Pressurized Gas Hadron Monitor for Intense Neutrino Beam Facilities

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Abstract
The alignment of the primary proton beam is critical. Small misalignment in beam angle will result in significant displacement for the neutrino beam once it reaches the far detector 800 miles away. Current designs 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.

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).

Design
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.

Methods
Nitrogen gas ionization process:

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

Bethe-Bloch Equation for Stopping Power, \(\frac{dE}{dx}\):

\[
\frac{dE}{dx} = \frac{K_0 E_{max}^2}{\rho} \left( \frac{1}{\ln(2 \rho m c^2 E_{max})} \right)^2 - \frac{5}{2} \frac{Q_0}{\rho} \quad \text{(Eq. 2)}
\]

Estimation of Electron-Ion Pair Production, \(n_{ei}\):

\[
n_{ei} = N_{ei} \times h \times \sum_w \frac{N_{ei,MAX}}{W^2} \quad \text{(Eq. 3)}
\]

Energy loss within the cavity, \(U\):

\[
U = \int n_{ei} dw \quad \text{(Eq. 4)}
\]

Results
• 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 \(\beta\) and \(\gamma\) 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:

\[
N_2^+ + e^- \rightarrow N_2 + \gamma
\]

Heat Deposition
How does temperature growth affect resonator performance?

Determination of Permittivity of Nitrogen Plasma:

\[
\varepsilon = \varepsilon_0 + \varepsilon_{ref} \left( \frac{E_{ref}}{E_{ref}} \right)^2 - 1
\]

References and Figures
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References

Figures