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Fermilab

A Novel Rad-hard RF Hadron Monitor (to steer neutrinos from FNAL to S. Dakota)

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Supported by Muons, Inc. and Fermilab under DOE HEP STTR Grant DE-SC0013764

What is Muons, Inc.?

- Muons, Inc.
  - Founded 2002, subsidiaries - MuPlus, Mu*STAR
    - by Scientists from US National Labs
  - Funded by DOE contracts and SBIR-STTR grants
    - total of ~$30M
  - Tools and technology for particle accelerators
  - 8 US university and 11 national lab research partners
    - extraordinary people work with us
  - Supported 18 post-docs and 7 Ph.D. students

  - accelerator-driven molten-salt nuclear reactors
    - Major focus of our companies

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Examples: ADSR, Magnetrons, BPM for LBNF

- Example #1: Muons, Inc. is a leading proponent of Superconducting RF (SRF) Accelerator-Driven Subcritical Reactors (ADSR) with Mu*STAR: https://www.youtube.com/watch?v=dS2dq13fTMk

- Example #2: Magnetron power sources, invented a century ago, can be the most cost-effective solution for ADSR. Our projects include a 1497 MHz magnetron development project supported by an NP STTR grant to replace CEBAF klystrons.

- Example #3: Radiation-Robust Beam Profile (Hadron) Monitor needed for LBNF – the subject of the presentation

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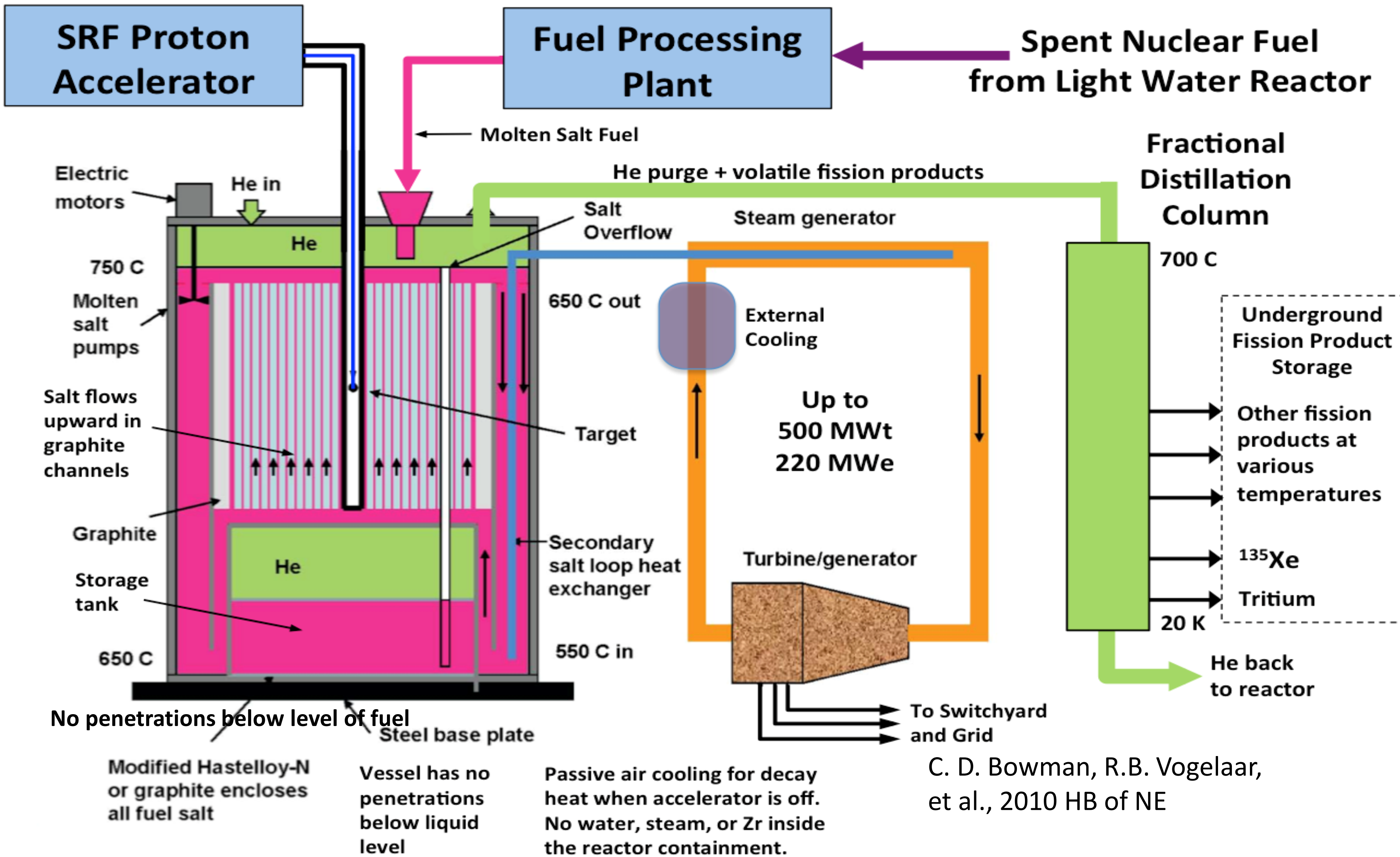
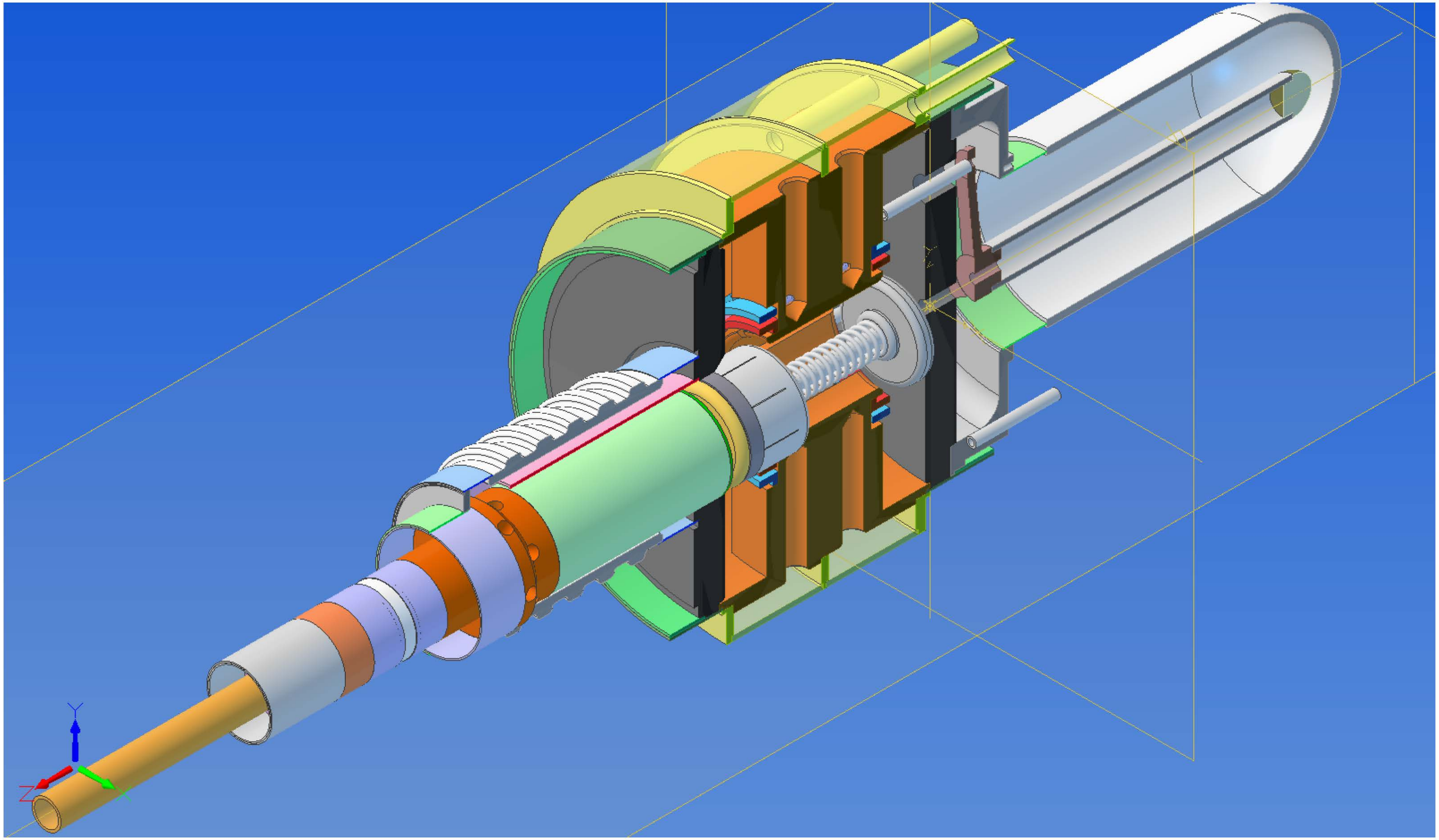
Mu*STAR Reactor Concept



C. D. Bowman, R.B. Vogelaar, et al., 2010 HB of NE

Parts Status – 1497 MHz

add cathode stem sub-assy



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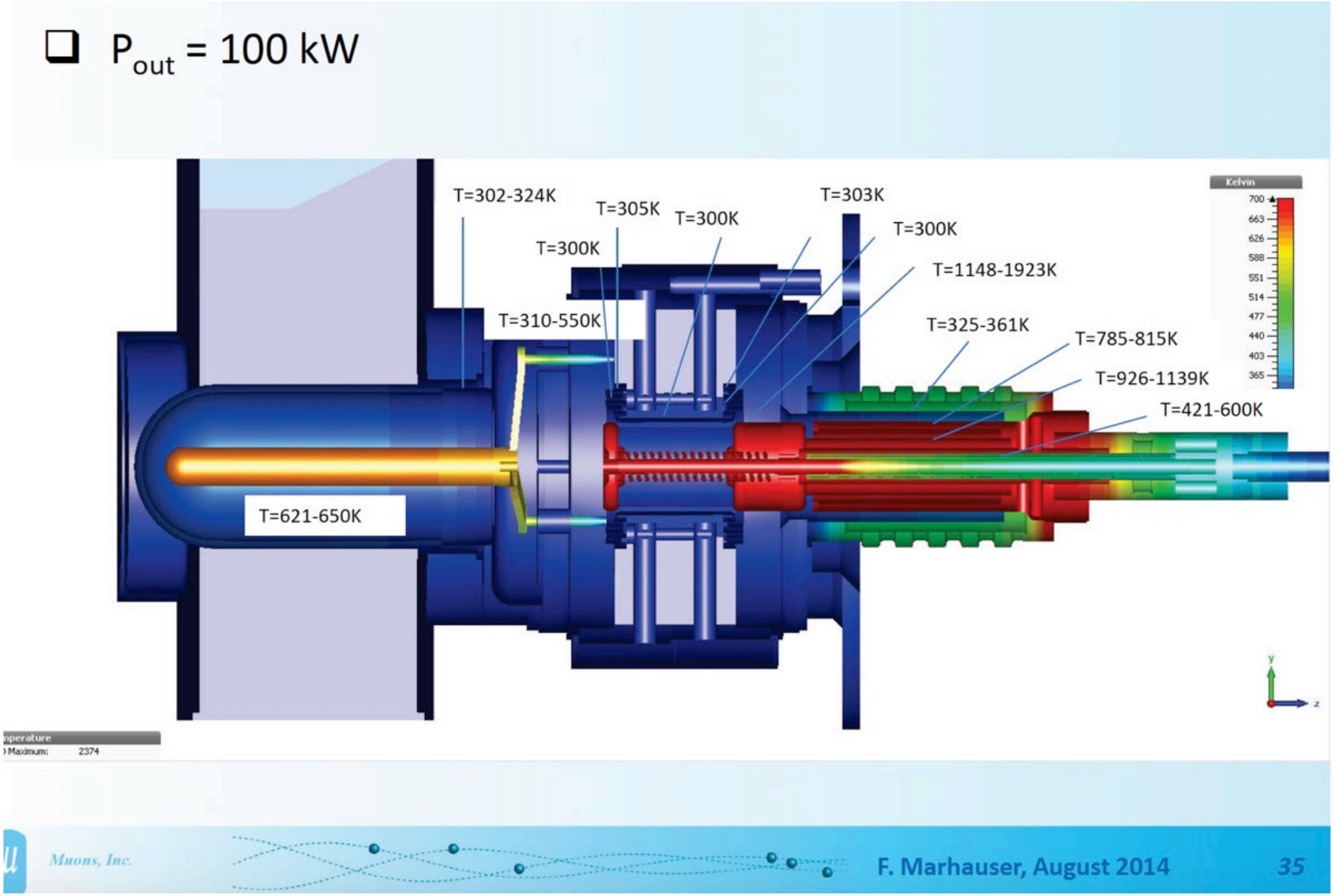
Modeling 350 MHz



SRF Linacs need efficient microwave power

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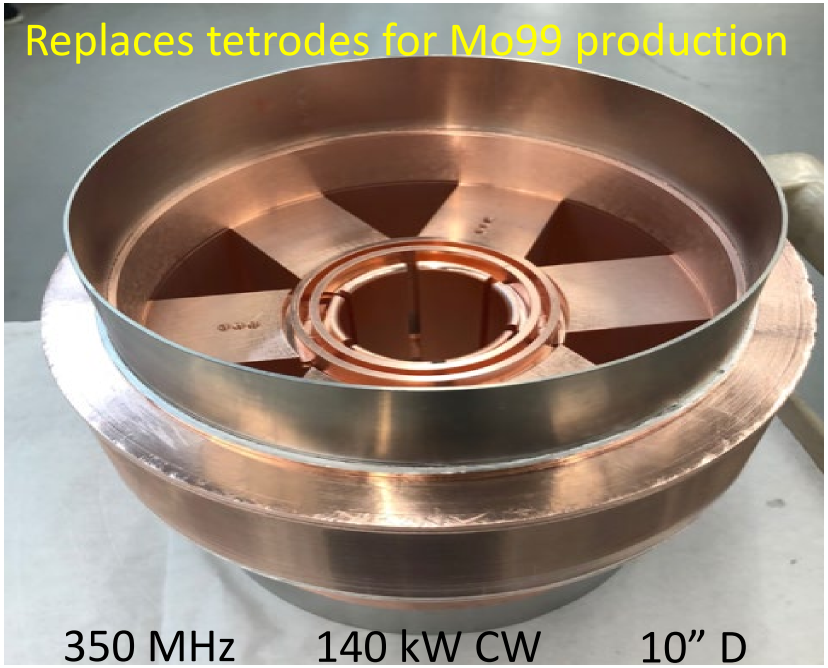
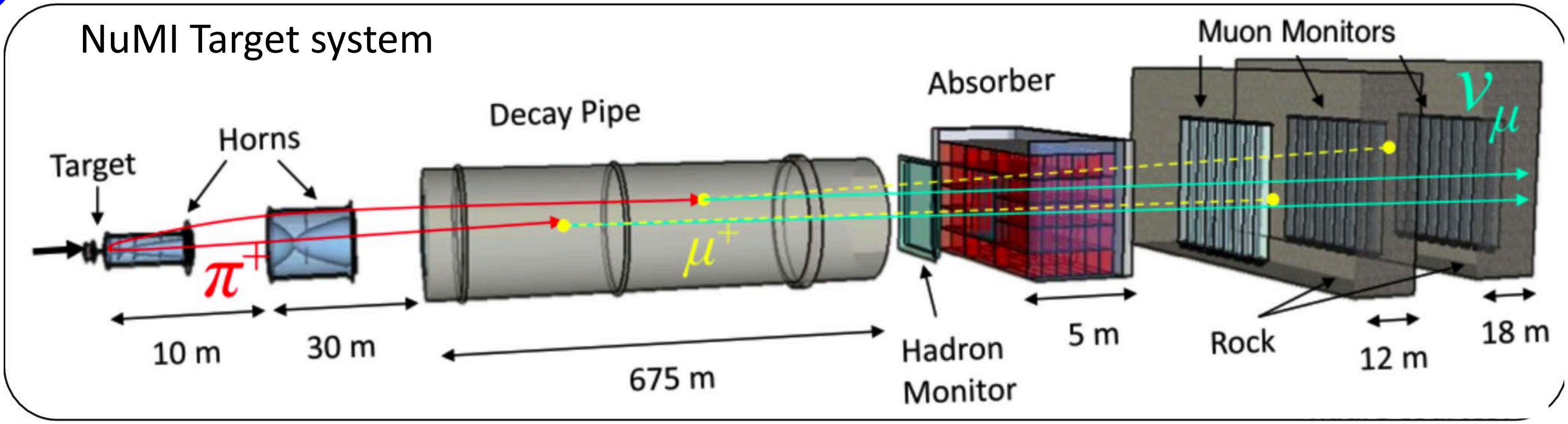
Muons, Inc. is developing power sources for Superconducting Radio Frequency Linacs
First tests of two magnetrons underway now. Magnetrons are up to 90% efficient vs klystrons 50%. Capital cost 1/5 of klystrons



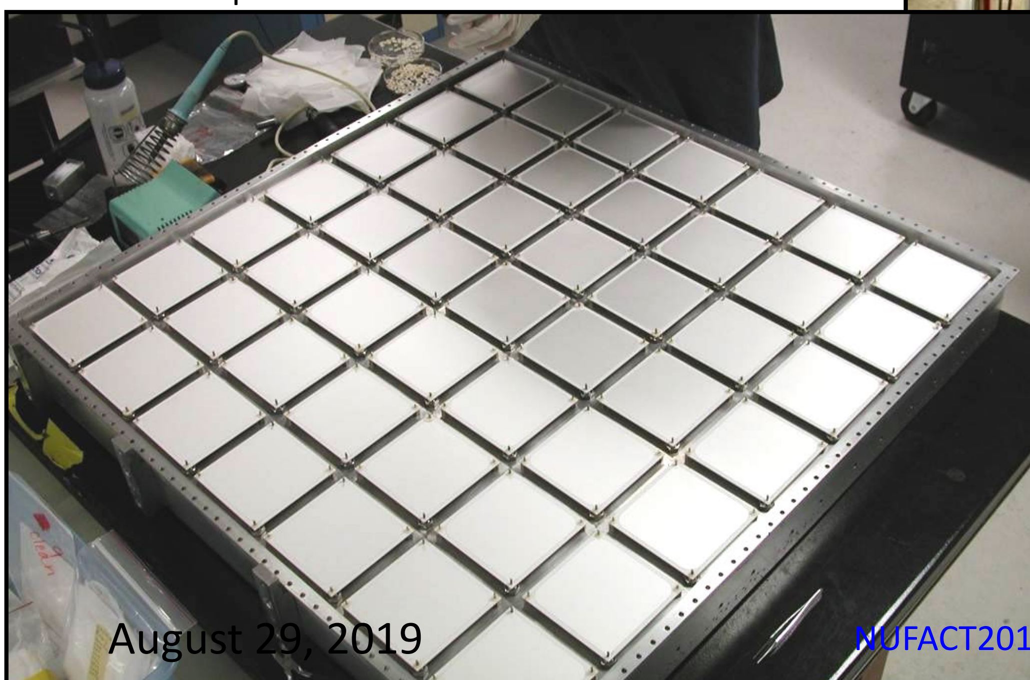
Beam Monitor in Neutrino Beam Line



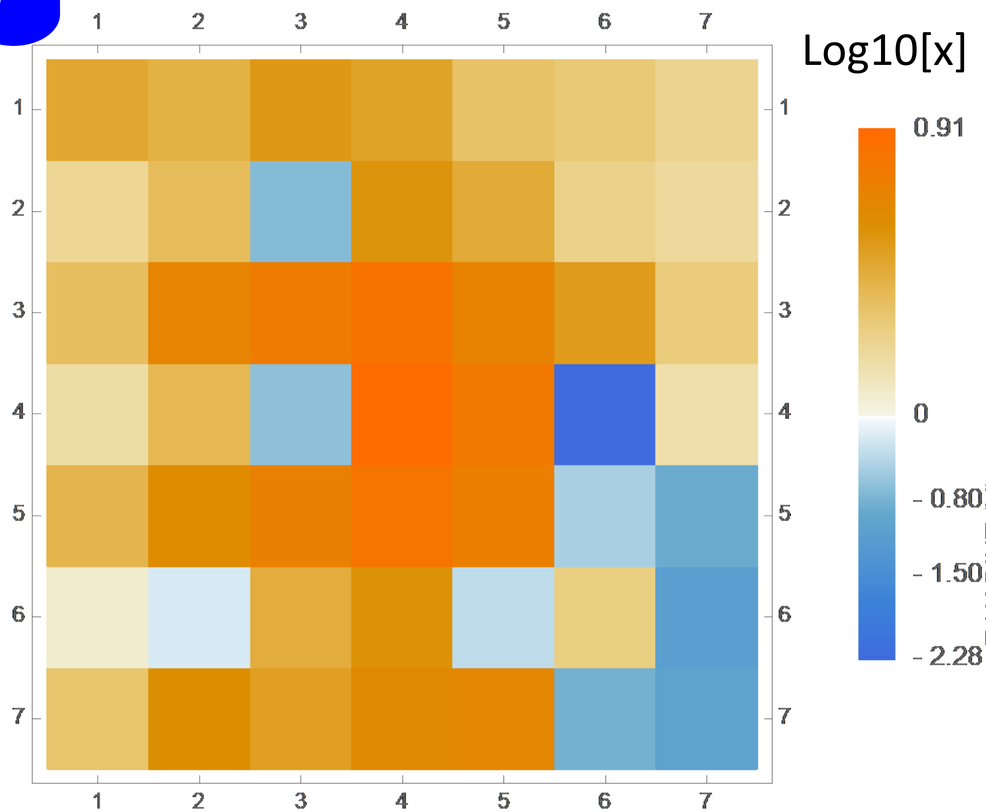
- 7X7 Multi-pixel ion chamber now used as beam monitor
- Primary function of Hadron Monitor
  - Monitor beam centroid and deterioration of target
  - Evaluate systematics of beam parameters
- Present Hadron Monitor shows low gain due to radiation damage
  - Only use for aligning beam element (baffle, target and horns)
  - Need rad-hard Hadron Monitor

Current System Design
750 kW operation

- Hadron Monitor
  - 7x7 grid → 1x1 m^2
    - 1 mm gap chambers
  - Radiation Hard design
    - ~ 10 Grad exposure
  - Mass minimized for residual activation
    - 57 Rem/hr
- Muon Monitors
  - 9 tubes of 9 chambers each → 2.2x2.2 m^2
    - 3 mm gap chambers
  - Tube design allows repair
- High Voltage (100-500 V) applied over He gas
  - Signal acquired with charge-integrating amplifiers

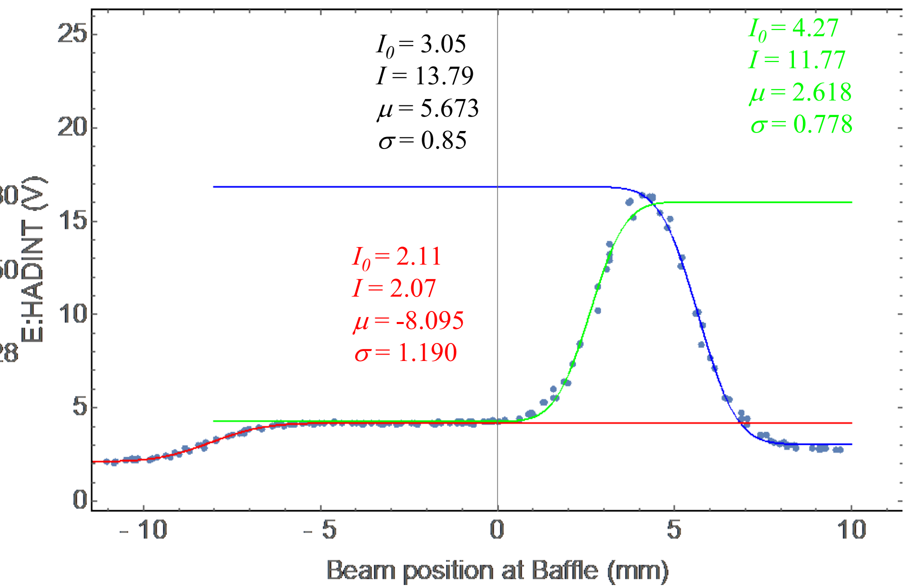


Present hadron monitor signal



Beam view

Example of vertical beam scan



- Blueish color pixel is low gain
- Central pixel still useful to align beam elements

Found:
Baffle = -1.211 mm
Target = 2.618 - 3.7 = -1.082 mm

MW beam monitor issues

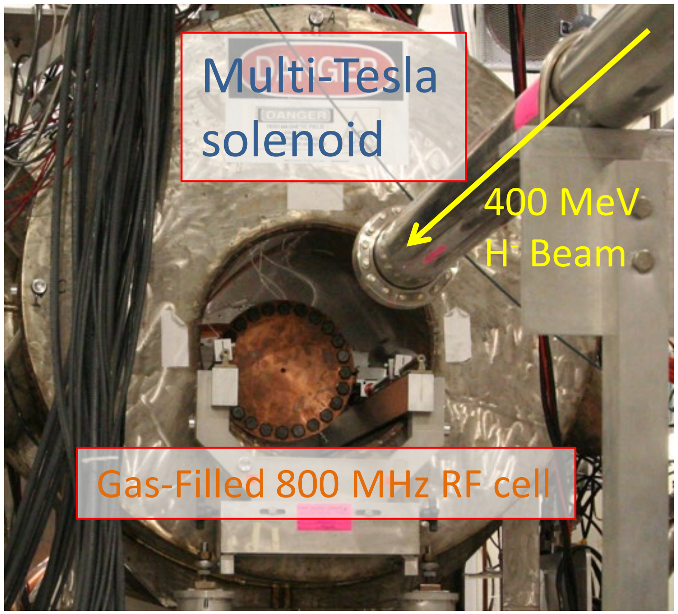
- Lifetime
  - Monitor should operate at least a year without any maintenance
  - Longer lifetime is better for cost and minimize systematic uncertainty on beam parameters
- Reliability and reproducibility
  - Linearity and gain stability are important
- Practicality
  - Simple and cost effective

One group look at SEM, but we found its intrinsic issue like gain change, high vacuum requirement, and lifetime.
We also evaluated various other methods, e.g. optical, thermal, acoustic, etc. Those require a serious R&D!

Past gas-filled RF cavity beam experiment

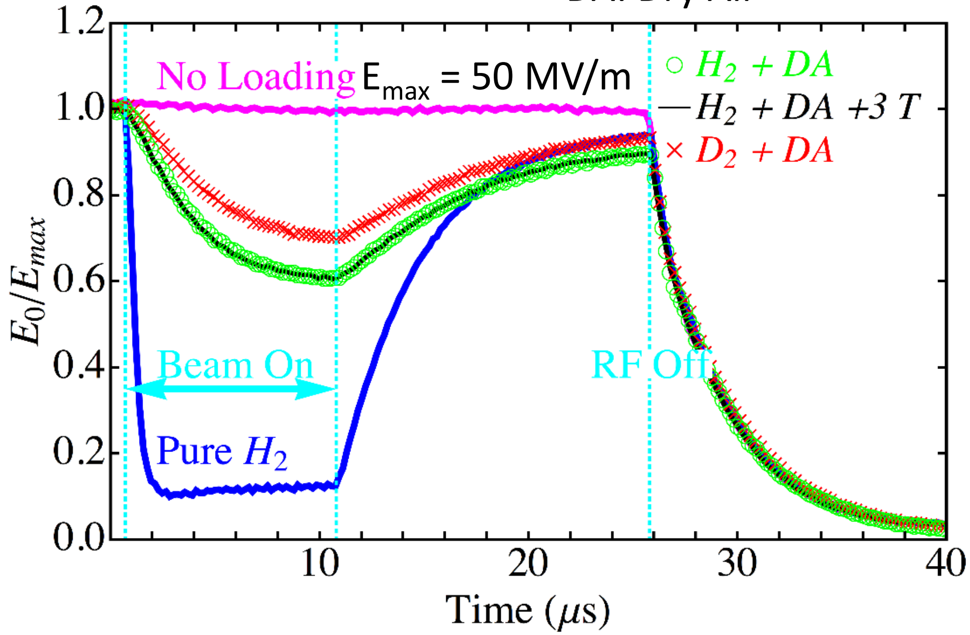
- Tested a gas-filled RF cavity with intense proton beams

Proton beam test at MTA



Proton beam energy → *400 MeV*
Protons per bunch → *O(10⁹/2 mm diameter beam)*
Bunch gap/length → *5 nsec/10 μsec*

Gas pressure = 100 atm
DA: Dry Air



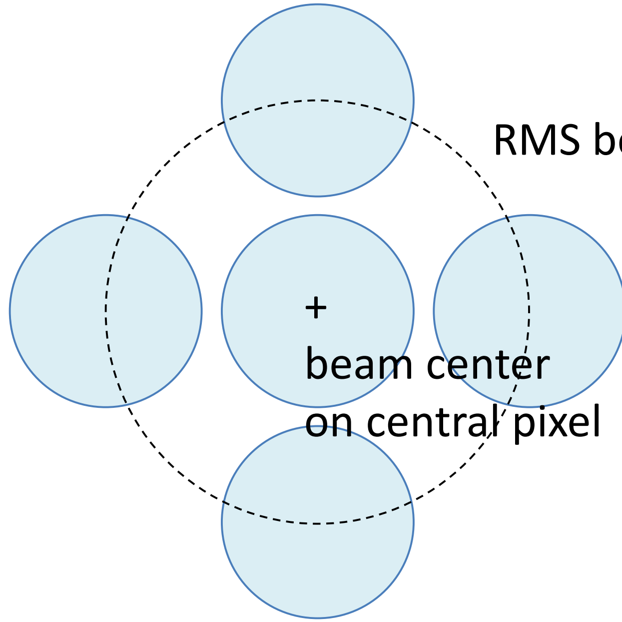
RF responses with proton beams [6]

Extract plasma population from RF signal

Concept of gas RF beam detector

- High-energy particles through a gas-filled RF cavity induce a plasma which changes gas permittivity
  - Charged particle flux follows from the permittivity change
  - Permittivity-shift changes the resonant frequency and Q, the quality factor of the RF cavity
  - RF wave passing through the cavity is phase shifted and reduced depending on the Q change
- Plasma dynamics must be controlled
  - Depends on gas species, plasma temperature, RF gradient, gas pressure
  - Drift velocity of electrons and ions in neutral gas
  - Plasma chemistry: Electron-ion recombination, electron capture, ion-ion recombination, crystallization, etc
  - These were addressed in previous muon cooling studies
    - (see previous slide)

Possible configuration for LBNF



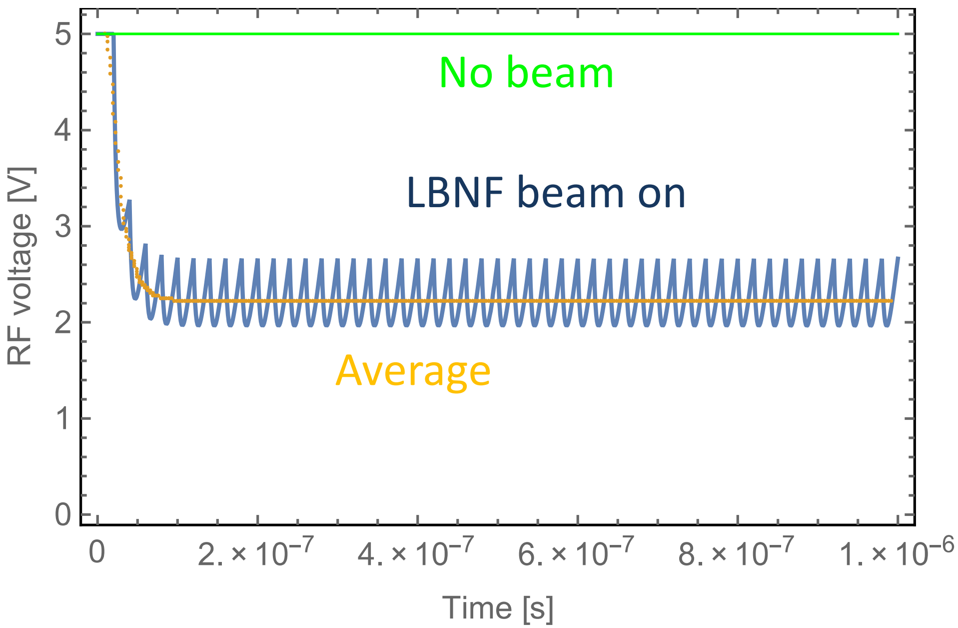
- Apply 5 RF cavities
  - Central RF cavity is sensitive to the peak beam intensity
  - 4 adjacent cavities are sensitive to the beam position (maximum sensitivity at cavity position on RMS beam size)

Simulate Transit RF Signal

Simulated plasma loading
in 1-atm N_2 gas filled RF

Courtesy of A. Tollestrup, Mathematica notebook, HadronCalorimeter4.nb

τ_e = 5 ns, τ_{ion} = 2 μs, RF frequency = 2.45 GHz,
Apply LBNF beam with 2 m graphite target,
Q factor = 500, Matched to RF source



- Low Q cavity is proposed to quickly recover plasma loading in the cavity
- Low gas pressure and low RF gradient are applied to realize a linear gas plasma response function
- Plasma parameter in this simulation is extrapolated from past tests

Rad-hard RF detector (test cavity)

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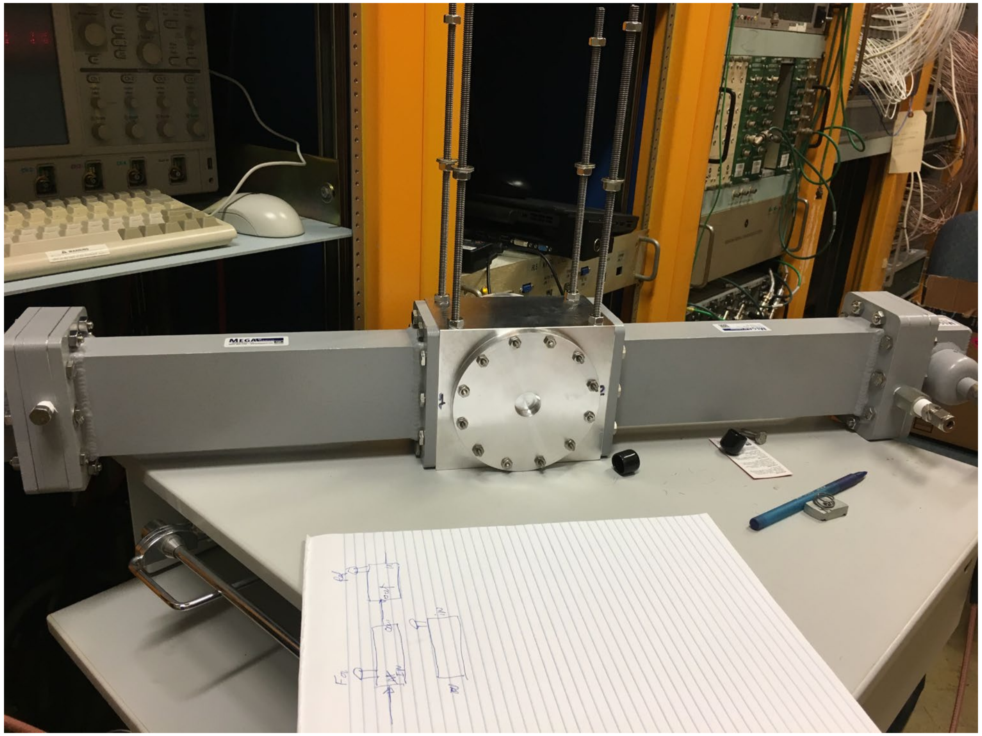
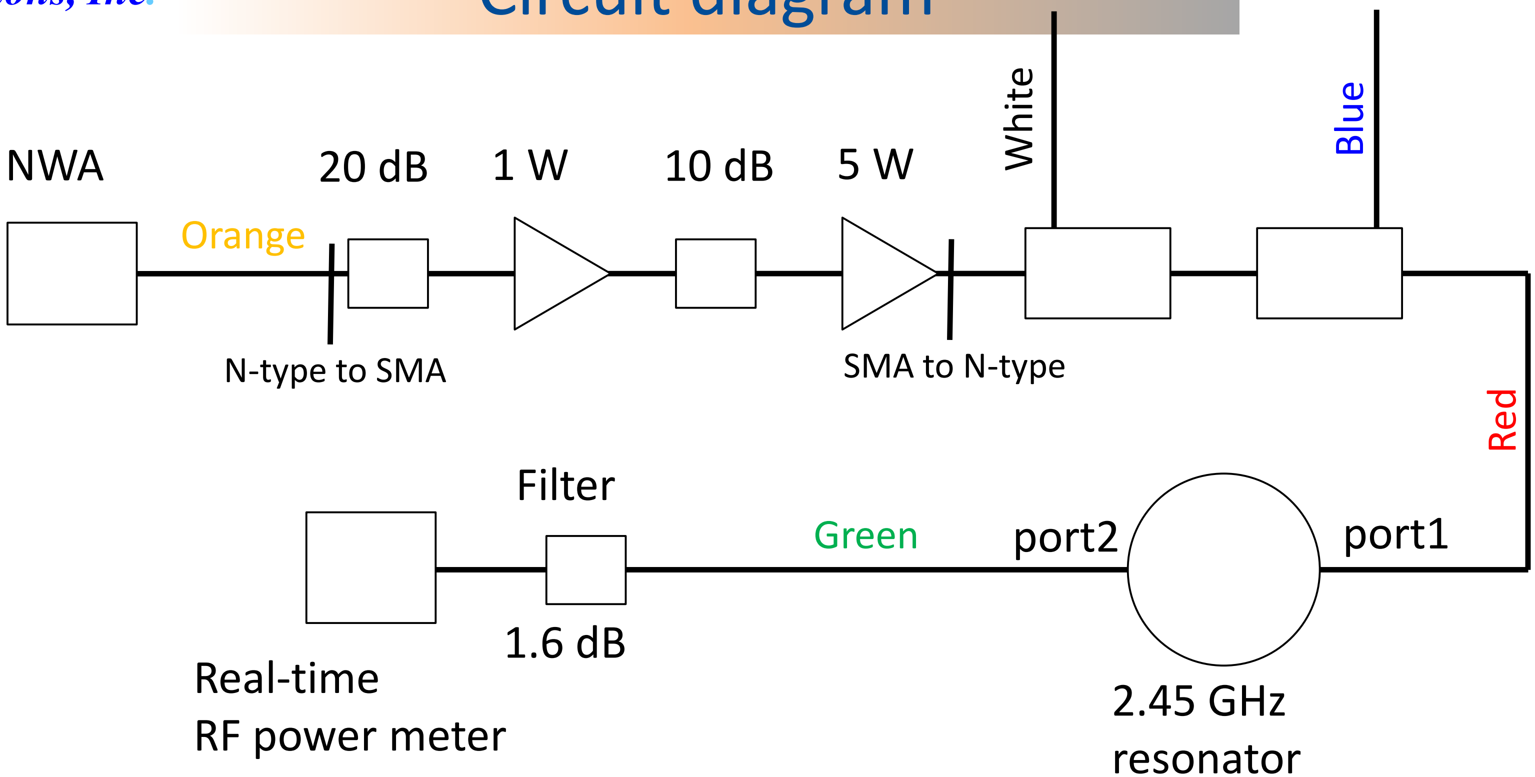


RF power consumption at equilibrium condition

$$p = \frac{V_0\left(V_0 - V(t)\right)}{R}$$

- 2.4 GHz gas-filled RF resonator
- Detector and wave guide made of aluminum for rad-hard
- Test cavity can be pressurized up to 2 atm
- Beam ionizing gas and form plasma in the cavity
- Plasma consumes RF power
- Consumption is proportional to the amount of incident beam
- Shunt impedance (R) can be measured without beam
- It suggests that beam intensity can be reproduced without beam calibration

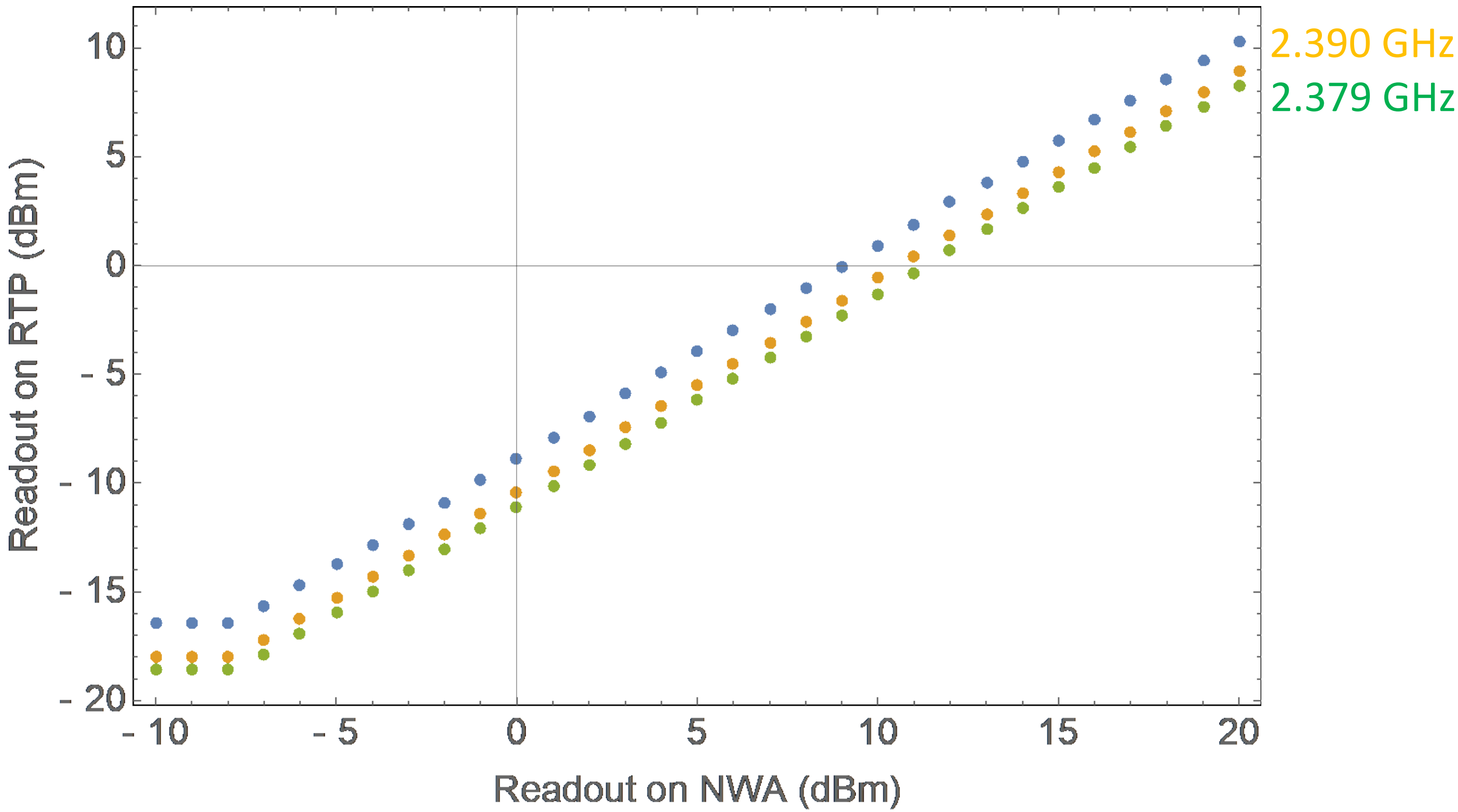
Circuit diagram



Unique structure of two sets of attenuator and RF amp to make a linear gain and the first RF amp has a narrow band pass to remove RF noise

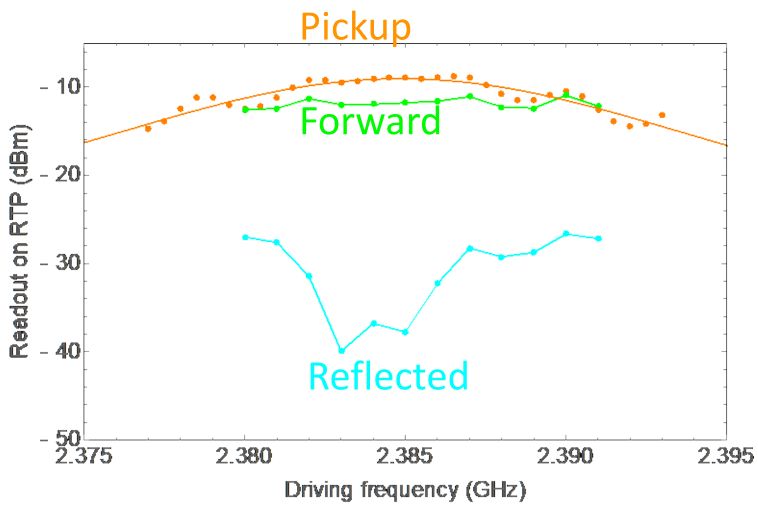
Linearity of gain of RF amp

ν = 2.385 GHz

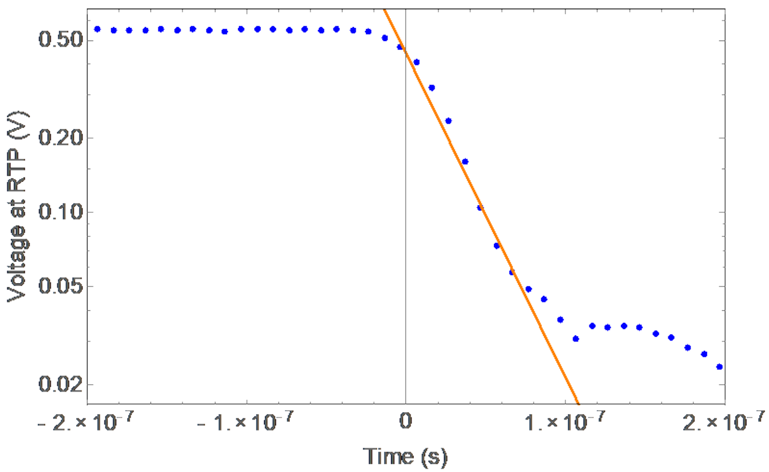


Q factor measurement

- RF signal calibration
  - Q factor measured by decay time
  - Q factor measured by spectrum
  - Accuracy in both measurements is within ~10 %



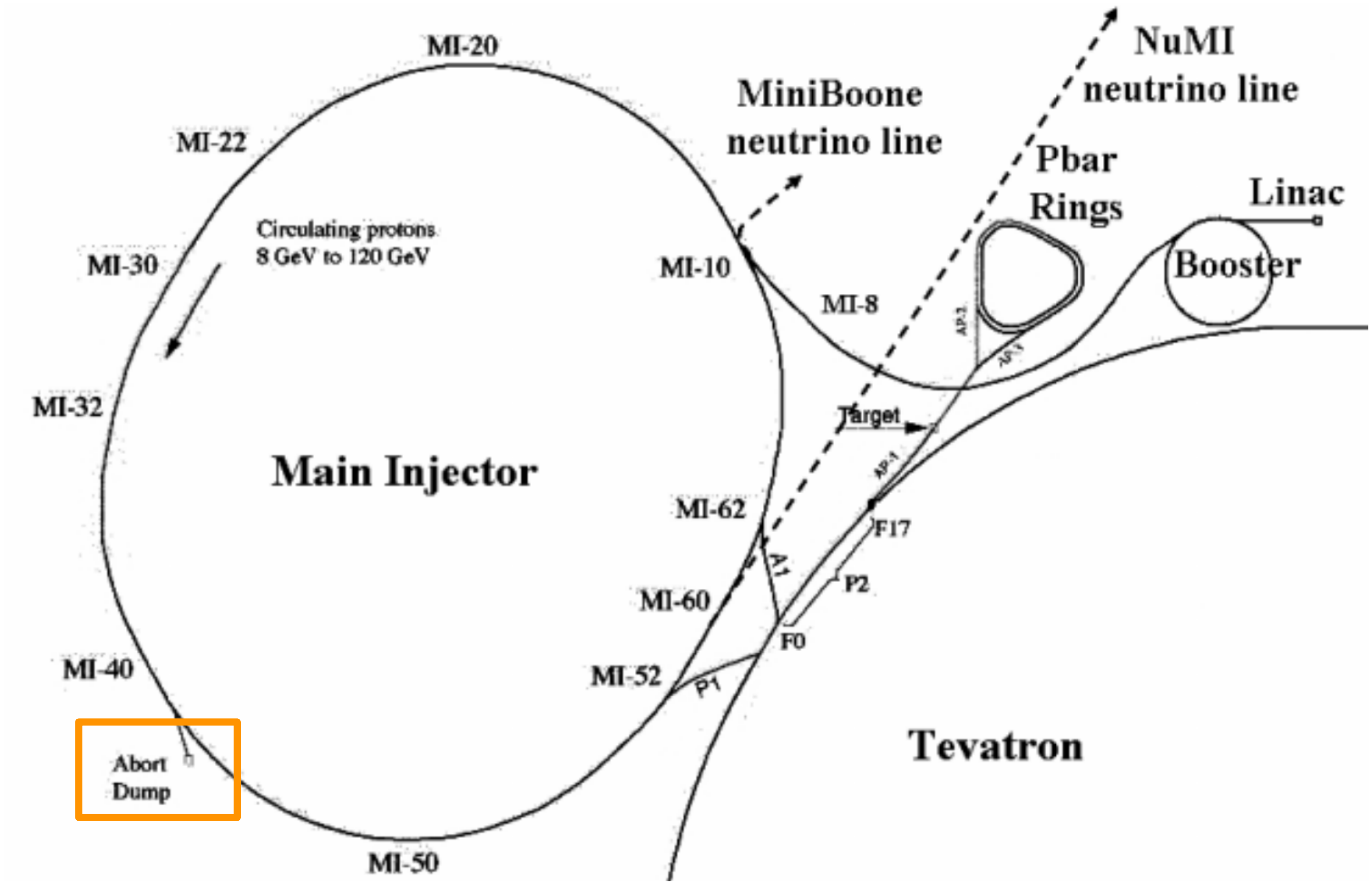
$$Q = \frac{\nu_0}{\Delta\nu} = 239$$



$$\tau = 1.65 \cdot 10^{-8}$$

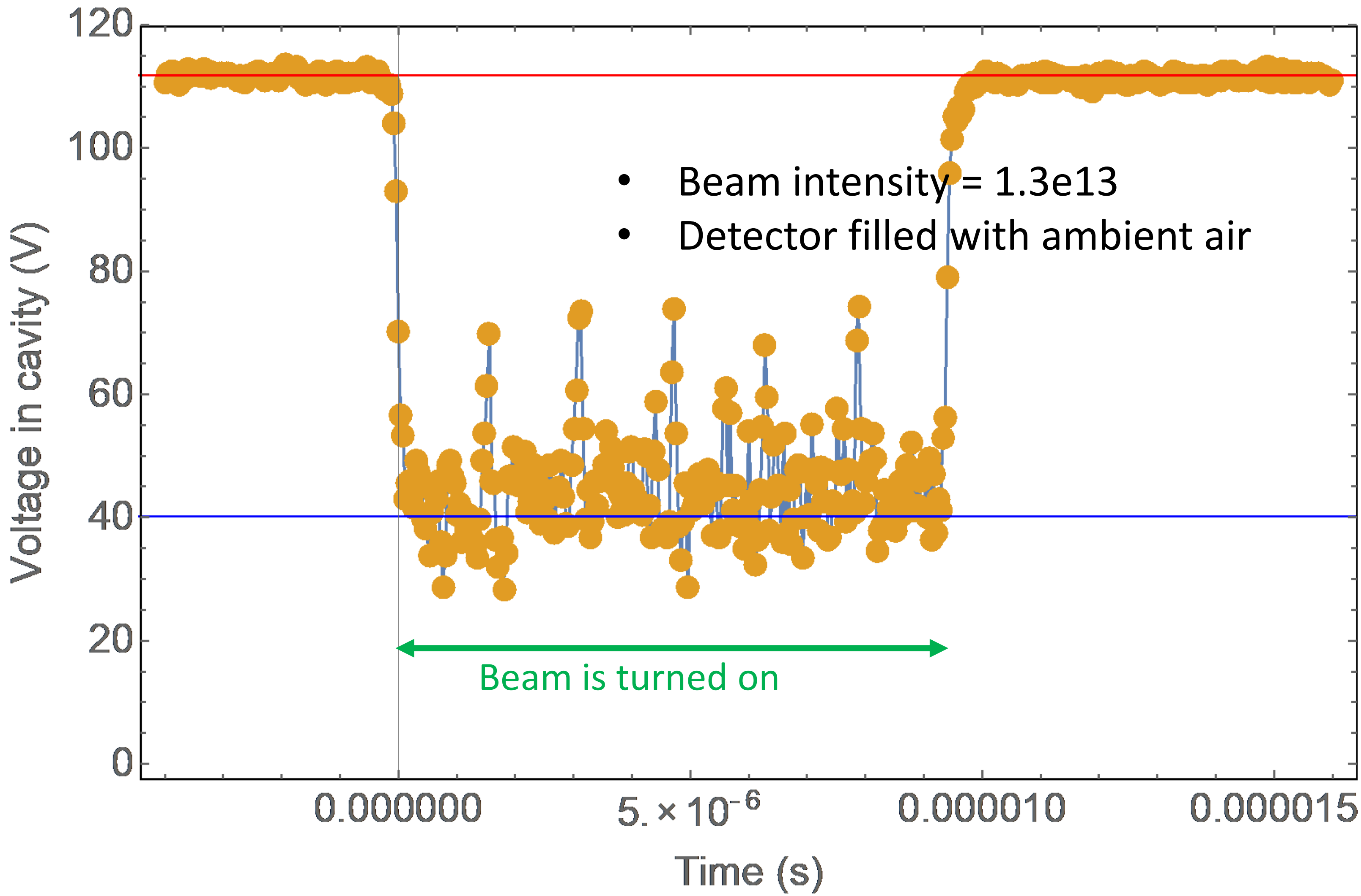
$$Q = 2\pi\nu_0\tau = 247$$

120 GeV MI Abort Dump line proton beam test



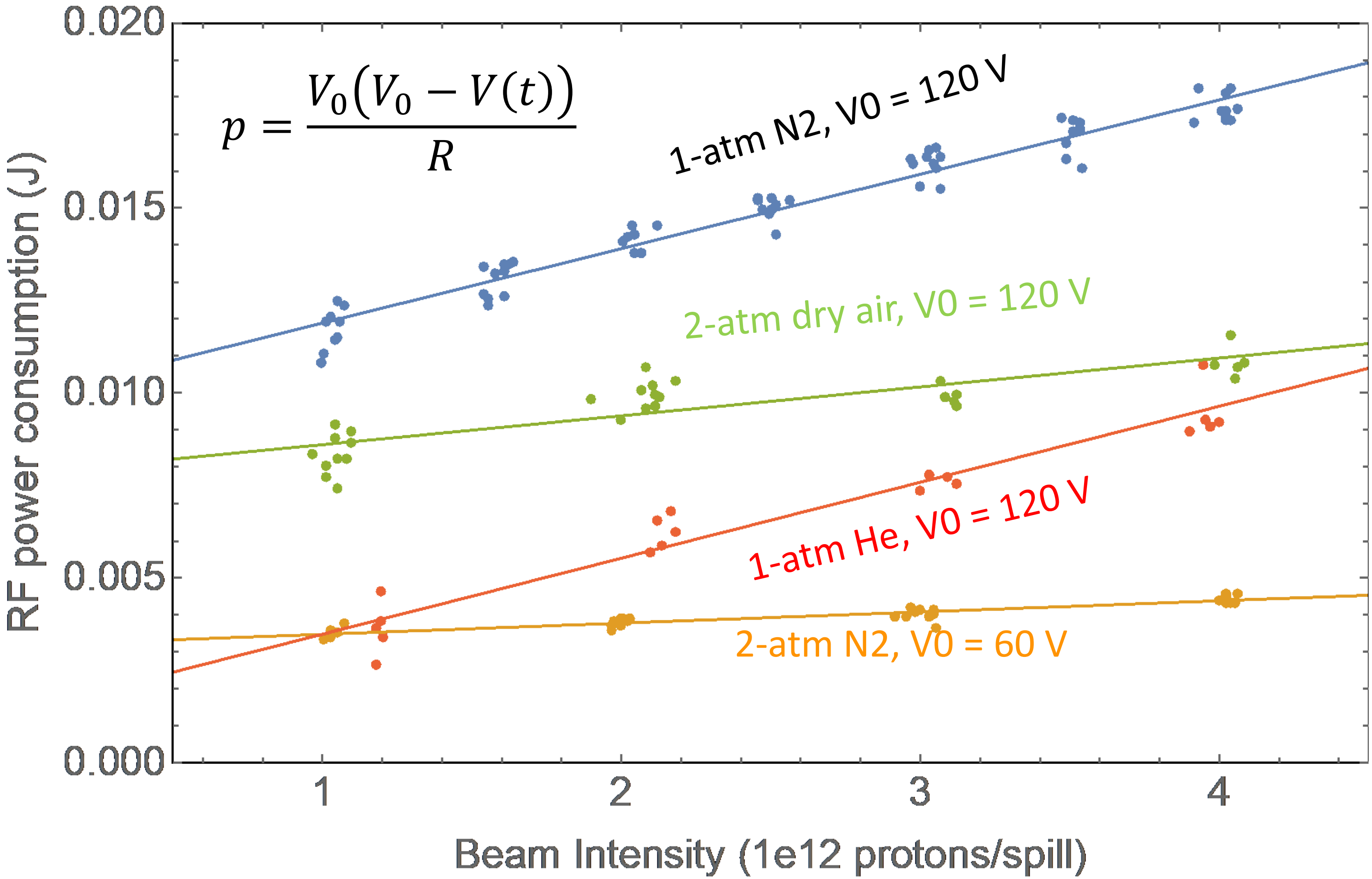
- 1e12 – 1e13 protons per spill are available
- Similar beam profile as the NuMI/LBNF beam

Beam loaded RF signal



Five peaks during the beam on shows the gap of MI beam batches

Linearity tests

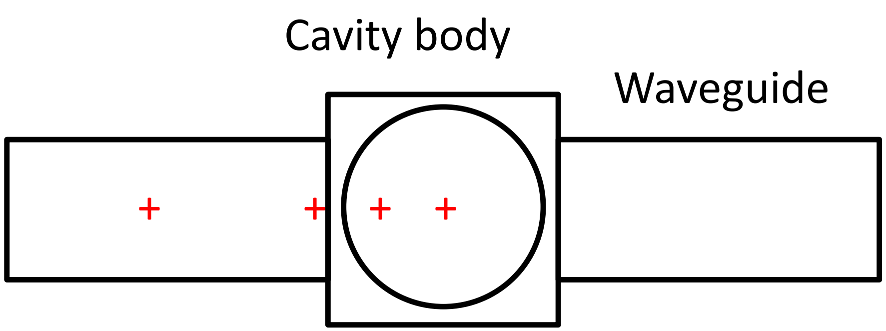


Linearity Discussion

- Nice linear correlation between incident beam intensity and RF power consumption
- 10 % data fluctuation at each group is mainly caused by the instability of beam
- Note that the linear fit line does not go through zero at no beam
  - It suggests that a plasma process and/or RF power amplification is linear in this operational range
  - The plasma process should be drastically changed when the beam intensity is extremely low or high
  - Need more precise beam test to investigate the plasma chemistry

Next steps to apply RF detector for LBNF

- Need more beam tests
  - Investigate more plasma chemistry
  - Study background RF signal when the beam strikes the waveguide
- Need automatic data acquisition system
  - Add phase shift change to amplitude change for better Q measure
  - LabVIEW base DAQ has been developed to control the RF source, take an automatic RF signal calibration run, and to convert RF signal into the beam signal



(+) Possible beam position to test the off-axis beam effect

Conclusions

- Rad-hard detector proof of principle experimentally verified
  - Only aluminum and gas in the high radiation field
    - detector is gas-filled rf cavity between waveguides
  - Charged particles ionize the gas in the cavity
    - Plasma changes the Q
  - Q change measured by passing an RF signal through the cavity
  - Real and imaginary parts of Q
    - Shift the phase and diminish the amplitude of the RF signal
  - Absolute calibration from beam independent shunt impedance
- Next Steps identified
  - Understand effects of beam position on detector/waveguide
  - Develop DAQ system
  - Design 5-element profile array