

# HADRON BEAM MONITOR DESIGN WITH GAS-FILLED RF RESONATORS IN INTENSE NEUTRINO SOURCE\*

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## Abstract

For the future Long Baseline Neutrino Facility at Fermilab, a new radiation-robust hadron beam profile monitor has been proposed consisting of an interface of gas-filled radiofrequency cavity detectors in the backward region of the LBNF decay pipe. A tailored monitor layout will be used along with the new RF instrumentation. Proposed designs for the detector configuration include a variety of radially symmetric arrangements of RF resonators located at the position of maximum gradient in the beam distribution across the monitor. Until the final detector cavities are available, a prototype tunable Q-factor RF cavity will provide functional emulation for studies of the monitor layout configurations presented here.

## INTRODUCTION

The production of a 'high quality' neutrino beam necessitates the careful monitoring of hadronic beam parameters in the neutrino production scheme. Among the measurable parameters of the beam, the diagnostic of its intensity profile is a critical element in the alignment of the beam with respect to a detection monitor. In this regard, an ion chamber has been a popular method of measuring the profile of the traversing beam. The current structure of the NuMI experiment includes an array rows and columns distributed across a rectangular area. This method has proven to be effective but also suffer from a number of disadvantages such as lack of an accurate calibration procedure, or severe damage due to radiation.

To solve this problems, a radiation-resistive beam profile monitor based on a gas-filled RF cavity has been proposed [1]. The RF cavity beam profile monitor has been exposed to numerous tests including a beam test at SY120 beam dump, and table top signal measurements with a tunable Q-factor RF cavity [1]. Building on these concepts, this study explores an alternative approach of designing a beam monitor with RF cavities. The main focus of this contribution is to design a cell monitor layout in which the detection sensitivity is maximized based on the beam intensity distribution.

In particular, the distribution of the hadronic beam due to scattering in the target is considered as a basis for determining the location of maximum sensitivity at the monitor. The ability to use individual RF cavity cells also provides the advantage of creating a monitor layout based on critical locations in the beam intensity distribution. Alternatively,

the location maximum sensitivity across the monitor could also lead to the design of a single RF cavity cell tailored to the beam distribution.

## DESIGN

A particle beam traversing through a medium will be deflected by small scatters, mostly resultant of Coulomb interactions from the nuclei. The net scattering and displacement of the beam through the target is described by a Gaussian distribution and the central limit theorem [2]. These Coulomb scattering distributions can be effectively modeled by the theory of Moliere. Then, the central 98% of the projected angular distribution can be described for many application with a Gaussian approximation given by,

$$\theta_0 = \frac{13.6}{\beta c p} z \sqrt{\frac{x}{X_0}} \left( 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right) \quad (1)$$

Where  $p$ ,  $\beta c$ , and  $z$ , are the momentum, velocity, and charge number of the incident particle, and  $x/X_0$  is the thickness of the scattering medium in radiation lengths.

Note that the scattering angle produced by a beam traversing a target is probabilistic in nature. Based on theory behind the previous approximation, the angle given by Eq. 1 also corresponds to the the standard deviation  $\sigma$  of the beam distribution reaching the back end monitor.

With this in mind, let us first consider just the simple 1-dimensional Gaussian distribution of a normal beam reaching the x-direction of the monitor as shown in Figure 1,

$$f(x) = y = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (2)$$

In this case,  $x$  is the physical location of the incident particle with respect to the center of the monitor,  $\mu$  then is the mean distance (namely the center of the monitor), and  $y$  is the probability that such particle will hit that distance  $x$  from the center.

Note that the probability of a particle hitting the monitor is the same across its whole area at any location  $x$ . This means that the likelihood of a particle hitting the monitor will only depend on the number of beam particles crossing that location. We can then say that in the normal distribution of the beam across the monitor,  $y$  is the 'intensity' of the beam at a given location  $x$ .

Directly from that conclusion, taking the first derivative,  $dy/dx$ , would lead to an expression for the the change of intensity with respect to a change in displacement of the beam. This expression is plotted in Figure 2. In other words, the absolute value of  $dy/dx$  provides the equation for the 'sensitivity' of the monitor as a function of displacement. It

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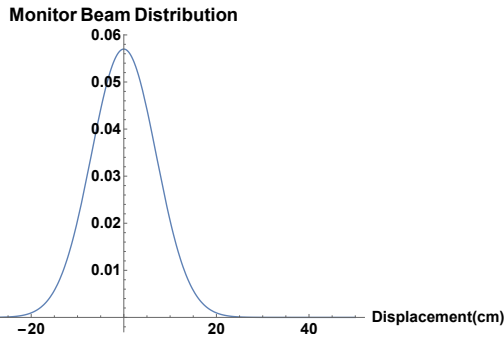


Figure 1: 1-Dimensional Beam normal distribution of hadron beam hitting the monitor target.

relates the change of intensity in the monitor to a change in position. Assuming a mean  $\mu = 0$  equal to zero at center of the monitor it follows,

$$\frac{dy}{dx} = -\frac{1}{\sigma\sqrt{2\pi}} \left(\frac{x}{\sigma^2}\right) e^{-\frac{x^2}{2\sigma^2}} \quad (3)$$

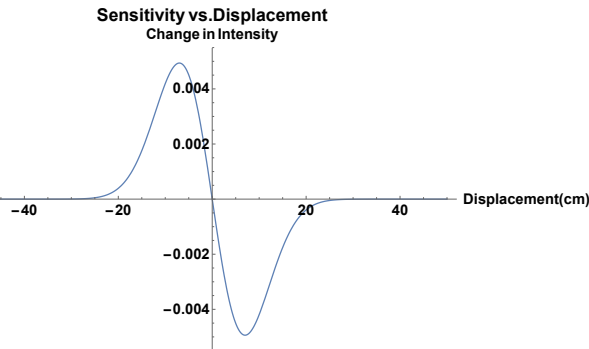


Figure 2: Plot of the derivative of the beam distribution. It shows the rate of change in intensity across the monitor as a function of displacement.

The change in 'intensity' of detection with respect to position is critical to establish the beam profile. Since the size of the pixels (or RF cavities) is much larger than the average physical displacement of the beam, the most appropriate way to detect a change in beam displacement is to detect a change in beam intensities across the cells.

Furthermore, in order to find the most sensitive region of the monitor at which the change in intensity  $dy/dx$  is maximum, the derivative with respect to position must be taken twice  $d^2/dx^2(dy/dx)$  and set equal to zero. In other words, if we wish to find the point at which the change in intensity is the **greatest** for a change in position  $x$ , then we must solve for

$$\frac{d^2y}{dx^2} = 0 \quad (4)$$

For the Gaussian distribution of Eq. 2 with mean of  $\mu = 0$  this is,

$$\begin{aligned} \frac{d^2 f(x)}{dx^2} &= -\frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{\sigma^2}\right) e^{-\frac{x^2}{2\sigma^2}} \\ &\quad + \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{x^2}{\sigma^4}\right) e^{-\frac{x^2}{2\sigma^2}} \end{aligned} \quad (5)$$

$$\frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{\sigma^2}\right) e^{-\frac{x^2}{2\sigma^2}} = \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{x^2}{\sigma^4}\right) e^{-\frac{x^2}{2\sigma^2}}$$

$$\therefore x = \pm\sigma$$

This means that at position  $x = \sigma$  the hadron monitor is the most sensitive to a change in displacement. This can be confirmed by observing the plot of the absolute value of  $dy/dx$  shown in Figure 3. This graph presents 'sensitivity as a function of displacement'.

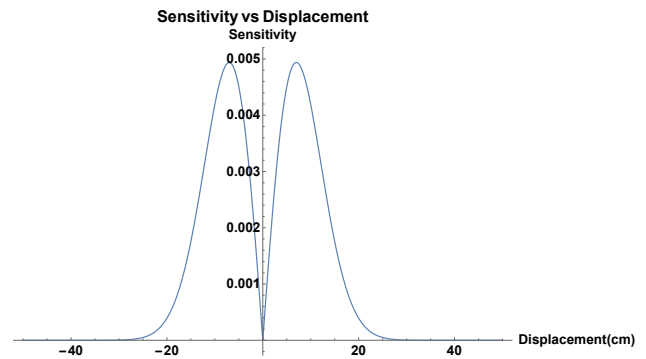


Figure 3: Plot of the absolute value of the derivative of the beam distribution. It shows the maximum sensitivity across the monitor as a function of beam displacement.

## MONITOR LAYOUT

Based on the previous conclusion, a more efficient pixel configuration can be designed across the hadron monitor such that it is highly sensitive to a change in the beam displacement. Based on the previous calculations of the beam distribution and sensitivity let us now consider a 3-Dimensional plot of a gaussian beam reaching the hadron monitor as shown in Figure 4.

A change in the displacement of the beam would result in a change in the number of particles hitting the monitor at all locations. This change in intensity will be best measured if the pixels are located at the most sensitive points across the beam distribution. This point will correspond to the location in the monitor at which a change in the number of particles detected results in the greatest **difference** from its previous count.

For example, since the center of monitor receives the greatest number of particles, a change in this number by a small difference (small beam displacement) will not result in a big change in the net number of particles hitting that location (intensity). The same is true for the tail of the distribution.

Based on the previous calculations, the most sensitive location to a change in beam intensity is exactly the location of

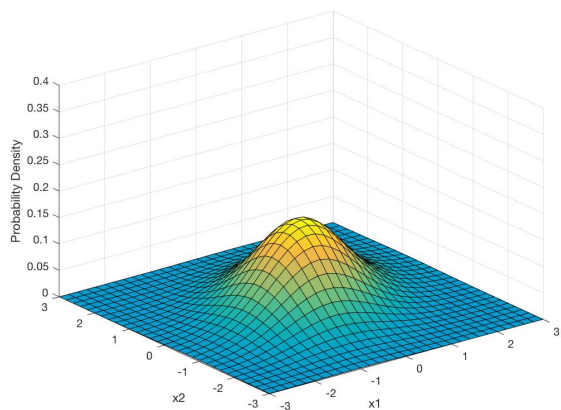


Figure 4: Gaussian beam distribution across profile monitor.

the standard deviation  $\sigma$ . Moreover, the standard deviation of the beam distribution directly corresponds to the scattering angle formula presented in Eq. 1. A 3-Dimensional plot of the **sensitivity of the monitor to a change in beam displacement** is shown in Figure 5 and Figure 6.

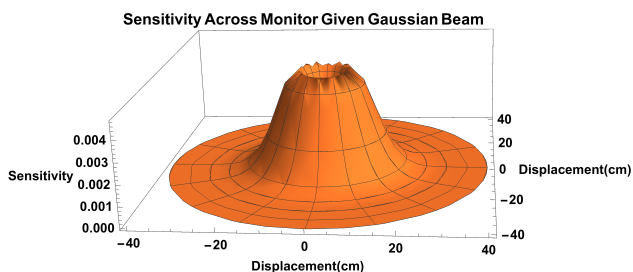


Figure 5: 3-Dimensional distribution of sensitivity across the monitor to a change in the beam displacement.

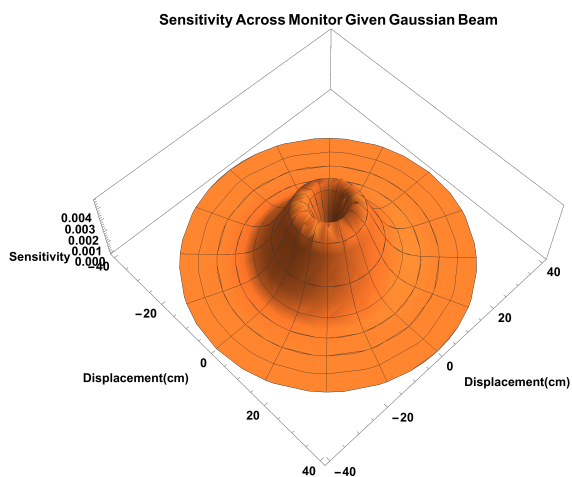


Figure 6: 3-Dimensional distribution of sensitivity across the monitor to a change in the beam displacement.

The previous plot directly reflects the conclusion that a detection monitor would be more sensitive to a change in displacement at the location of the standard deviation of the

scattering of the beam (high peaks). Additionally note that the sensitivity of the monitor quickly approaches zero near the center. Therefore, a toroidal pixel configuration would result in the greatest sensitivity to beam displacements for reconstruction of the transverse profile.

This leads to the final stage of the initial RF Cavity Hadron monitor design. Two monitor layouts are proposed in this study. In the first design a center RF cavity is located in the middle of the monitor and it is surrounded by a single 'doughnut' shaped cell gas-filled RF cavity. In the second design, 5-7 RF cavities are used including, one in the center, and additional 4-6 cavities distributed across the most sensitive zone of the monitor. Given a normally distributed gaussian beam reaching the monitor, these configurations will provide to high sensitivity in changes in intensity due to changes in position. Such changes in intensity will then lead to more efficient reconstruction of the beam's transverse profile across the monitor.

### ACKNOWLEDGEMENTS

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