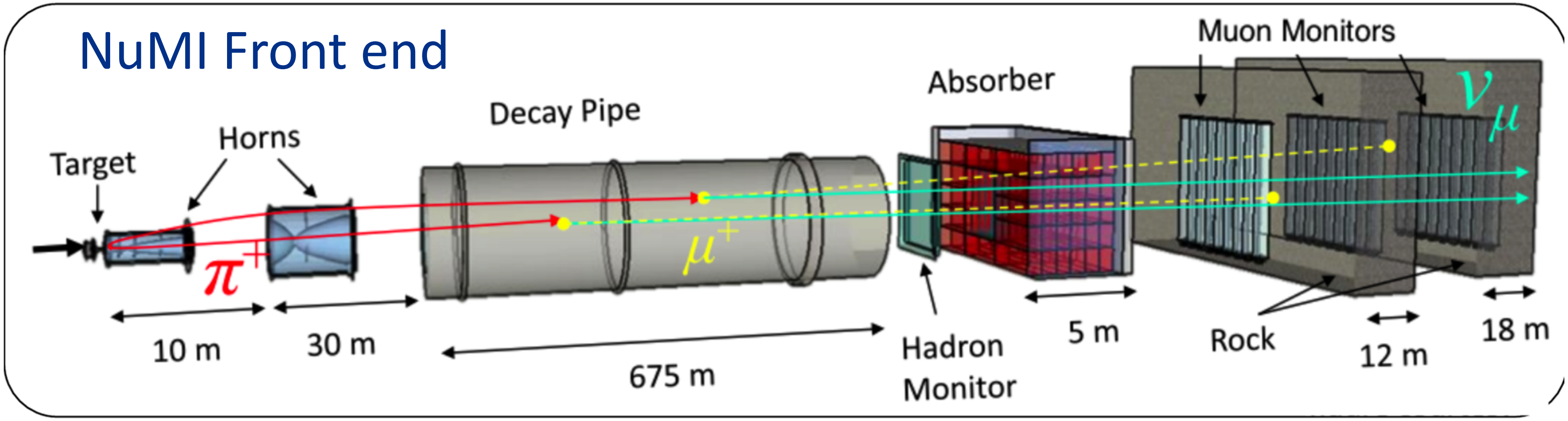
Progress of Gas-Filled Multi-RF-Cavity Beam Profile Monitor for Intense Neutrino Beams

Katsuya Yonehara
NAPAC at Chicago
10/14/2016

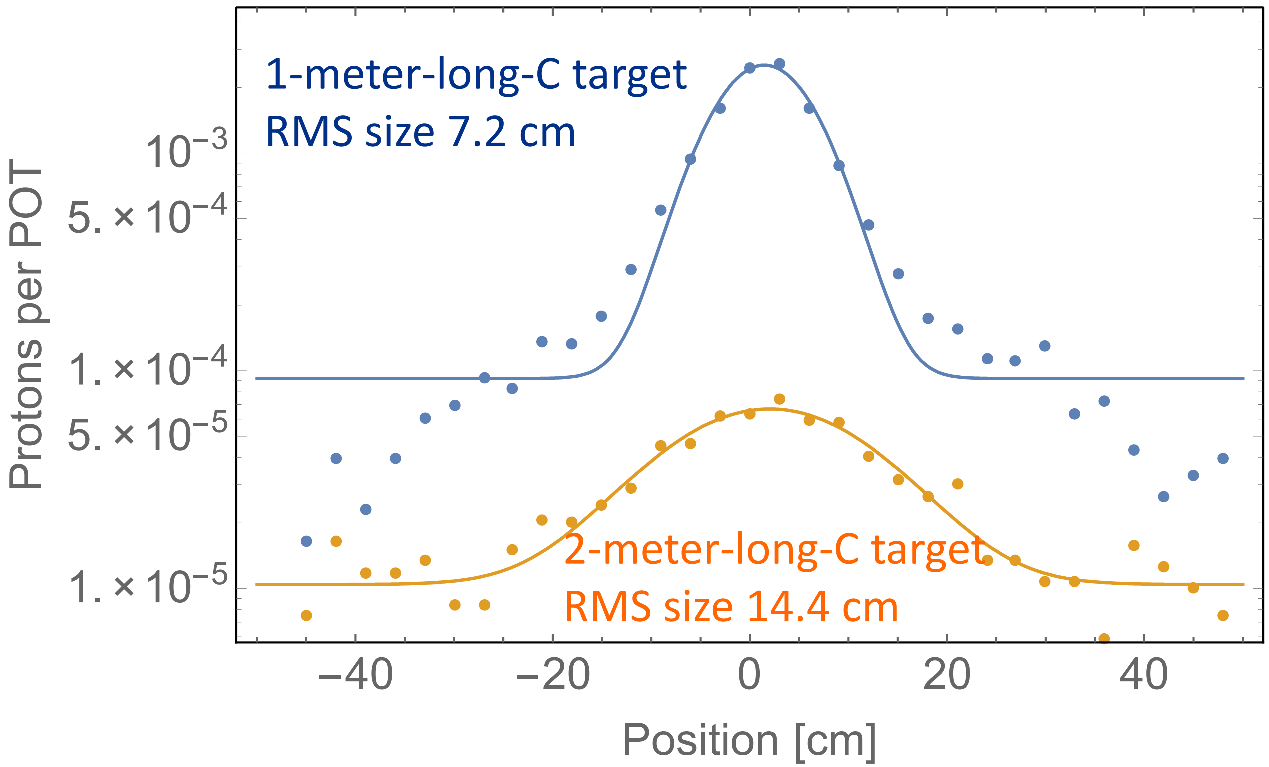
Beam Profile Monitor in Neutrino Beam Line



- Beam profile monitor in a front end of a neutrino beam
  - Combination of hadron and muon monitors
  - Monitor beam centroid
- Hadron monitor is exposed to severe radiation[1]
  - It locates at the end of a decay pipe without shielding
  - Radiation hardness is a potential issue for multi-MW beam

Simulated Secondary Beam Profile in LBNF

Fraction of secondary protons per single proton on target at the end of a 200-m decay pipe (by using G4Beamline[2])



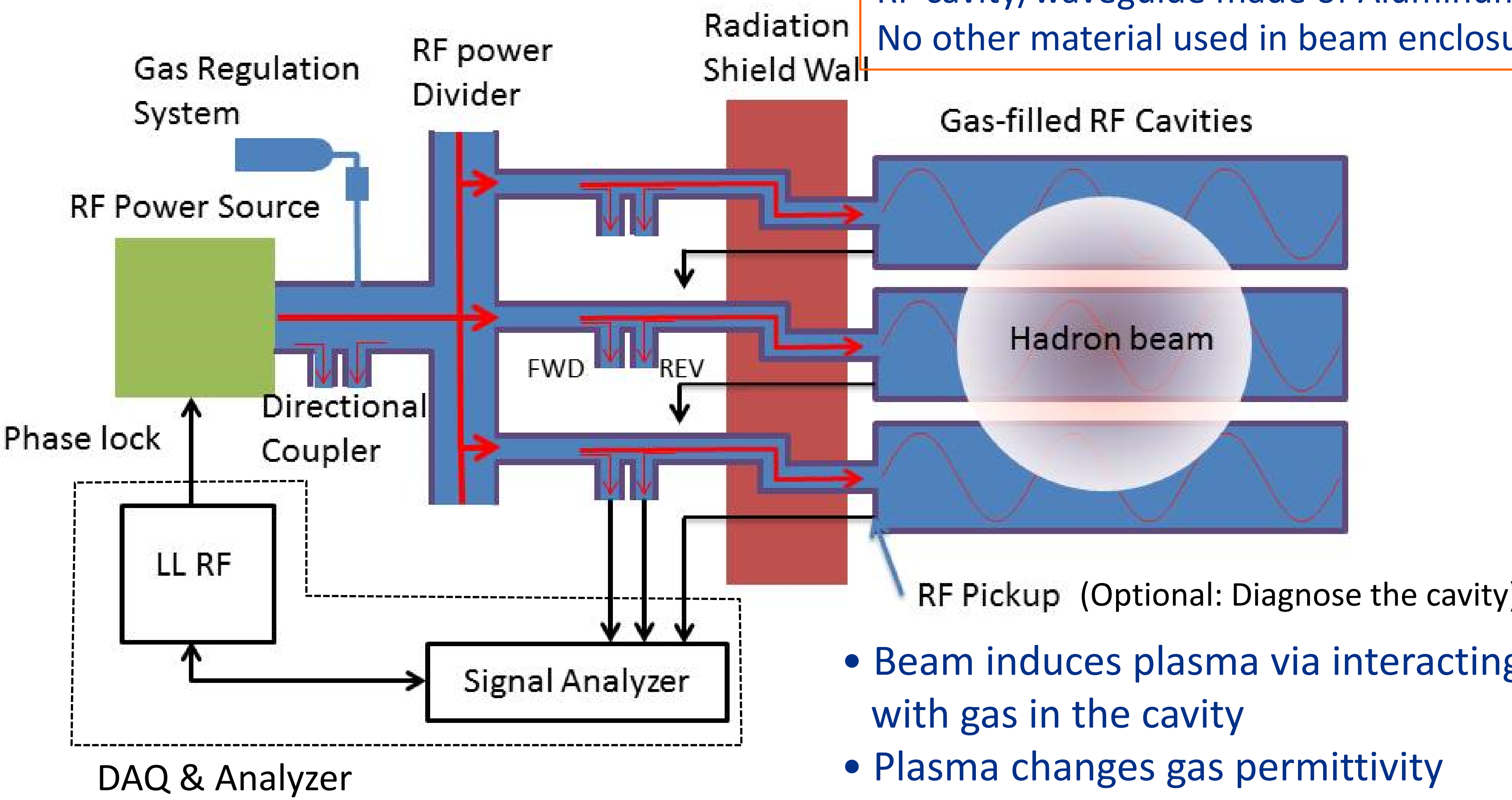
Bin size 3×3 cm^2, which is the required pixel size in the monitor for LBNF

Primary proton beam for LBNF (Long Baseline Neutrino Facility)

- 120 GeV protons; 1.5E14 ppp for 2.4 MW; 20 ns bunch gap
- 10 μsec pulse length; 1.2 s cycle time
- Highest secondary proton intensity 5E10 ppp/cm^2 in this bin size

Possible Radiation Hard RF Gas Monitor

RF cavity/waveguide made of Aluminum
No other material used in beam enclosure



- Beam induces plasma via interacting with gas in the cavity
- Plasma changes gas permittivity
- Permittivity change is measured by observing frequency shift and Q factor change

Concept of RF Gas Monitor

- Gas permittivity is sensed by a microwave-resonant cavity
  - Permittivity change modulates the resonant frequency and the quality factor
- Permittivity change is proportional to the number of ion pairs in the RF cavity
  - Measure the number of ion pairs to reconstruct the number of incident charged particles in the cavity
- Degree of permittivity change is dependent on the species of plasma particles
  - Electrons contribute the most for RF modulations because of their light mass
  - Control the plasma population in cavities is essential
  - The change is also influenced by the RF amplitude and gas pressure

R&D of RF Gas Monitor

- Verify the concept of RF gas monitor in experiment
- Study plasma dynamics in the range of RF gas monitor
  - RF amplitude: Available lowest amplitude – 0.1 MV/m
  - Gas pressure: Available lowest pressure – 10 atm
  - Gas species: N_2, He, H_2, O_2, Dry Air, CO_2, etc
  - High RF frequencies: 2.45 GHz, 9.6 GHz
- Demonstrate feasibility of the system

↓

Propose beam test

Plasma Population

Simplified time domain rate equation

No dissociation
No distinguish of ion cluster nor ion polymer

$$\frac{dn_e}{dt} = \dot{n} - \beta n_e n_+ - \frac{n_e}{\tau},$$

$$\frac{dn_+}{dt} = \dot{n} - \beta n_e n_+ - \eta n_+ n_-,$$

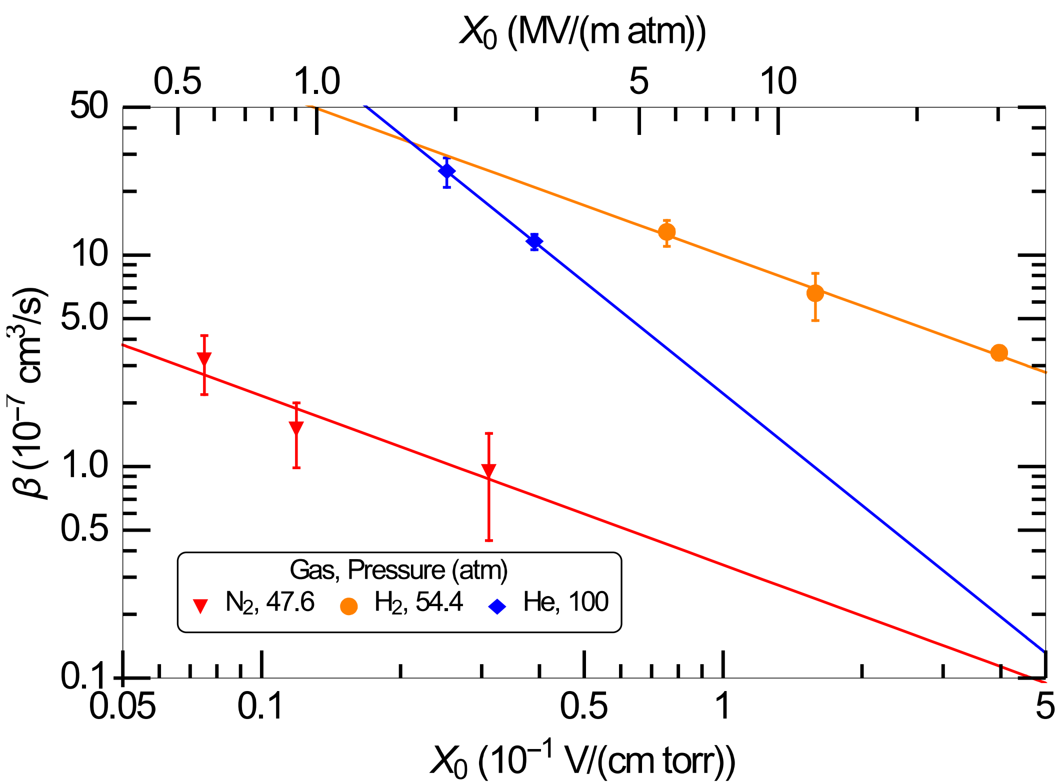
$$\frac{dn_-}{dt} = \frac{n_e}{\tau} - \eta n_+ n_-$$

Need β, τ, η to complete the rate equation

Ion pair production rate has been studied and tested its validation in experiment

$\dot{n}$: Ion pair production rate [cm^{-3} s^{-1}]
n_e: Number density of electrons [cm^{-3}]
n_+: Number density of positive ions [cm^{-3}]
n_-: Number density of positive ions [cm^{-3}]
β: Effective electron-ion recombination rate [cm^3/s]
τ: Effective electron capture time [s]
η: Effective ion-ion recombination rate [cm^3/s]

Effective Electron-Ion Recombination[3]



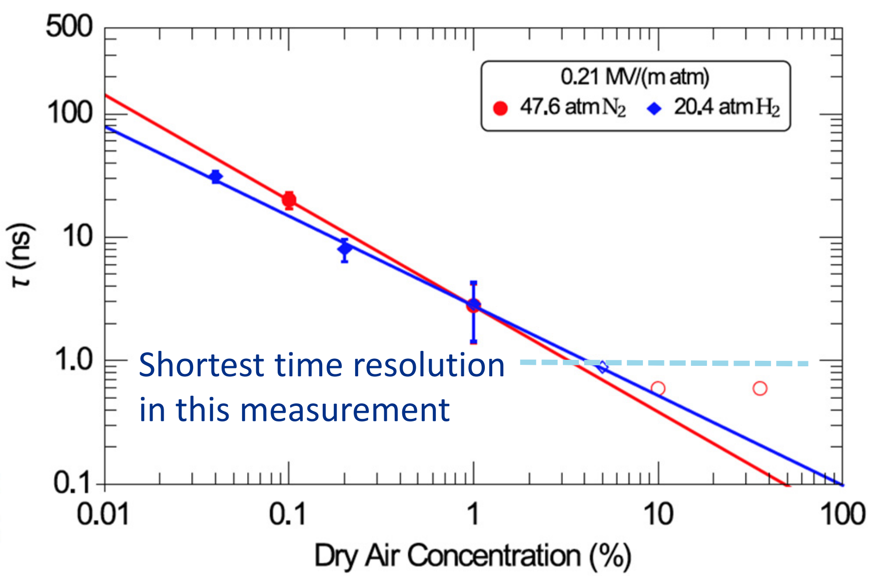
$X_0 = E/p$
E = RF amplitude
p = gas pressure

Electron-Ion recombination time = (Positive ion density × β)$^{-1}$
≈ $(10^{13} \times 10^{-7})^{-1} = 10^{-6}$ sec < Beam pulse length @ LBNF (10 μs)

Great amount of ion pairs disappear at the end of beam pulse!!
It induces a systematic uncertainty to reproduce plasma population

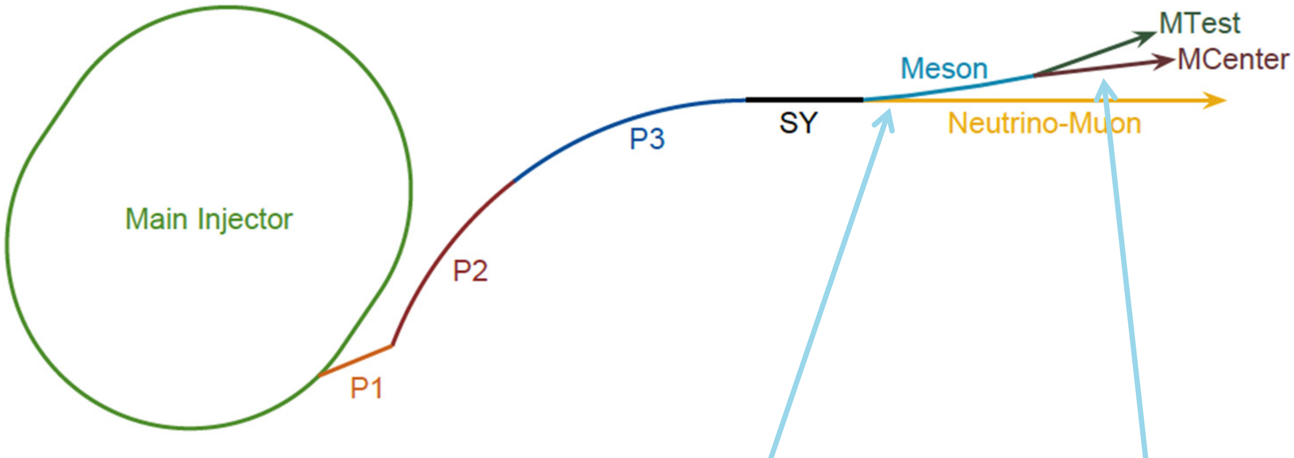
Remove Electrons by Electronegative[3]

- Doping electronegative in gas to remove electrons
  - Produce positive-negative ion pairs instead of electron-ion one
  - Ion-ion recombination time is order of magnitude longer than electron-ion recombination time
  - Contribution of electrons is negligible when $\tau \leq$ a half RF period
  - $\tau \leq 1$ ns is probably acceptable to have a practical system
- Plasma loading is ~100 times less with dopant
  - Save stored RF energy from RF power consumption by plasma



Require τ measurement in the range of RF gas monitor

Possible Beam Test at Fermilab



	SY dump[4]	M01
Proton energy	120 GeV	120 GeV
Beam pulse length	10 μsec (fast kicker)	4 sec (slow ext.)
Integrated beam intensity per pulse	1E13	4E12
Availability	Limited	Unlimited
Purpose	Close to NuMI/LBNF beam profile: Verify the concept: Study plasma physics	Pretest the RF test equipment including with gas filled cavities and RF sources

Summary

- Propose a novel pressurized gas-filled multi-RF-cavity beam profile monitor that is robust in high-radiation environments
  - Useful for intense neutrino beam line, e.g. NuMI and LBNF
- R&D of the RF gas monitor in experiment
  - Control the plasma population in cavities is essential
  - Doping electronegative removes electrons in cavities within 1 nsec or shorter than a half RF period
- Consider possible beam test facility
  - M01 and SY dump are a good candidate

Citations

[1] R. Zwaska, “NuMI Hadron Monitor”, http://docs.dunescience.org/cgi-bin/RetrieveFile?docid=1403&filename=zwaska_hadmon_final_v1_shortened.pdf&version=1

[2] G4Beamline, http://www.muonsinternal.com/muons3/G4beamline

[3] B. Freemire, “Pressurized rf Cavities in Ionizing Beams”, PRAB **19**, 062004, 2016,

[4] A. Watts, “Magnetic Control of Fermilab Switchyard Beam Splits”, http://beamdocs.fnal.gov/AD/DocDB/0050/005040/002/magnetic-control-fermilab%20%281%29.pdf

Q. Liu, “Future Prospects of RF Hadron Beam Profile Monitors for Intense Neutrino Beam”, TUPOA44

– Discuss about temperature increment of RF cavities and possible cavity shapes