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Accelerator Physics Center
Muon Accelerator R&D Department

Feasibility of a Gas-Filled RF Resonator for a Hadron Monitor

Giorgio Fasce, Electrical Eng.
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Supervisor:
Dr. Katsuya Yonehara

Introduction

- In the intense neutrino beam facilities for the fundamental physics research, a **hadron monitor** plays an important role to **measure a profile and a flux of secondary particles** at downstream of a target to align from the beam element to the neutrino detector system, and to check the beam quality on-line.

- The designed **beam power** of primary proton for the LBNF (Long Baseline Neutrino Facility) will be **2.3 MW**.

- Since the monitor has been exposed directly to the intense proton beam the **lifetime of the monitor is noticeably short** due to extremely high radiation damage.

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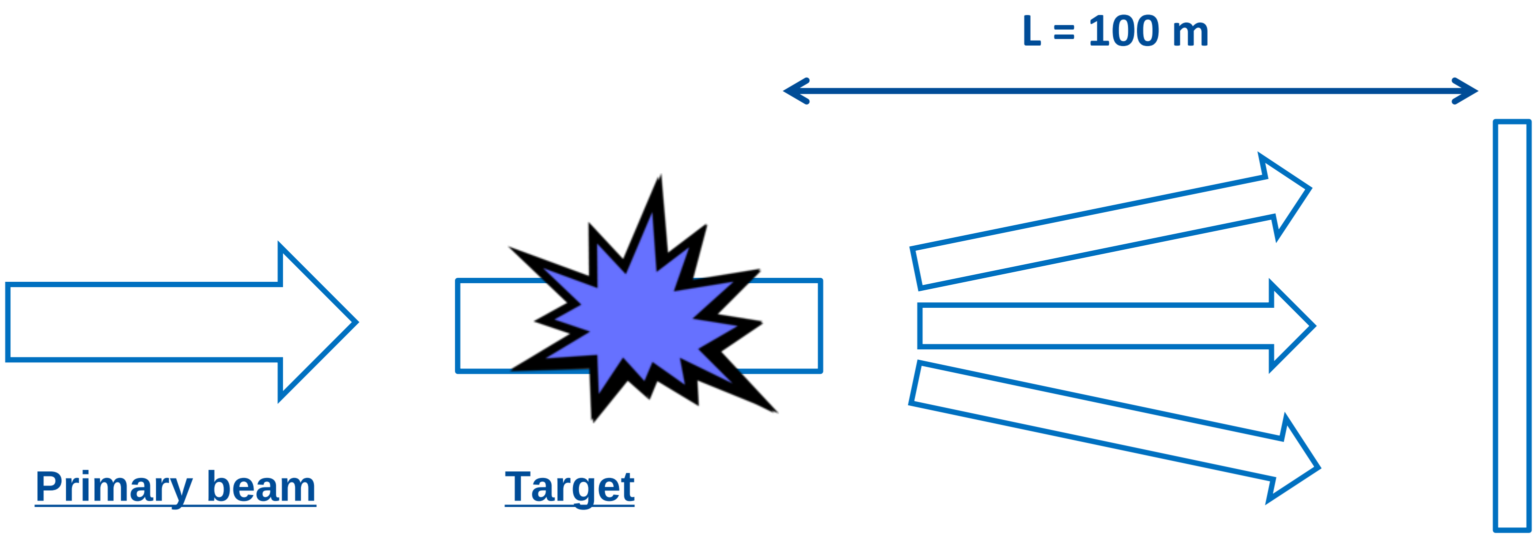
LBNF Beam Line



Primary beam

- **Protons 120 GeV**

Target

- **Carbon Graphite**

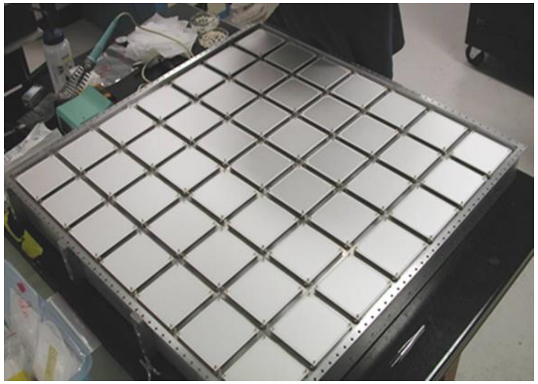
Secondary beam

- **Protons**
- **Pions**
- **Electrons**
- **γ-rays**
- **…**

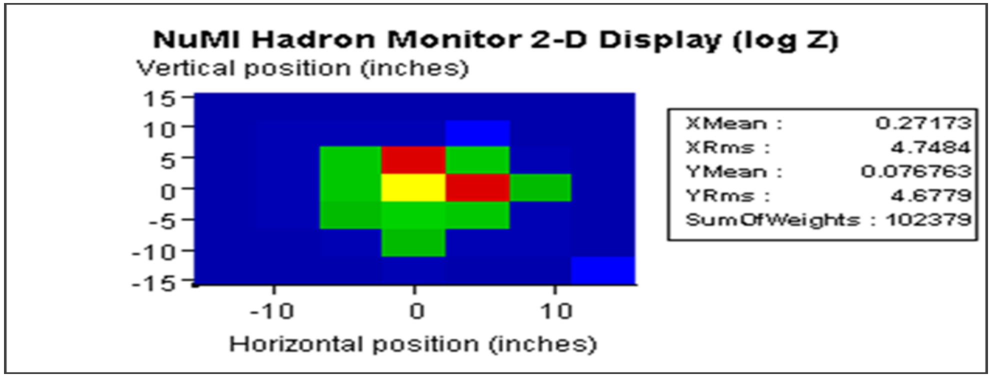
Hadron monitor

Existing Hadron Monitor

- The existing hadron monitor based on an ionization chamber is not robust in the high-radiation environment vicinity of MW-class secondary particle production targets.



The ionization chamber for the NuMI experiment.



The observed beam profile in the NuMI beam line.

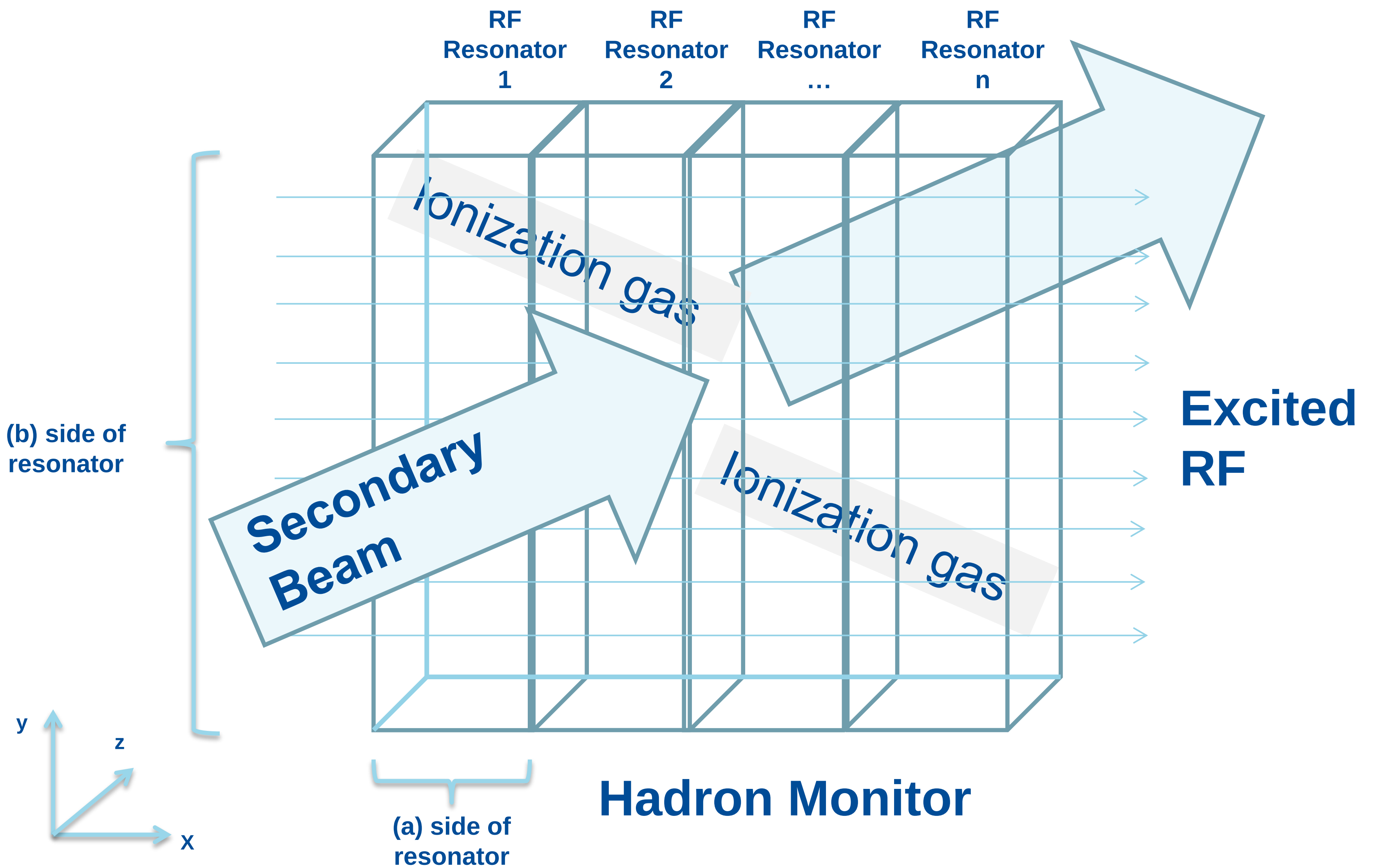
A pixel represents a segment size of the ionization chamber (7×7 pixels in 1×1 m^2).

- The new hadron monitor should be:
  - Radiation robust.
  - Highly sensitive to the secondary particle.
  - Cost effective.

Proposal for a New Hadron Monitor

- **Gas-Filled RF Resonator Project:**
  - **New hadron monitor** formed by a set of **RF resonators** containing an **ionization gas**.
  - When the beam passes through the resonator the beam produces a **great amount of electron-ion pairs** by interacting with gas.
  - **The permittivity in the resonator is changed** proportional to the amount of produced ion pairs.
  - The number of ion pairs is proportional to the hadron flux.

Schematic Drawing of New Hadron Monitor



How to Measure the Hadron Flux

Resonance Frequency f	**Measurement**	
Permittivity ε'	**Evaluation**	$f = \frac{x_{mn}}{2\pi\sqrt{\mu\varepsilon'}}$
Total number of electron-ion pairs n_e	**Evaluation**	$\varepsilon' = 1 + \frac{\boldsymbol{n_e}(p_{gas})e^2}{\varepsilon_0 m\left[\omega^2{}_{rf} + \nu\left(T_e(E, p_{gas})\right)^2\right]}$
Total number of particle $I_{incident}$	**Evaluation**	$n_e = \frac{\left(\frac{dE}{dx}\right)_{p=p_0}}{W_i}\rho_{gas}\boldsymbol{I_{incident}}$

W_i *= average energy to require single electron-ion pair production*
T_e *= electron temperature*
p_{gas} *= gas pressure*
v *= collision frequency*
μ *= permeability*
ω_{rf} *= resonance pulsation*
m *= electon mass*
x_{mn} *= wave number*
E *= electric field*
e *= electron charge*

Project Plan

Goal: evaluate the feasibility of a gas-filled RF resonator for a hadron monitor.	
Step 1	Make a code to generate a TMmn field map of the resonator.
Step 2	Find out a secondary particle by using g4beamline.
Step 3	Import a TMmn field map into g4beamline and estimate the frequency shift.
Step 4	Optimization.
Step 5	Start engineering design.

Step 1 - TM_{mn} Field Map of the Resonator - Basic Equations

Electric Field Components

$$Re\ (E_x) = -B_{mn}\frac{\beta m\pi}{{k_c}^2 a}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\sin\beta z$$

$$Re\ (E_y) = -B_{mn}\frac{\beta n\pi}{{k_c}^2 b}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}\sin\beta z$$

$$Re\ (E_z) = B_{mn}\ \sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\cos\beta z$$

Magnetic Field Components

$$Re\ (H_x) = B_{mn}\frac{\omega\varepsilon n\pi}{{k_c}^2 b}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}\sin\beta z$$

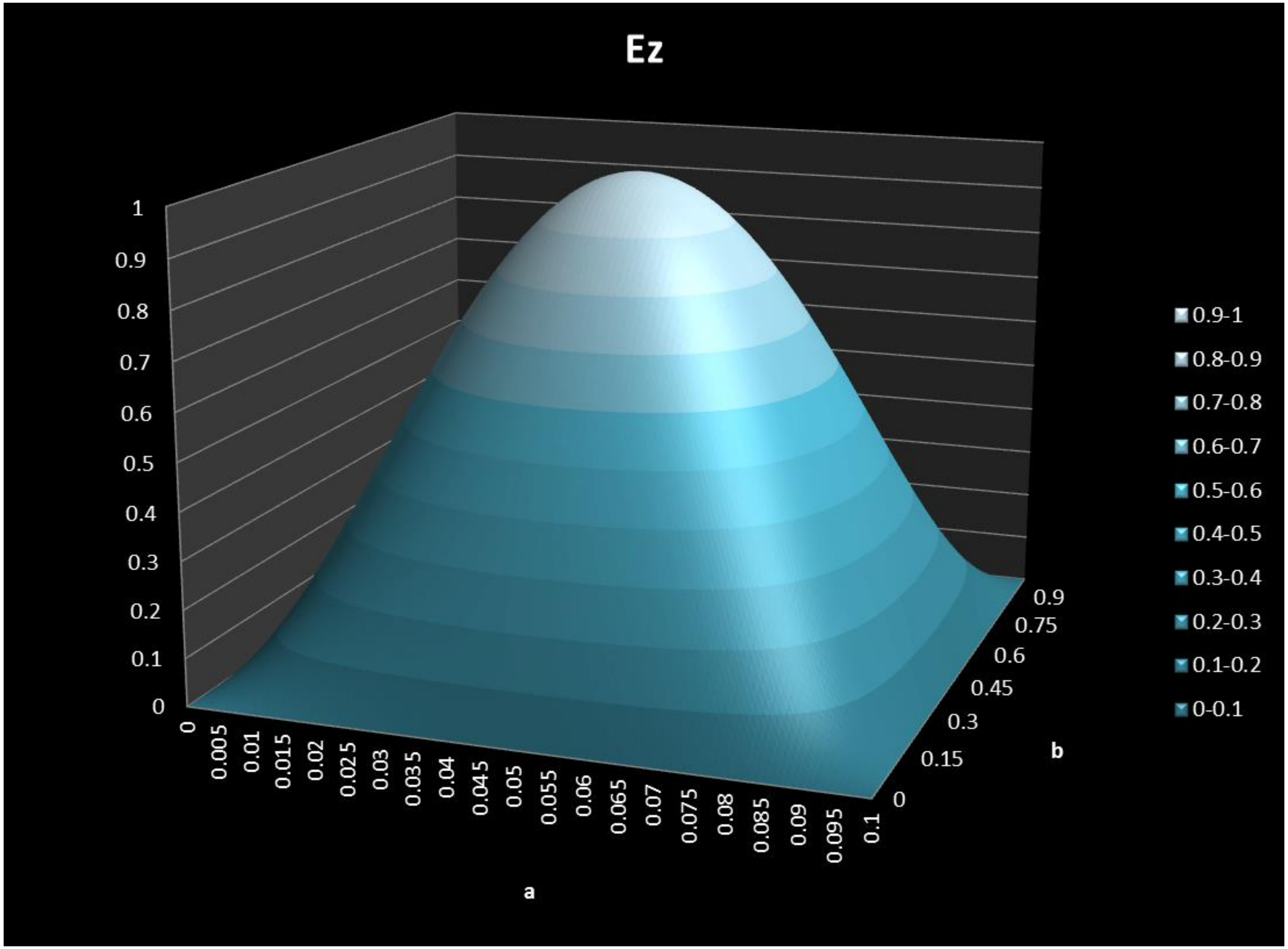
$$Re\ (H_y) = -B_{mn}\frac{\omega\varepsilon m\pi}{{k_c}^2 a}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\sin\beta z$$

$$Re\ (H_z) = 0$$

Wave Number	Cut-Off Wave Number	Propagation Constant	Cut-Off Wavelenght	Cut-Off Frequency
$k = \omega\sqrt{\mu\varepsilon}$	$k_c = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$	$\beta = \sqrt{k^2 - {k_c}^2}$	$\lambda_c = \frac{2\pi}{k_c}$	$f_c = \frac{c}{\lambda_c}$

$\omega = 2\pi f$ = pulsation; m, n = mode numbers; a, b = dimensional numbers;
μ = permeability; ε = permittivity; c = speed of light

Step 1 - TM_{mn} Field Map of the Resonator - Plot



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Step 2 - Secondary Particles by G4beamline

- G4beamline is a particle tracking simulation program based on Geant4 and optimized for the simulation of beamlines.

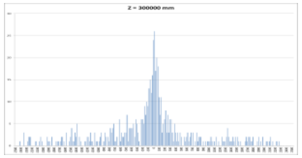
G4beamline output

```
#BLTrackFile VirtualDetector/Det0
#x y z Px Py Pz t PDGid EventID TrackID ParentID Weight
#mm mm mm MeV/c MeV/c MeV/c ns - - - - -
#BLTrackFile VirtualDetector/Det0
#x y z Px Py Pz t PDGid EventID TrackID ParentID Weight
#mm mm mm MeV/c MeV/c MeV/c ns - - - - -
#BLTrackFile VirtualDetector/Det0
#x y z Px Py Pz t PDGid EventID TrackID ParentID Weight
#mm mm mm MeV/c MeV/c MeV/c ns - - - - -
15.4683 -1.89771 1000 294.328 -28.1919 5592.02 3.35091 2212 1 1001 1 1
-59.1731 -64.4177 1000 -115.995 -126.065 583.737 3.40422 -211 1 1002 1 1
1.22983 0.997633 1000 36.161 20.4311 4449.37 3.33621 211 1 1003 1 1
805.825 455.596 100000 36.161 20.4311 4449.37 333.741 211 1 1003 1 1
8.1329 29.7158 1000 132.835 481.745 4719.16 3.34161 -211 1 1006 1 1
-11.432 -18.929 1000 -102.7 -169.957 2690.6 3.33968 211 1 1007 1 1
115.412 106.875 1000 275.89 255.836 706.457 3.48395 -211 1 1008 1 1
-6.36794 30.0736 1000 -77.2058 362.039 2511.81 3.34481 -211 1 1009 1008 1
-245.73 -222.763 1000 -359.033 -323.518 318.089 5.12781 2212 1 1010 1009 1
23.622 -20.9261 1000 121.782 -104.927 1511.65 3.34546 211 1 1011 1008 1
11.4225 24.8694 1000 48.8025 111.559 1294.8 3.5698 2212 1 1014 1 1
33.1737 -117.714 1000 39.4572 -138.738 350.646 3.48624 211 1 1015 1 1
1.14786 12.4992 1000 5.34775 68.0714 1627.35 3.34019 -211 1 1016 1 1
-4.86578 6.69411 1000 -257.961 397.687 16850.9 3.33615 -211 1 1017 1 1
13.7197 -0.42557 1000 335.108 -1.31314 7083.4 3.337 211 1 1018 1 1
-183.191 123.716 1000 -179.724 121.884 291.26 3.66823 211 1 1019 1 1
-21.9044 4.34396 1000 -431.873 85.3389 16723.3 3.33674 211 2 1002 1 1
511.802 324.653 1000 289.719 183.8 479.608 4.08031 211 2 1005 1 1
```

Microsoft Excel evaluation

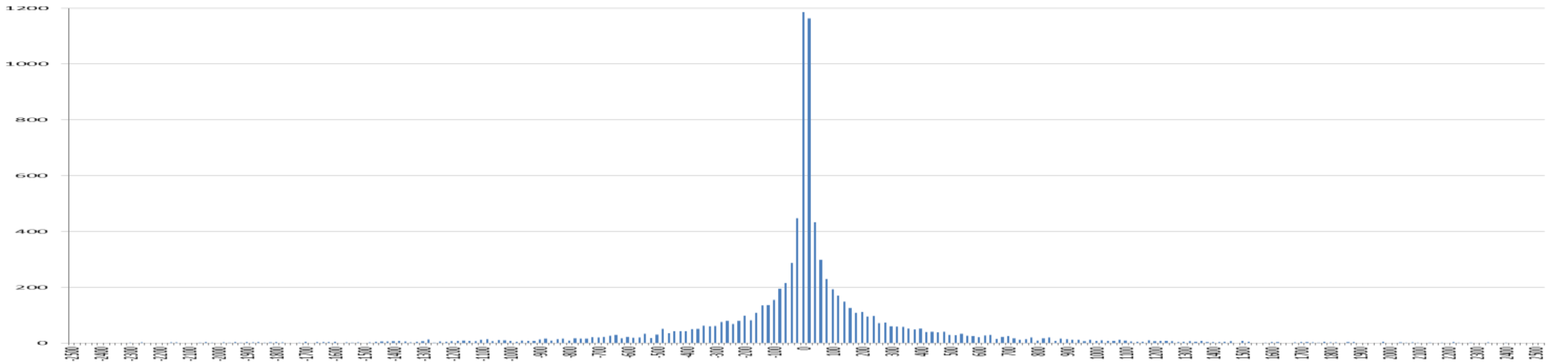
#BLTrackF	VirtualDetector/Det0															
#x	y	z	Px	Py	Pz	t	PDGid	EventID	TrackID	ParentID	Weight					
#mm	mm	mm	MeV/c	MeV/c	MeV/c	ns	-	-	-	-	-					
#BLTrackF	VirtualDetector/Det0															
#x	y	z	Px	Py	Pz	t	PDGid	EventID	TrackID	ParentID	Weight					
#mm	mm	mm	MeV/c	MeV/c	MeV/c	ns	-	-	-	-	-					
#BLTrackF	VirtualDetector/Det0															
#x	y	z	Px	Py	Pz	t	PDGid	EventID	TrackID	ParentID	Weight		X	Y	Z	|P|
#mm	mm	mm	MeV/c	MeV/c	MeV/c	ns	-	-	-	-	-		[mm]	[mm]	[mm]	[MeV/c]
15.4683	-1.89771	1000	294.328	-28.1919	5592.02	3.35091	2212	1	1001	1	1		15.4683	-1.89771	1000	5599.831
-59.1731	-64.4177	1000	-115.995	-126.065	583.737	3.40422	-211	1	1002	1	1					
1.22983	0.997633	1000	36.161	20.4311	4449.37	3.33621	211	1	1003	1	1					
805.825	455.596	100000	36.161	20.4311	4449.37	333.741	211	1	1003	1	1					
8.1329	29.7158	1000	132.835	481.745	4719.16	3.34161	-211	1	1006	1	1					
-11.432	-18.929	1000	-102.7	-169.957	2690.6	3.33968	211	1	1007	1	1					
115.412	106.875	1000	275.89	255.836	706.457	3.48395	-211	1	1008	1	1					
-6.36794	30.0736	1000	-77.2058	362.039	2511.81	3.34481	-211	1	1009	1008	1					
-245.73	-222.763	1000	-359.033	-323.518	318.089	5.12781	2212	1	1010	1009	1		-245.73	-222.763	1000	578.5751
23.622	-20.9261	1000	121.782	-104.927	1511.65	3.34546	211	1	1011	1008	1					
11.4225	24.8694	1000	48.8025	111.559	1294.8	3.5698	2212	1	1014	1	1		11.4225	24.8694	1000	1300.513
33.1737	-117.714	1000	39.4572	-138.738	350.646	3.48624	211	1	1015	1	1					
1.14786	12.4992	1000	5.34775	68.0714	1627.35	3.34019	-211	1	1016	1	1					
-4.86578	6.69411	1000	-257.961	397.687	16850.9	3.33615	-211	1	1017	1	1					
13.7197	-0.42557	1000	335.108	-1.31314	7083.4	3.337	211	1	1018	1	1					
-183.191	123.716	1000	-179.724	121.884	291.26	3.66823	211	1	1019	1	1					
-21.9044	4.34396	1000	-431.873	85.3389	16723.3	3.33674	211	2	1002	1	1					
511.802	324.653	1000	289.719	183.8	479.608	4.08031	211	2	1005	1	1					
-199.026	-624.199	1000	-68.555	-214.927	291.712	4.32936	-211	2	1006	1	1					
993.881	2102.43	1000	174.746	371.008	141.888	20.2209	2212	2	1008	1007	1		993.881	2102.43	1000	433.9531
463.416	143.709	1000	533.041	169.826	930.467	4.79286	2212	2	1010	1007	1		463.416	143.709	1000	1085.699
-518.54	-694.722	1000	-217.229	-288.55	336.057	4.74859	211	2	1012	1007	1					

Particles distribution histogram

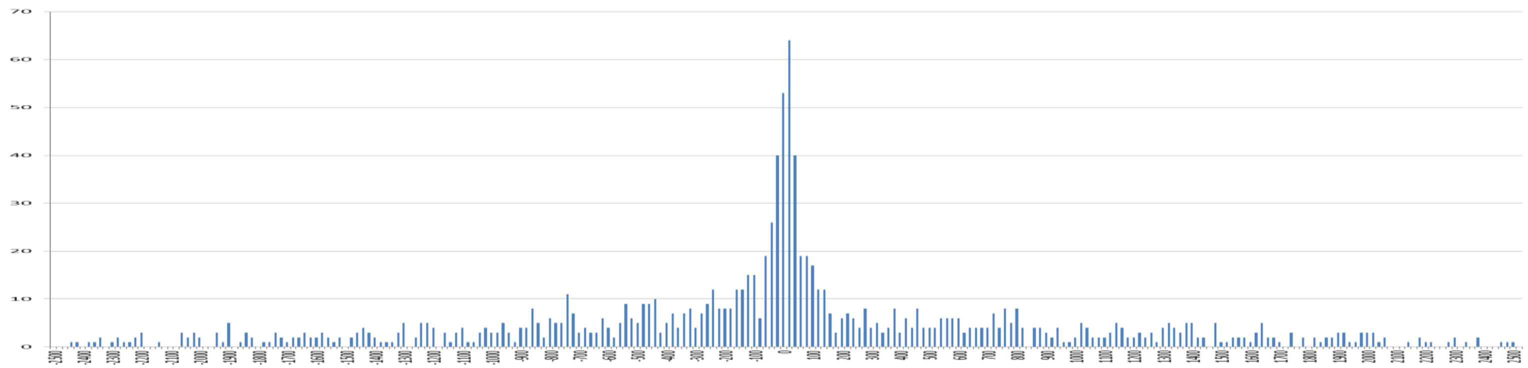


Step 2 - Particles Distribution Histogram

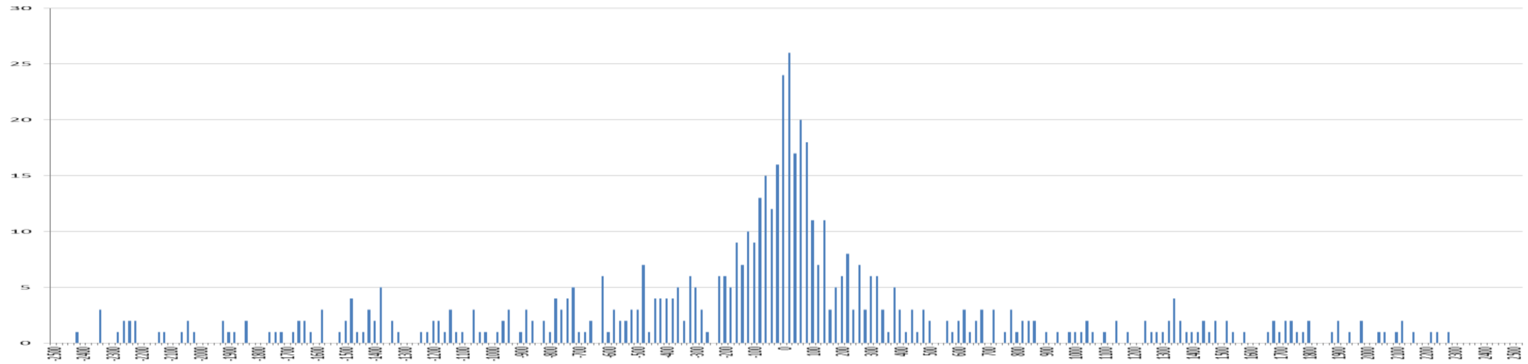
L = 1 m



L = 100 m

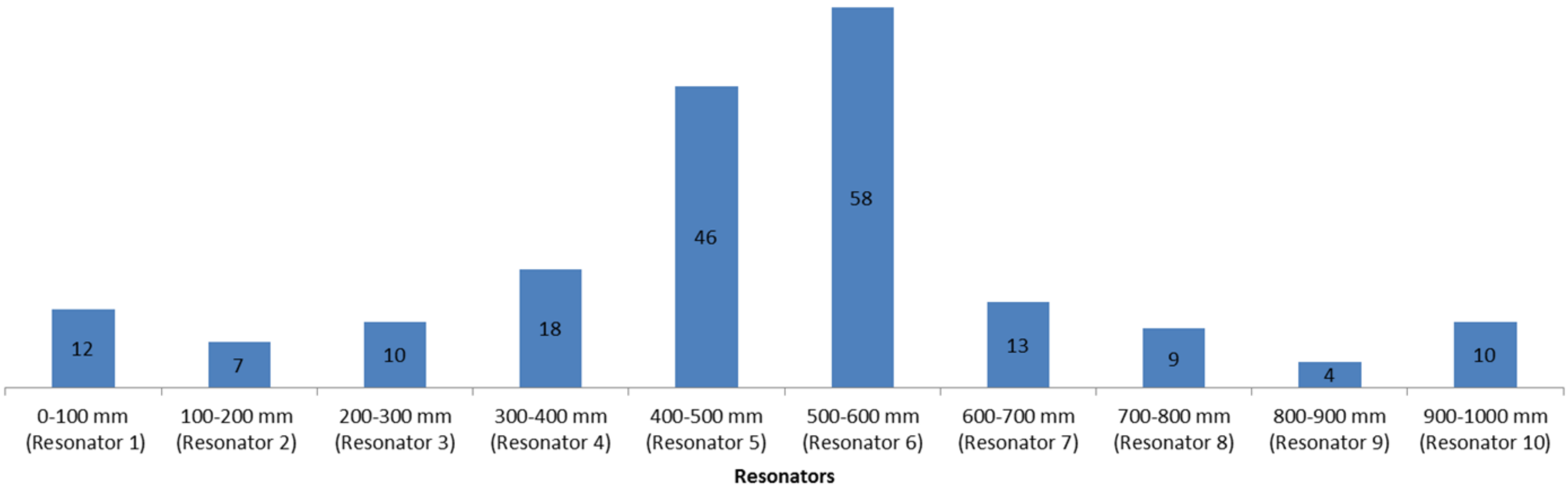


L = 300 m



Step 3 - Particles Distribution in Each Resonator

- **Hp:**
  - Hadron Monitor Size: 1 [m] x 1 [m]
  - Resonators Size, (a) x (b): 0.1 [m] x 1 [m] → 10 Resonators
  - Hadron Monitor's Distance from the Target, (L): 100 [m]



Step 3 - Ionization Loss dE/dx Evaluation

Protons	Unit	Value
c	m/s	299792458
e	Cb	1.60218E-19
h	Js	6.62608E-34
m0	kg	1.67E-27
m_{μ}	MeV	938.2727884
p input	MeV/c	63436
p	kg*m/s = J/(m/s)	3.3902E-17
p	eV/(m/s)	211.5997194
$\beta\gamma$		67.61
β		0.99989063
γ		67.62
m_e	MeV	0.510998918
T_{max}	MeV	4352.064371

GN2 absorber	Unit	Value
Z_H		7
A_H	g/mol	14.0067
I_{GH2}	eV	82
K	MeV cm^2/mol	0.307075163
c1	K*ZH/AH	0.153464138
T_0	K	273.15
P_0	atm	1
ρ_{GH2}	g/cm^3	1.17E-03
operating temperature	K	298.07
thermal conductivity	W/(K.m)	0.181264665
operating pressure	atm	1
ρ_{GH2}	g/cm^3	1.0676E-03
ε_{GH2} (measured at 298.07 K)		1.0002854
m_e	MeV	0.510998918
argument og Ln()		3.02365E+15
dE/dx (analytical)	MeV cm^2 /g	2.58
dE/dx	MeV/cm	2.7568E-03

Bethe-Bloch formula

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}ln\frac{2mc^2\beta^2\gamma^2W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1+\frac{2\gamma m_e}{M}+\left(\frac{m_e}{M}\right)^2}$$

Step 3 - Evaluation of Electron-Ions Pairs Number, n_e

- The number of the electron-ions pairs generated from each particle collision with the gas can be given by using:

$$n_e = \frac{\frac{dE}{dx}}{W_i} = \frac{2.7568 * 10^3 \left[\frac{eV}{cm}\right]}{33.6\ [eV]} = 82.04852297\ \left[\frac{1}{cm}\right]$$

- Where

$$W_i = 33.6\ [eV]$$

is the average electron-ions pairs production energy for nitrogen.

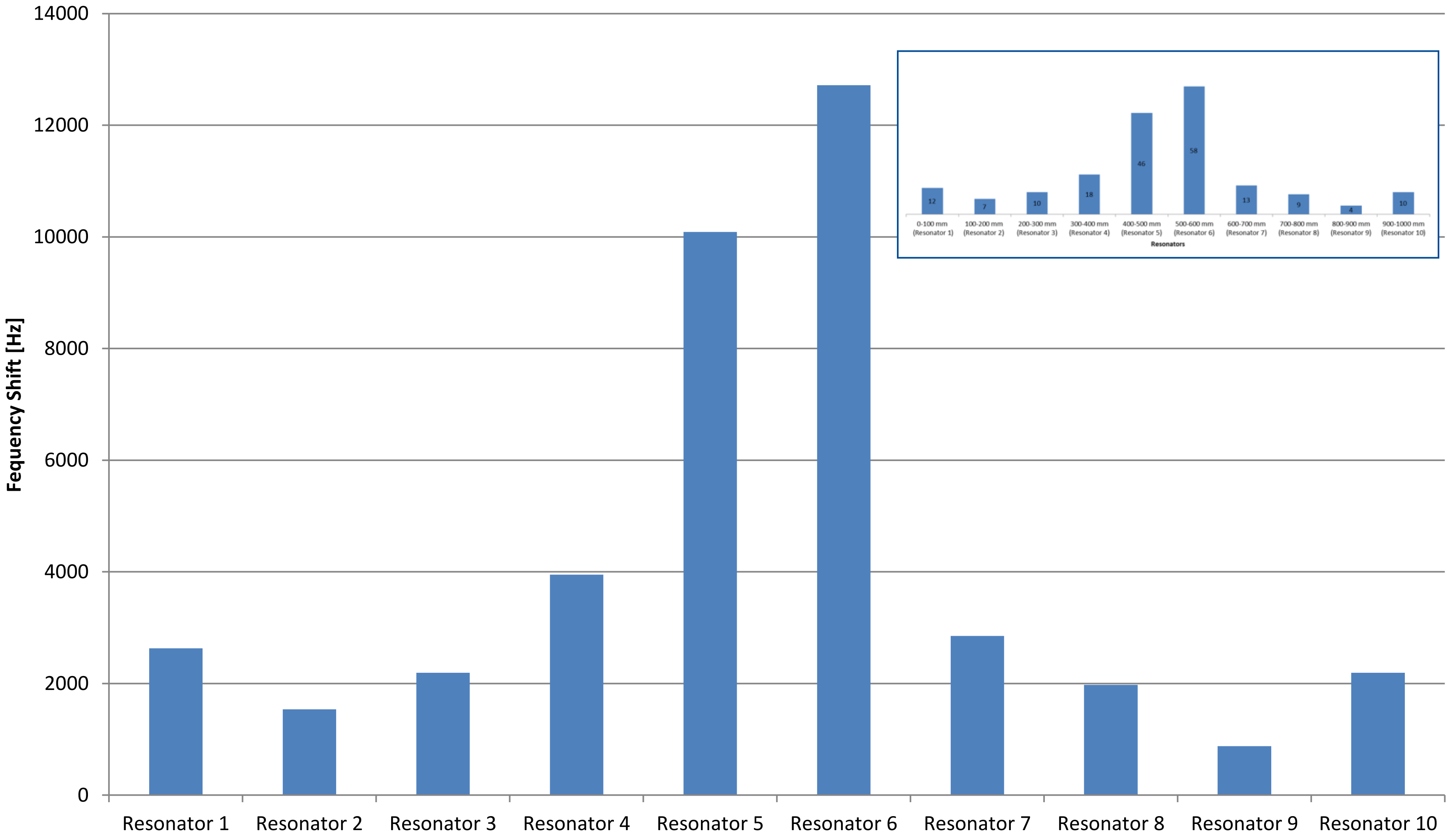
Step 3 - Frequency Shift Estimation

$$f_{shift} = f_c \frac{d\omega}{\omega} = f_c\left(-\frac{1}{2}\frac{d\varepsilon}{\varepsilon}\right); f_c(driving\ frequency) = 1.5[\mathrm{GHz}]$$

Pairs Number n_e	Statistic Weight $I_{incident}$	Resonator Depth	Electron Charge^2 e^2	Nitrogen Permittivity $\varepsilon_0\varepsilon_r$	Electron Mass $m_{electron}$	RF Pulsation^2 ω_{rf}^2	Nitrogen Density n_{N2}	Electron Temperature T_e	Collision Frequency v
[1/m]	[#]	[m]	[C2]	[F/m]	[kg]	[rad^2]	[1/m^3]	[eV]	[Hz]
8.2049E+03	1.0000E+08	1.0000E-02	2.5670E-38	8.8591E-12	9.1096E-31	8.9715E+19	2.4463E+25	3.0000E-02	1.7099E+07

Resonator	Proton Number (Simulation)	Total Pairs $n_{e(tot)}$	Permittivity (Real Part) ε'	Permittivity (Imaginary Part) ε''	dω/ω	Frequency Shift
[#]	[#]	[#]	[F/m]	[F/m]	[#]	[Hz]
1	12	9.8458E+10	1.00000349E+00	6.3018E-09	1.7454E-06	2.6311E+03
2	7	5.7434E+10	1.00000204E+00	3.6760E-09	1.0181E-06	1.5348E+03
3	10	8.2049E+10	1.00000291E+00	5.2515E-09	1.4545E-06	2.1926E+03
4	18	1.4769E+11	1.00000524E+00	9.4527E-09	2.6181E-06	3.9467E+03
5	46	3.7742E+11	1.00001338E+00	2.4157E-08	6.6906E-06	1.0086E+04
6	58	4.7588E+11	1.00001687E+00	3.0459E-08	8.4360E-06	1.2717E+04
7	13	1.0666E+11	1.00000378E+00	6.8269E-09	1.8908E-06	2.8504E+03
8	9	7.3844E+10	1.00000262E+00	4.7263E-09	1.3090E-06	1.9733E+03
9	4	3.2819E+10	1.00000116E+00	2.1006E-09	5.8179E-07	8.7704E+02
10	10	8.2049E+10	1.00000291E+00	5.2515E-09	1.4545E-06	2.1926E+03

Step 3 - Frequency Shift - Histogram



Summary & Conclusions

Goal: evaluate the feasibility of a gas-filled RF resonator for a hadron monitor.		
Step 1	Make a code to generate a TMmn field map of the resonator.	**COMPLETED**
Step 2	Find out a secondary particle by using g4beamline.	**COMPLETED**
Step 3	Import a TMmn field map into g4beamline and estimate the frequency shift.	**COMPLETED**
NEXT STEPS		
Step 4	Optimization.	• **Increase the frequency shift.** • **Optimize the evaluation tools developed in the last 3 Steps.**
Step 5	Engineering design.	• **Development of the equivalent electrical circuit of the resonator.** • **Find out the sensitivity.** • **Estimate the RF power source.**

An abstract of this work was submitted to IPAC 2015 and I plan to contribute to the proceedings.

References

- **Yonehara, Katsuya**, (2014), «*Study Gas-Filled RF Resonator for Hadron Monitor in LBNF beam line*», Fermi National Accelerator Laboratory, Accelerator Physics Center, Muon Accelerator R&D Department, http://www.fnal.gov/, http://apc.fnal.gov/

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- **Poisson Superfish Manual**, http://laacg.lanl.gov/laacg/services/download_sf.phtml

- **G4Beamline User's Guide,** http://www.muonsinternal.com/muons3/G4beamline

THANK YOU FOR ATTENTION!