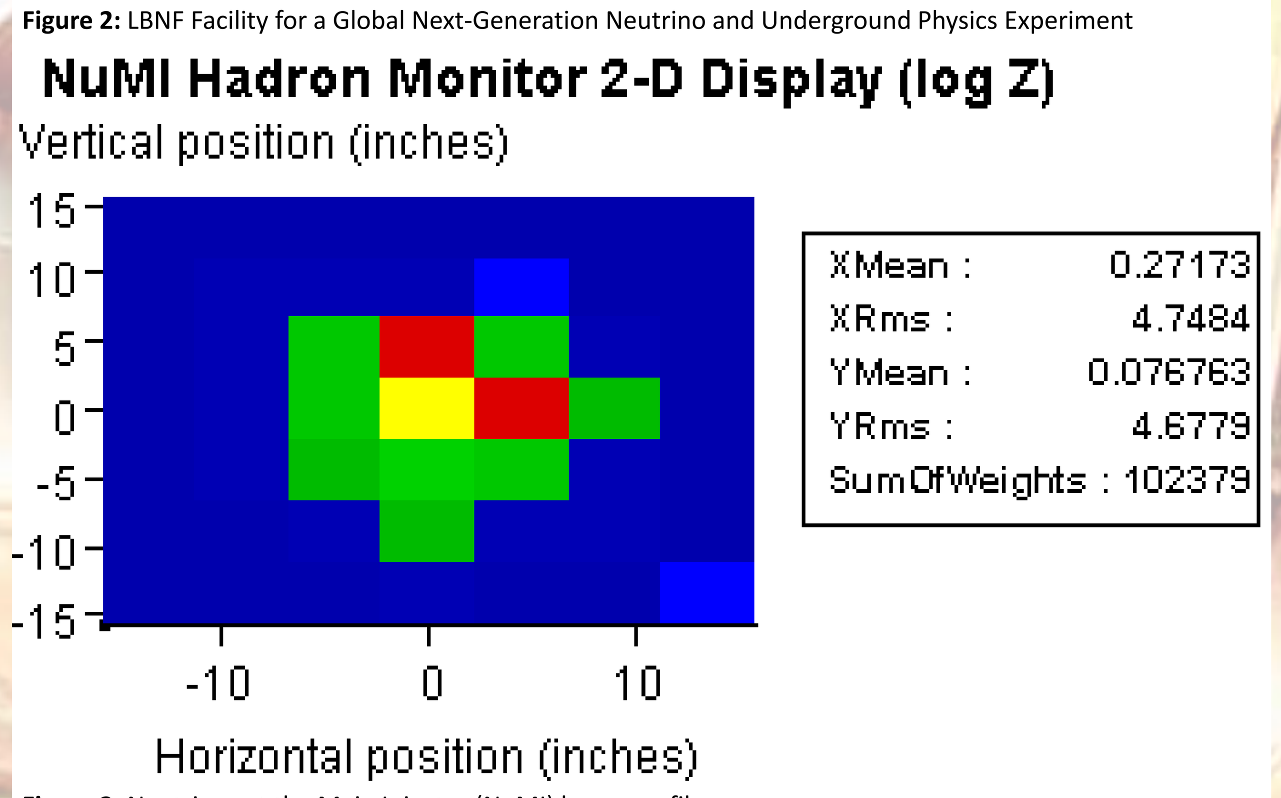

Figure 3: Neutrinos at the Main Injector (NuMI) beam profile

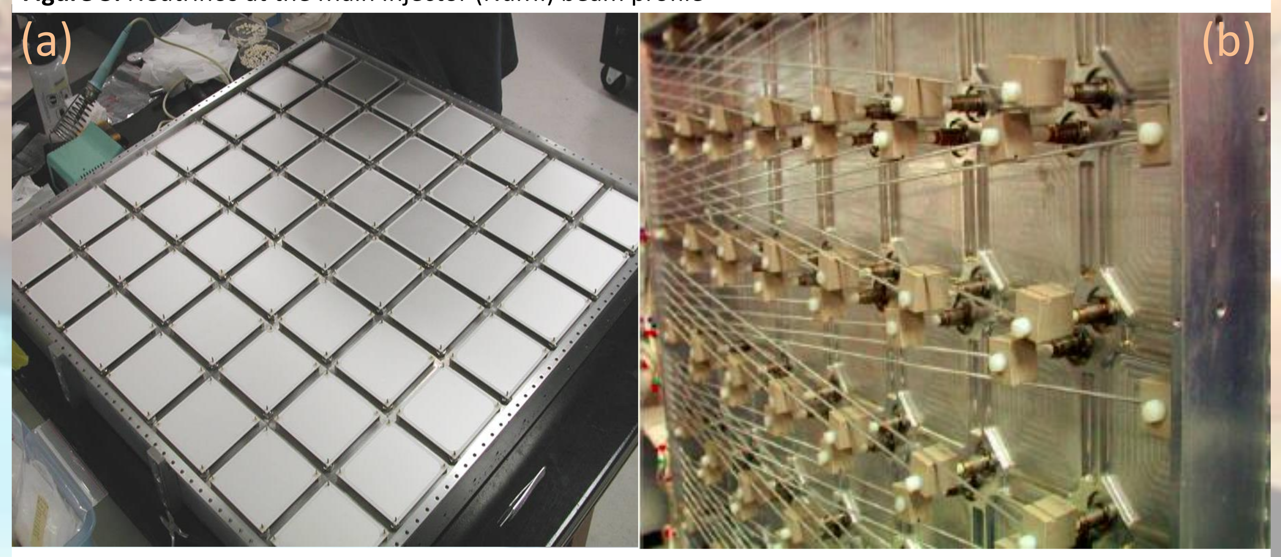

Figure 4: (a) The NuMI hadron monitor is an ionization chamber with a 7x7 array of pixels. **(b)** Each pixel is connected to both a high voltage and a signal readout cable. High beam intensities and robust radiation environments at the LBNF threaten the integrity of these cables.

Design

The motivation for this novel hadron monitor design derives itself from the threatened integrity of high voltage and signal readout cables (Figures 4a, b) of existing technologies (such as at the Neutrinos at the Main Injector, or NuMI, facility) at Fermilab.

NuMI:
- Beam intensities up to 700 kW
- 7x7 array of ionization chambers

LBNF:
- Beam intensities of 2-4 MW
- Gas-filled RF Resonator

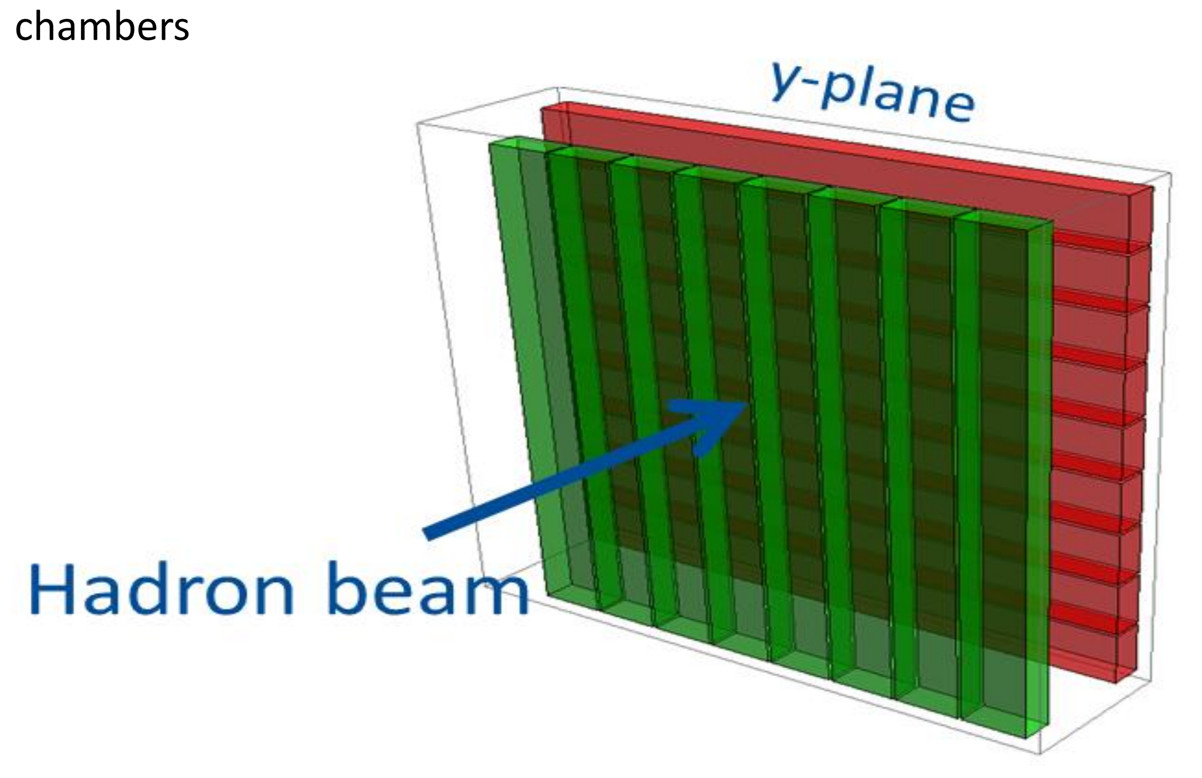

Figure 5: Proposed Hadron Monitor Rendering for LBNF

G4Beamline Simulation

G4Beamline is a beamline simulation software based on the Geant4 toolkit. It was used to generate primary and secondary beam profiles around the proposed target.

Input

Beamline Specifications
- Beam profile: Gaussian
- Number of proton events: 10,000
- σ_X=0.2 and σ_Y=0.2
- Particles tracked: protons, π^+, π^-, K^+, K^-, μ^+, μ^-
- Mean momentum: 120 $\frac{\text{GeV}}{\text{c}}$

Target Specifications
- Dimensions:
  - Height =15 mm
  - Width=6.4 mm
  - Length=999.9 mm
- Material: Carbon

Detector Specifications
- Detector placement: 100 m from target

Output

The following variables are generated for all tracks:
- x, y, and z [mm] positions
- P_X, P_Y, and P_Z $\left[\frac{\text{MeV}}{\text{c}}\right]$ momenta
- t [ns], global time
- PDGid, particle data group ID

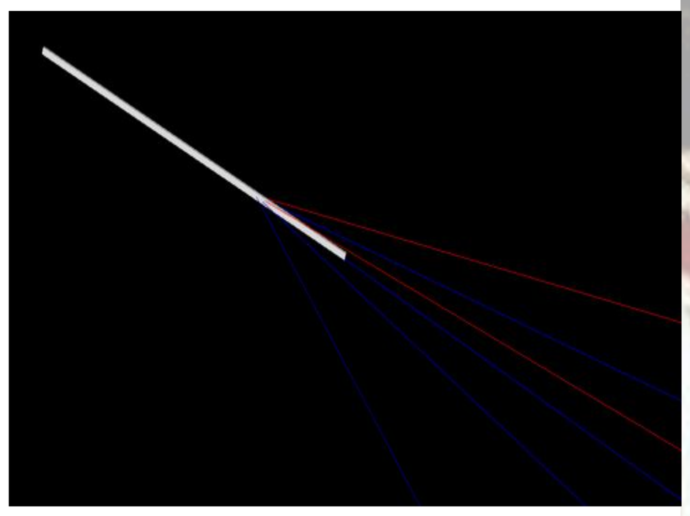

Figure 6: G4Beamline allows for visualization of the Primary Beam – Target – Secondary Beam simulation. Red lines track negatively-charged particles and blue lines track positively-charged particles.

Methods

Nitrogen gas ionization process:

$$proton + N_2(g) \rightarrow proton + N_2^+ + e^- \quad \text{(Eq. 1)}$$

Bethe-Bloch Equation for Stopping Power, $\left\langle\frac{dE}{dx}\right\rangle$:

$$-\left\langle\frac{dE}{dx}\right\rangle = \frac{Kz^2\left(\frac{Z}{A}\right)}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}(\beta,\gamma)}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right) \quad \text{(Eq. 2)}$$

Estimation of Electron-Ion Pair Production, n_e:

$$n_e = N_b \times h\sum_k w_k\left(\frac{\rho_m\left\langle\frac{dE}{dx}\right\rangle}{W_i}\right)_k \quad \text{(Eq. 3)}$$

Energy loss within the cavity, U:

$$U = \int n_e\, dw \quad \text{(Eq. 4)}$$

Results

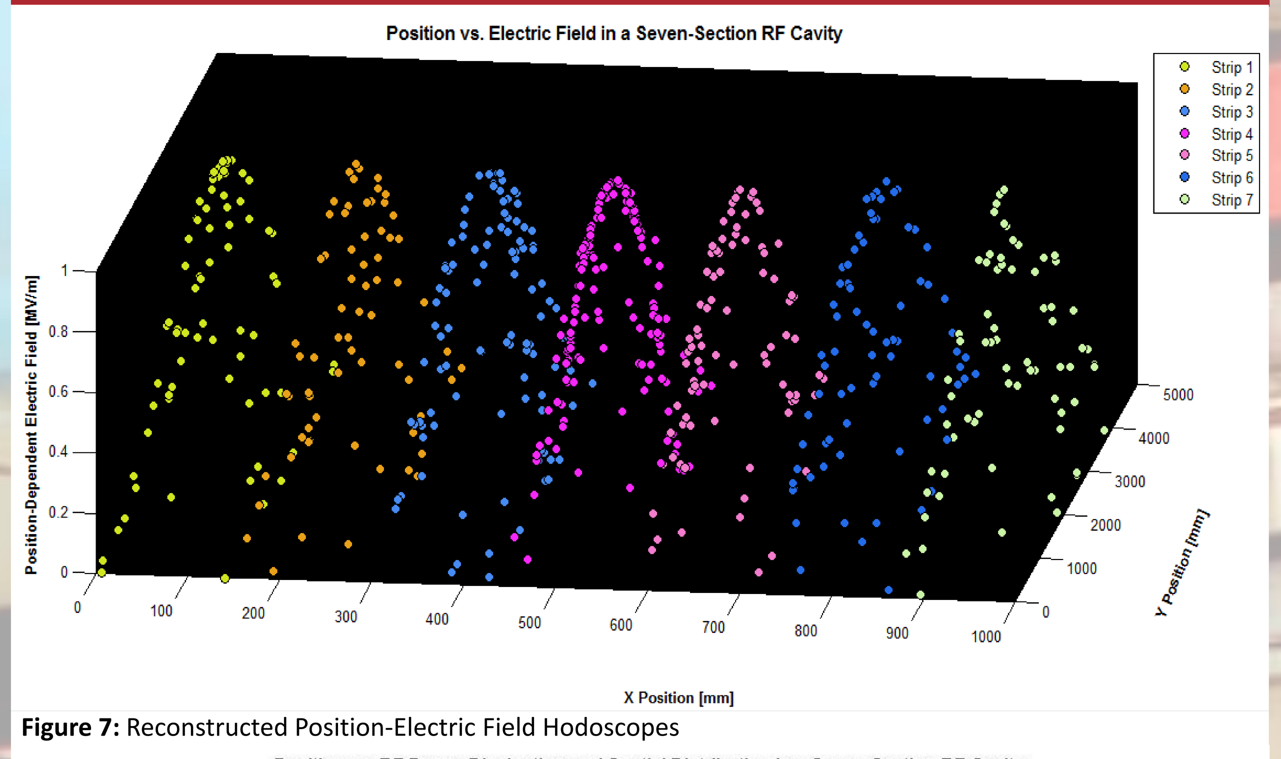

Figure 7: Reconstructed Position-Electric Field Hodoscopes

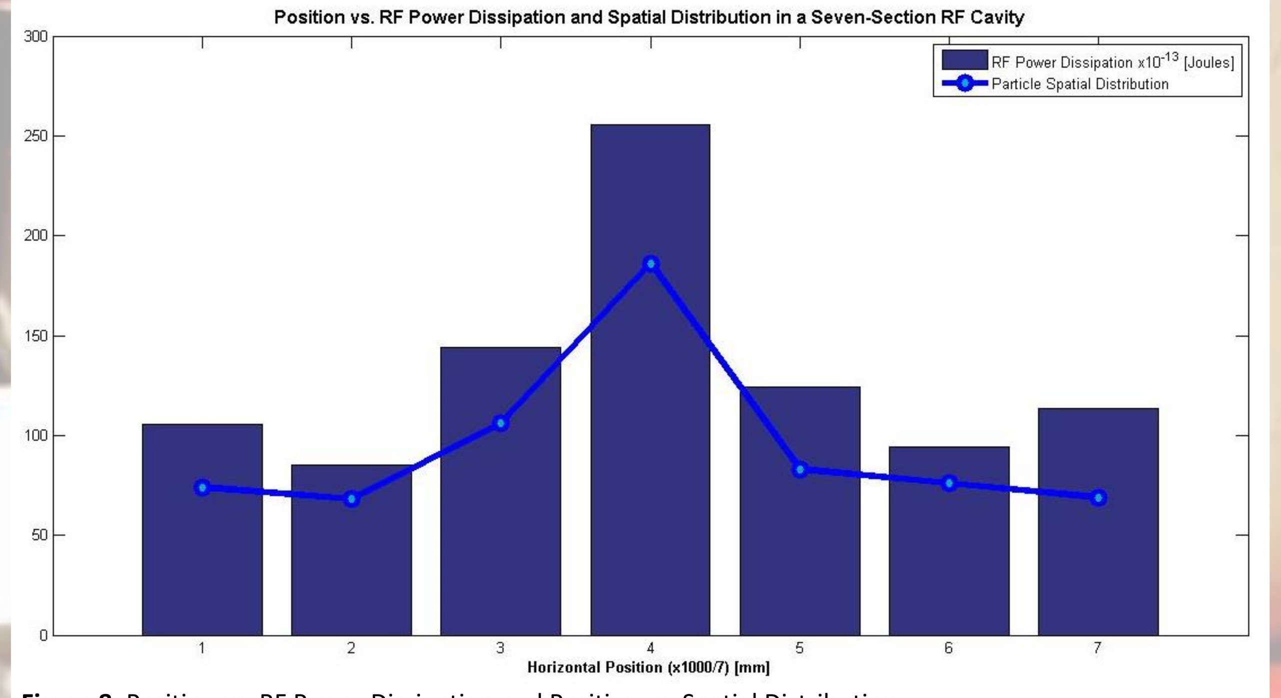

Figure 8: Position vs. RF Power Dissipation and Position vs. Spatial Distribution

- The position variables output from the G4Beamline Simulation were reconstructed in MATLAB for the detector at the specified location from the target.
- Reconstructed coordinates were used to calculate the position-dependent electric field (Figure 7).
- PDGids associated with each particle in the G4Beamline output were reassigned with particle mass energies. Relativistic β and γ values were calculated for each tracked particle, and then used to determine the stopping power (Eq. 2) of Nitrogen gas for each track.
- Electron-ion pair production (Eq. 3) was determined using the stopping power of nitrogen plasma, the statistical weight of Nitrogen plasma, and electron- ion pair production energy in Nitrogen.
- Total RF power loss (Eq. 4) was determined by integrating the number of electron-ion pairs produced over the power dissipation by a single electron (dw) curve in Nitrogen.

Future Work

Electron-Ion Recombination Considerations:

$$N_2^+ + e^- \rightarrow N_2^* \rightarrow N_2 + \gamma$$

Heat Deposition

How does temperature growth affect resonator performance?

Determination of Permittivity of Nitrogen Plasma:

$$\frac{\epsilon}{\epsilon_0} = 1 + \frac{n_e e^2}{\epsilon_0 m\left(\omega_{rf}^2 + \nu^2\right)}\left(1 + i\frac{\nu}{\omega_{rf}}\right)$$

References and Figures

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Figures

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