Precision measurement of muonium hyperfine splitting at J-PARC

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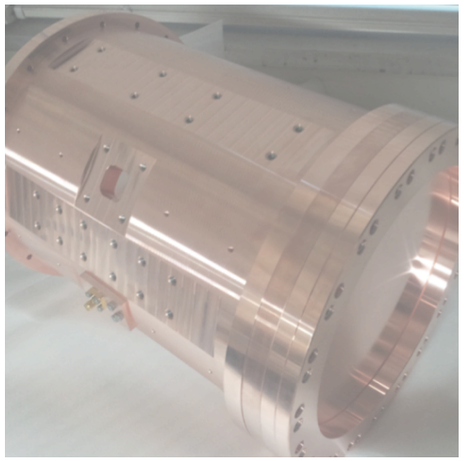
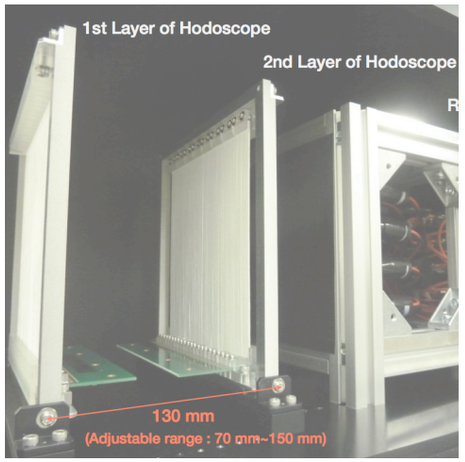
Overview

- Introduction of Muonium HyperFine Splitting (MuHFS)
- Measurement precision
- New Experiment at J-PARC
  - Muon beam at J-PARC, Superconducting magnet
  - Online/Offline beam profile monitors
  - Gas chamber and Cavity
  - High rate capable positron detector
    - Detector R&D
- Summary and prospects

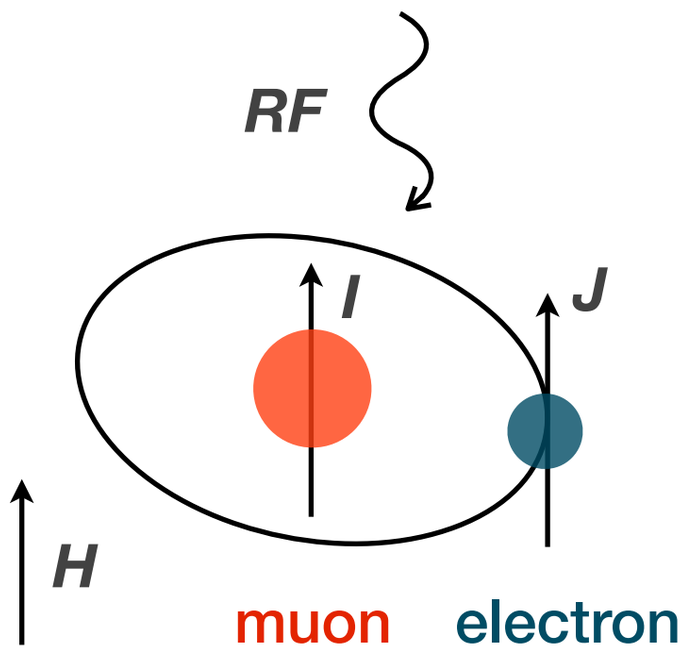


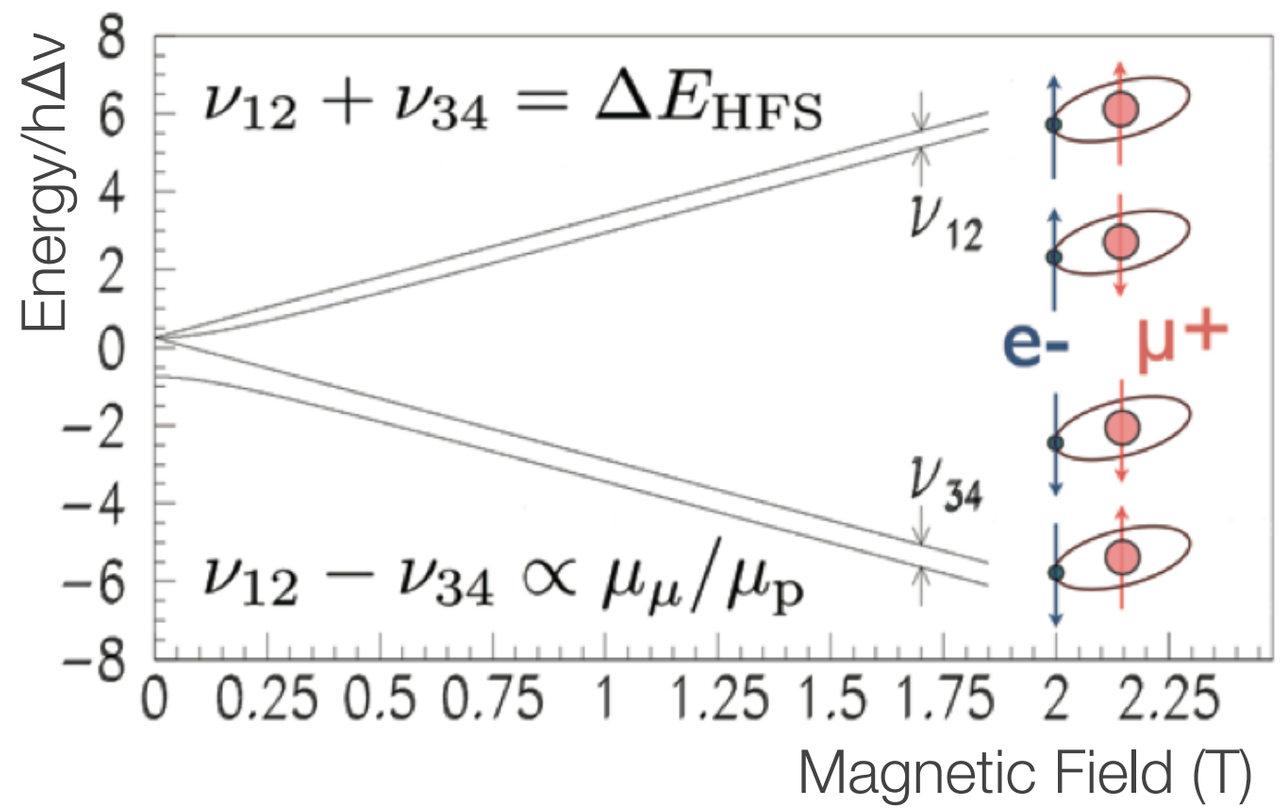


Muonium Hyperfine Splitting

$$\mathcal{H} = a\,\vec{I}\cdot\vec{J} + \mu_B^e g_J\,\vec{J}\cdot\vec{H} - \mu_B^\mu g_\mu^{'}\,\vec{I}\cdot\vec{H}$$ +RF term

Hamiltonian of Muonium HFS Zeeman Splitting





Muonium:

- Bound state of μ+ and e-
  (Less affected by recoil than Ps)
- Pure leptonic system
  (Composite particle free)

Objectives:

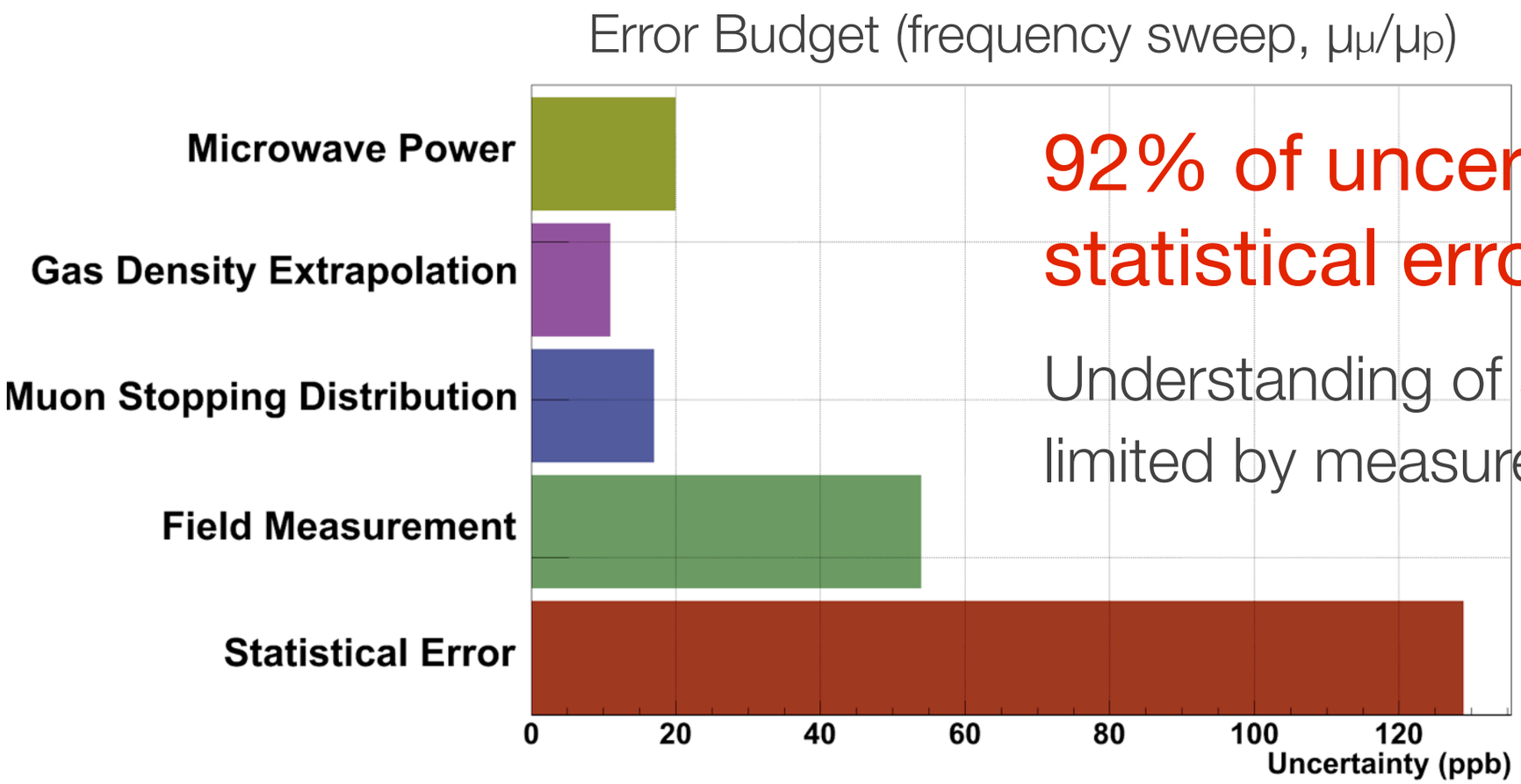
- Precision test of bound state QED
- Muon mass determination
- Test of Lorentz invariance
- Muon g-2

Precision of measurement

$$\Delta E_{\mathrm{HFS}} = 4463302765(53)\ \mathrm{Hz}\ (12\mathrm{ppb})$$

$$\mu_\mu/\mu_p = 3.18334513(39)\ (120\mathrm{ppb})$$

Liu et al., PRL. 82, 711 (1999)



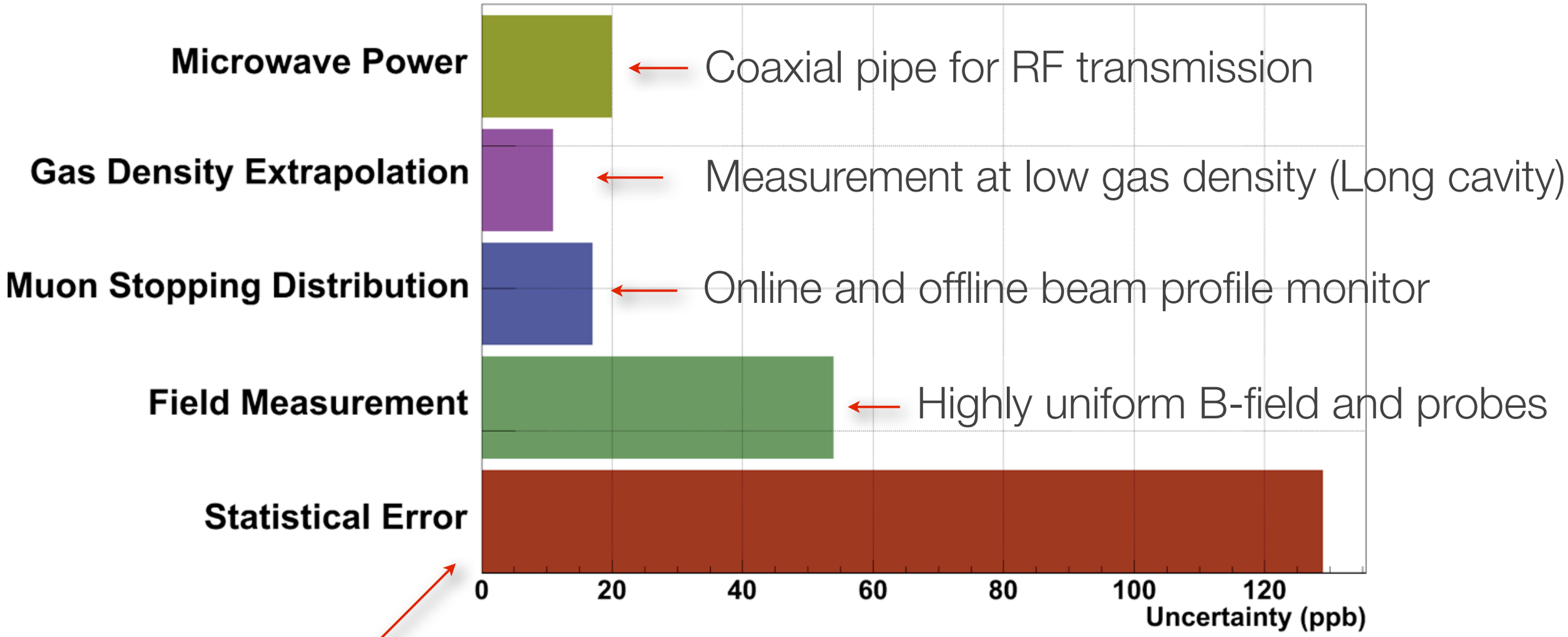
92% of uncertainty is statistical error

Understanding of systematics is limited by measurement time

Our goal : 200 times of statistics and minimization of systematic uncertainty

How to improvement

Error Budget (frequency sweep, μ_μ/μ_p) and our approach to improvement

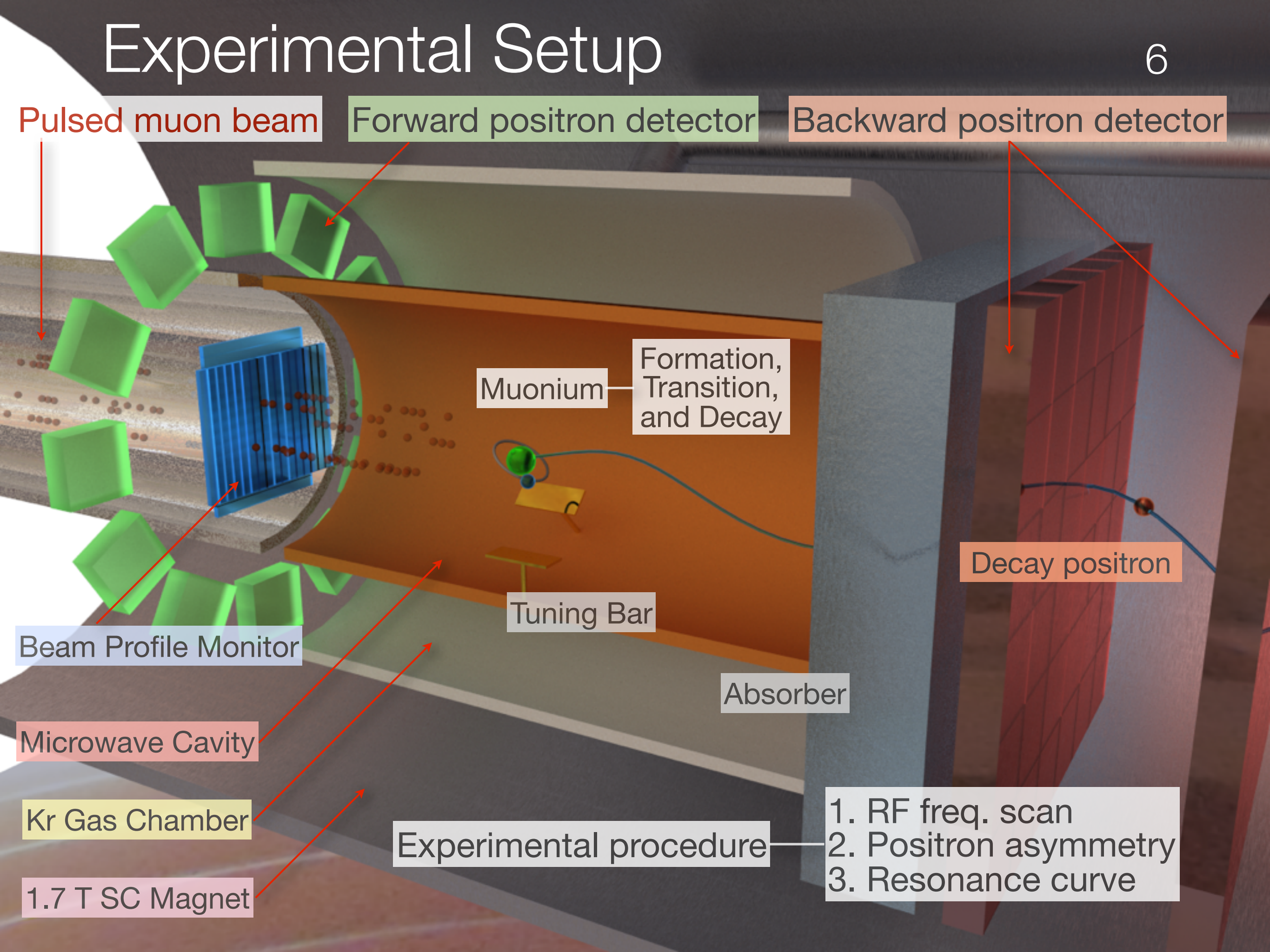


The Keys: Highest intensity pulsed muon beam at J-PARC

Various calibration runs and well understanding in systematic errors

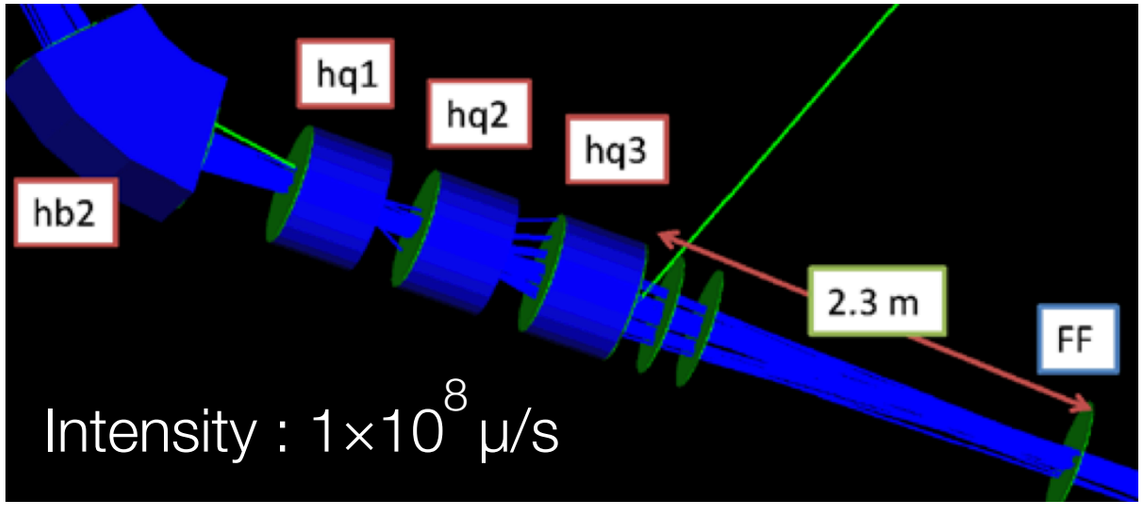
Requirement: High rate capable positron counter

Experimental Setup



Muon beam and Magnet

- H-Line : The highest intensity pulsed muon beam at J-PARC (Under construction)



Simulated muon beam by G4Beamline

Simulation Result:
- Profile at final focus
  - σx=13 mm, σy=13 mm
  - xp=161.5 mrad, yp=137.4 mrad
- 93.6% transmission efficiency
- Leakage field 0.5 Gauss
- (Requirement < 1.7 Gauss)

A. Toyoda *et al.* J.Phys.Conf.Ser. 408 (2013)

- Magnet : 1.7 T high precision superconducting magnet (Installed at J-PARC)

Magnet at J-PARC

Requirement to the magnet:
- 1ppm homogeneity in z300 mm, r100 mm region

Specification of the magnet:
- Field strength 1.7 T
- Bore diameter 925 mm

Field correction is performed by main coil, iron shim, and shim coil

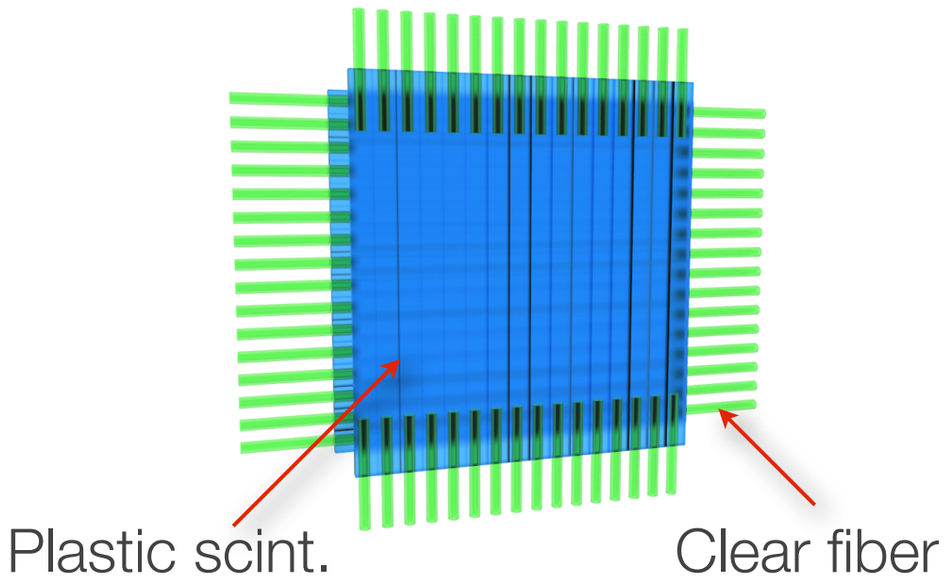
Field strength is monitored by NMR probes

K. Sasaki, M. Sugano, The 5th and 6th g-2/EDM Collaboration Meeting (2012)

T. Mizutani *et al,* Japan Phys. Soc. Autumn Meeting (2013)

Beam Profile Monitors

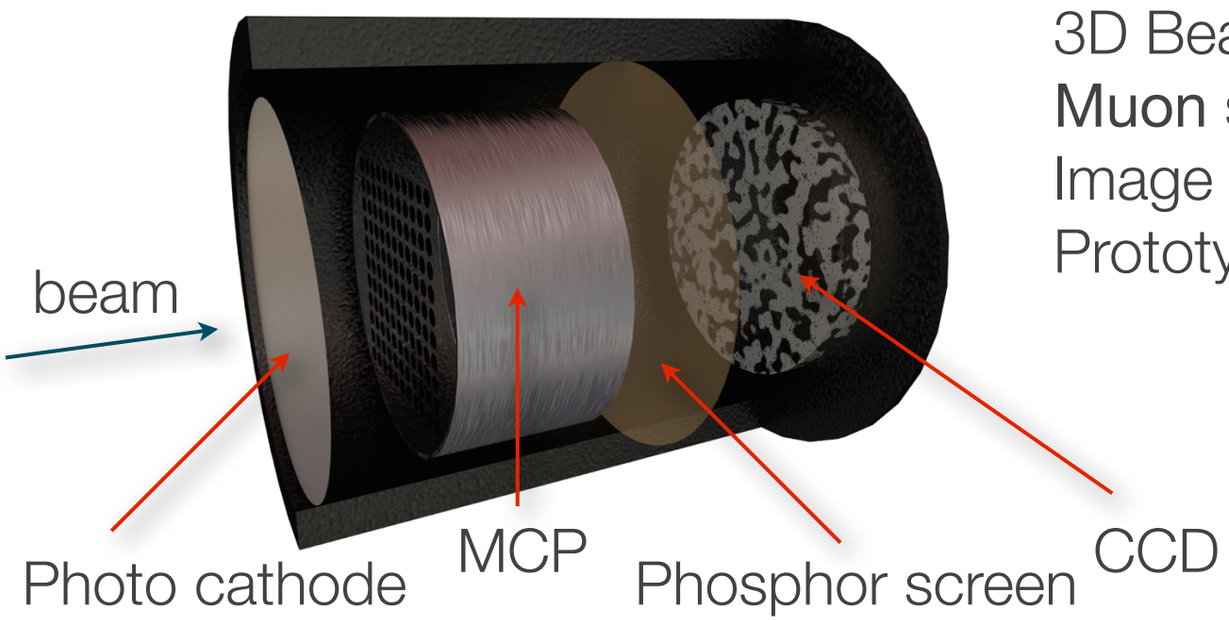
- Online beam profile monitor : 2D non destructive muon monitor



Non destructive 2D Beam profile monitor
Beam stability measurement
150 μm plastic scint. + clear fiber + MAPMT (or SiPM)
16 ch. × 2 Layers
Prototype is developed and beam test is performed

M. Tajima *et al,* Japan Phys. Soc. Ann. Meeting (2013)

- Offline beam profile monitor : 3D monitor for muon stopping distribution measurement

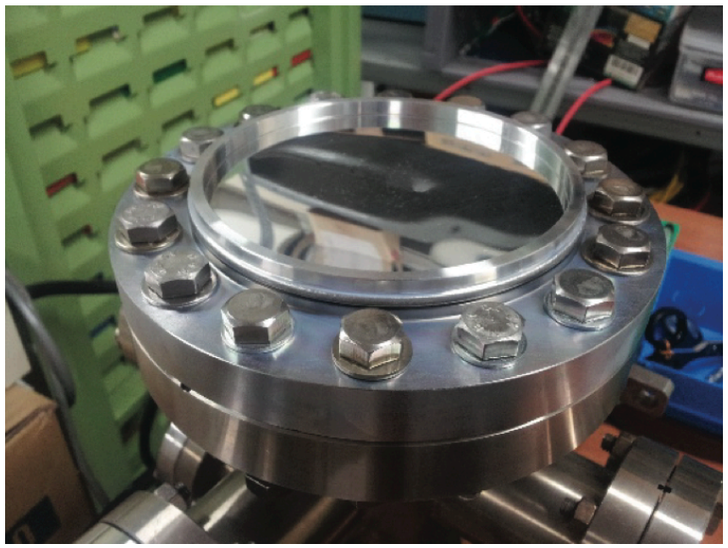


3D Beam profile monitor
Muon stopping distribution in the cavity
Image intensifier + CCD
Prototype is developed and beam test is performed

T. U. Ito *et al*, USM2013 (2013)

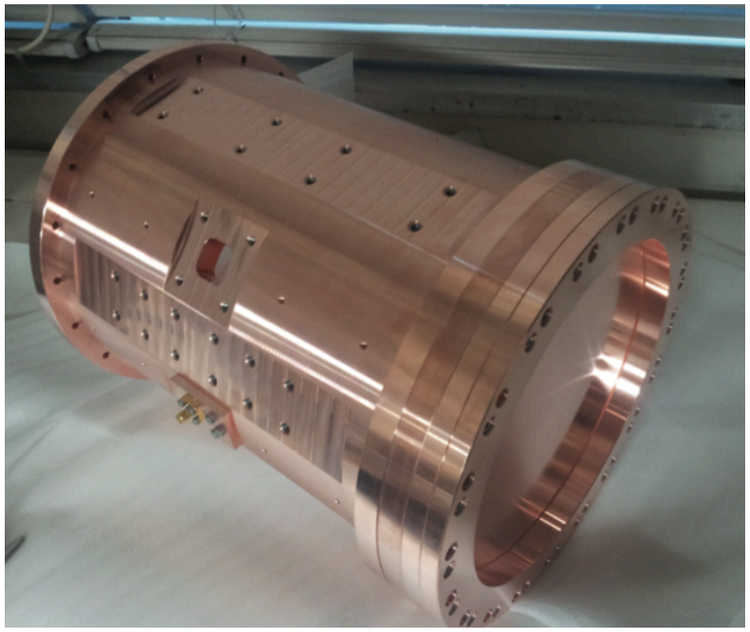
Chamber and Cavity

- Kr Gas Chamber



Prototype of the gas chamber

- Microwave Cavity

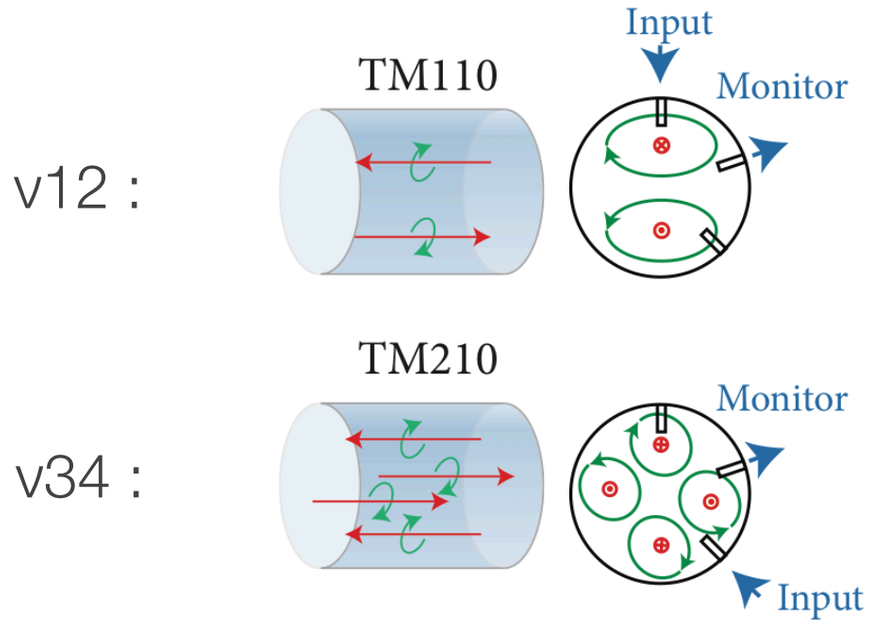


Prototype of the cavity

Extrapolation to lower gas density
->Long cavity is required for muon stop

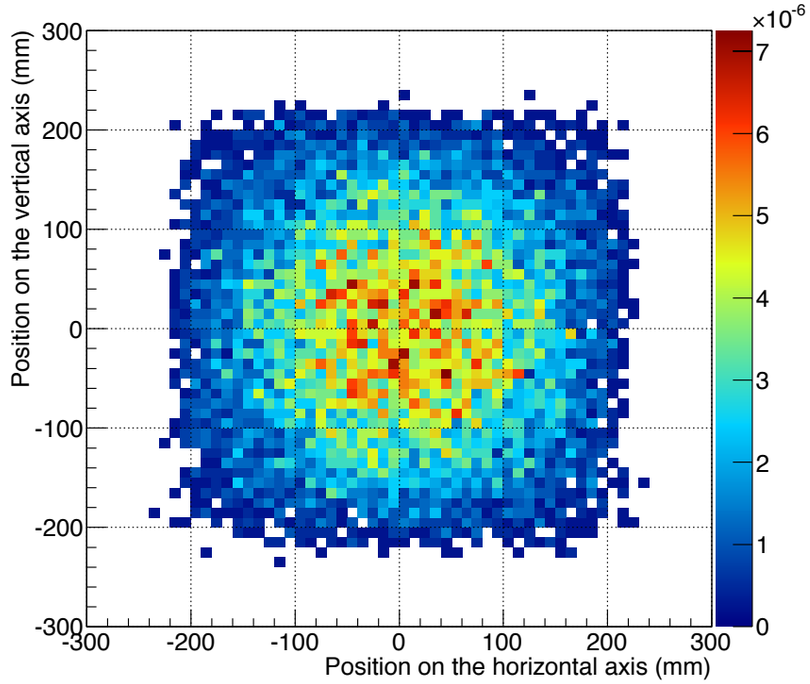
Two transition frequencies
->Two modes should be tuned by tuning bars

Prototype development
->Pressure test and RF test is performed



K. Tanaka, The 6th g-2/EDM Collaboration Meeting (2013)

Positron Detector

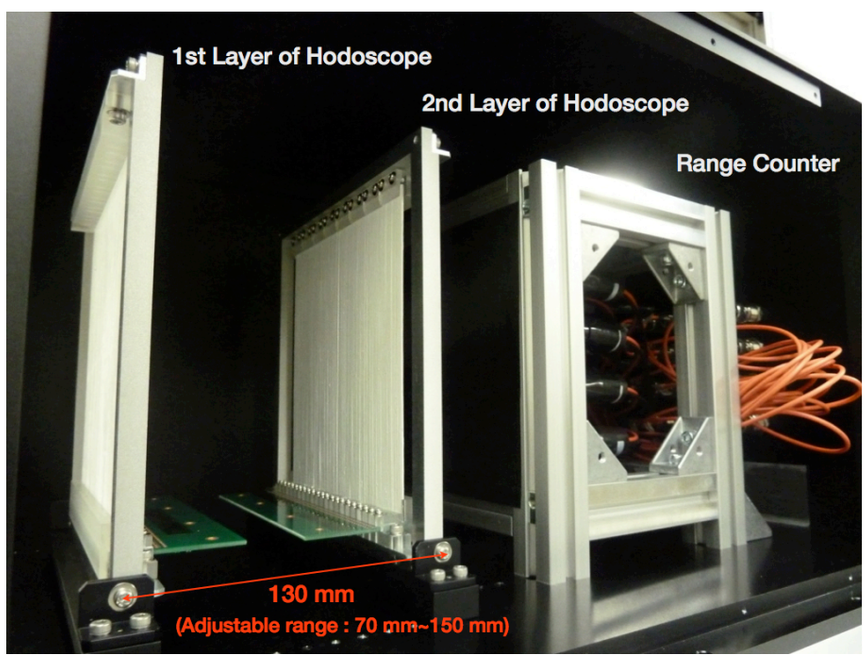


Simulated positron hits per stopped muon

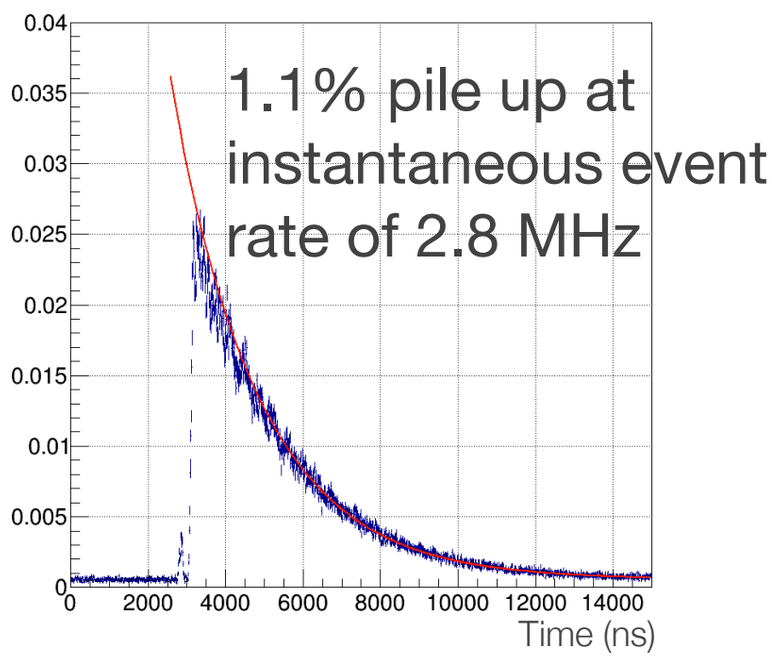
Requirement: Suitable for high intensity pulsed beam
Highly segmented positron counter
-> 2~4 layers of scintillating fiber hodoscope
Expected event rate ~ 3 MHz/cm2
Scintillation fiber+MPPC+ASIC based ASD+FPGA MHTDC

Prototype is developed and beam test is performed

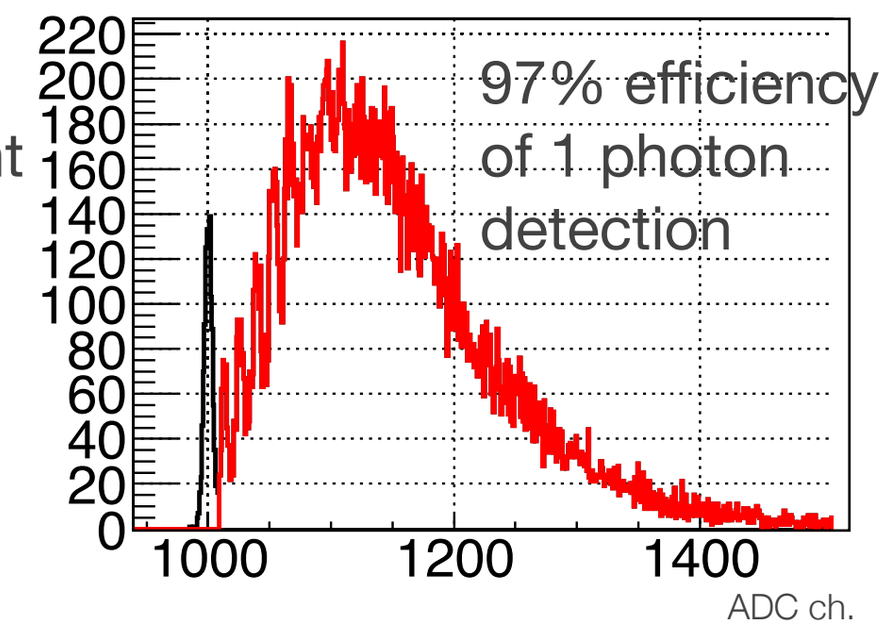
Y. Fukao, The 6th g-2/EDM Collaboration Meeting (2013)
S. Kanda *et al*, USM2013 (2013)



Prototype of the detector



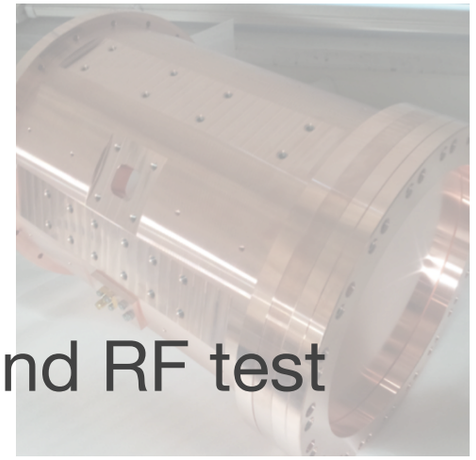
μe decay time spectra
※Old prototype data

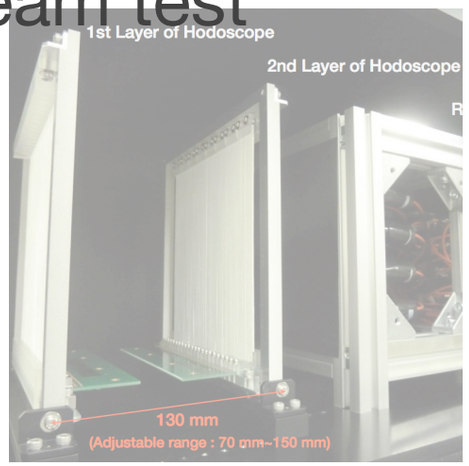


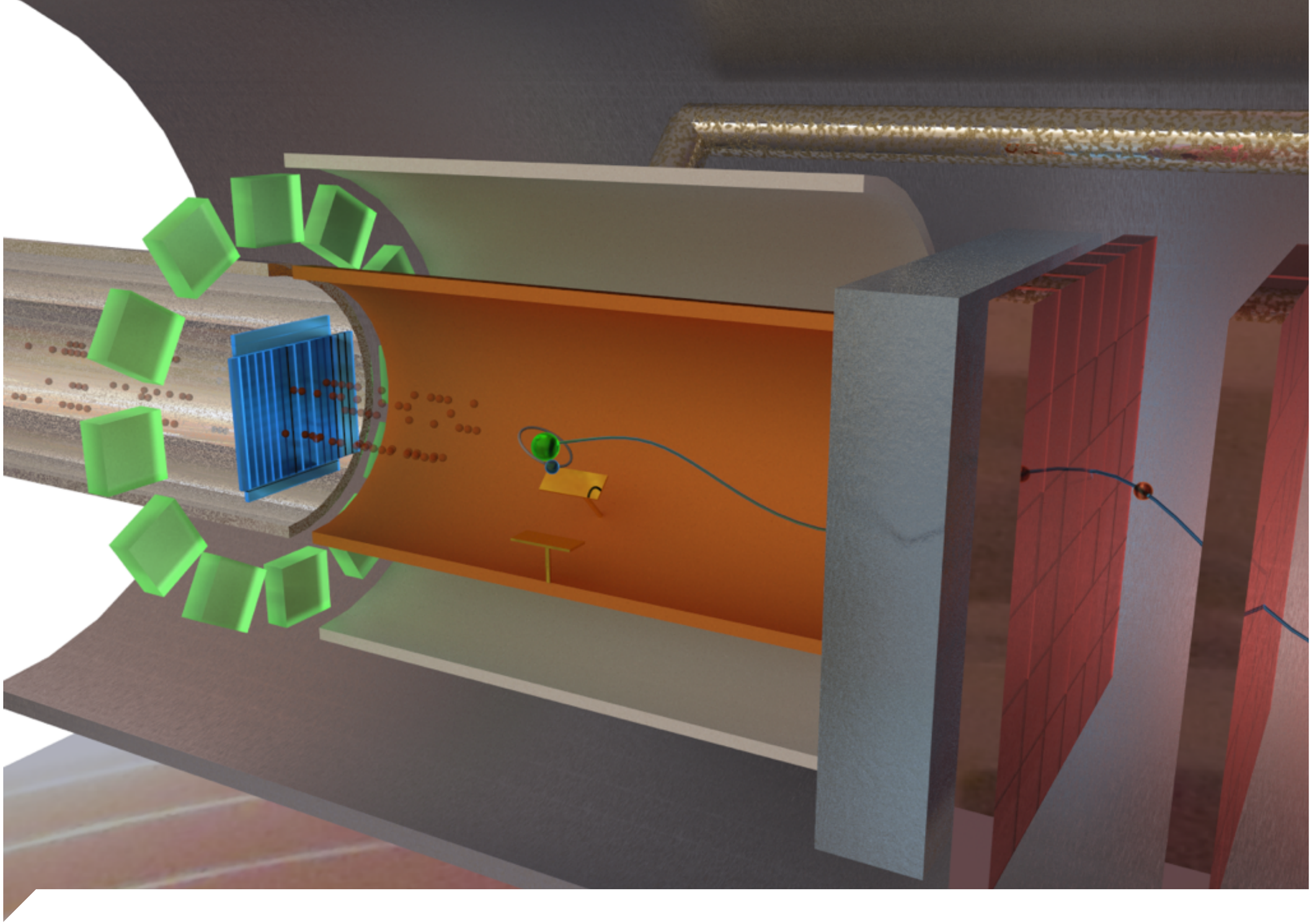
Detected photon # distribution (Sr90)

Summary and Prospects

- MuHFS measurement is a good test of bound system QED
  - New Experiment at J-PARC can improve the measurement precision
    - The keys are intense muon beam and high rate capable detector
- R&D in progress
  - Profile monitor -> Prototype development, beam test
  - Chamber, cavity-> Prototype development, pressure and RF test
  - Detector -> Simulation, prototype development and beam test
- The experiment will start in FY2014
- We are looking for new collaborators!

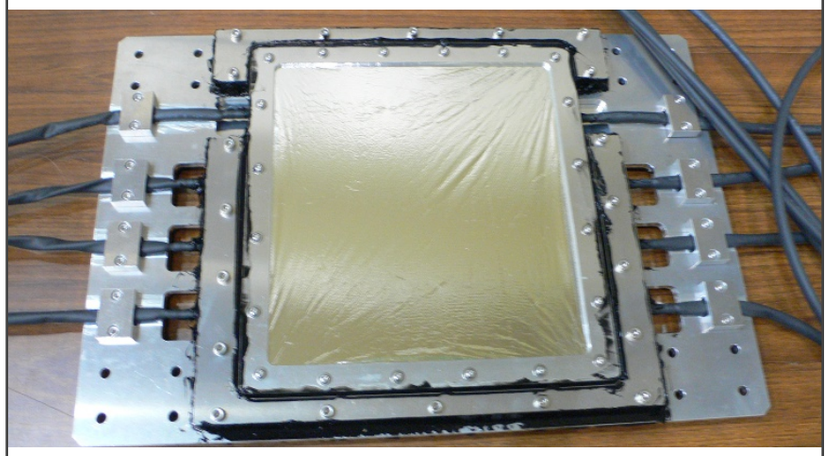
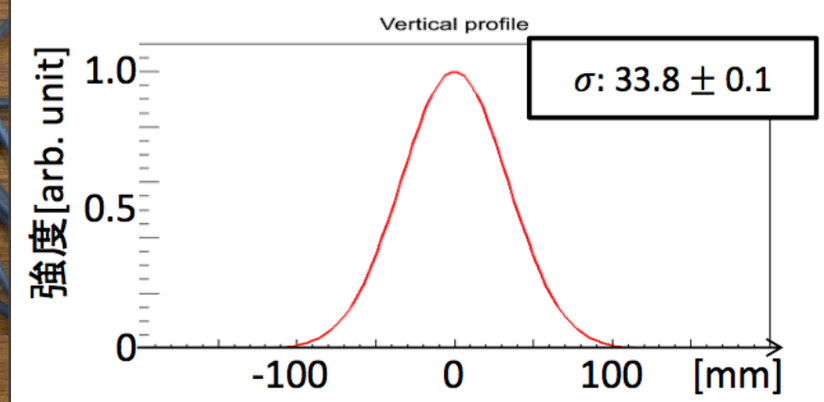
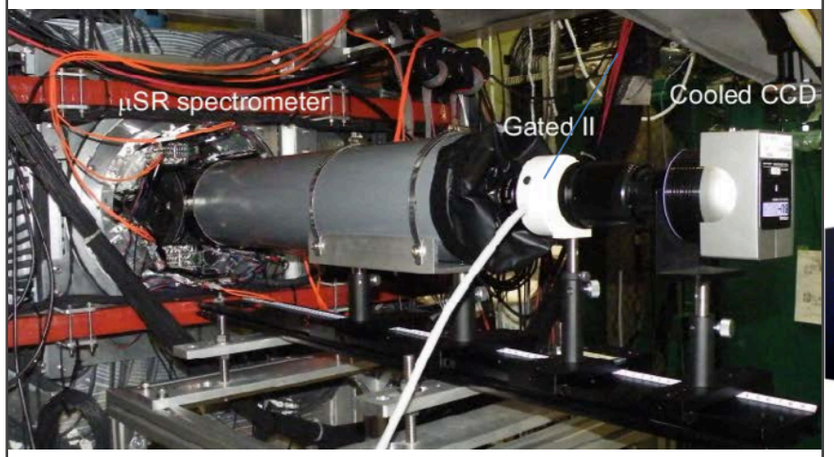
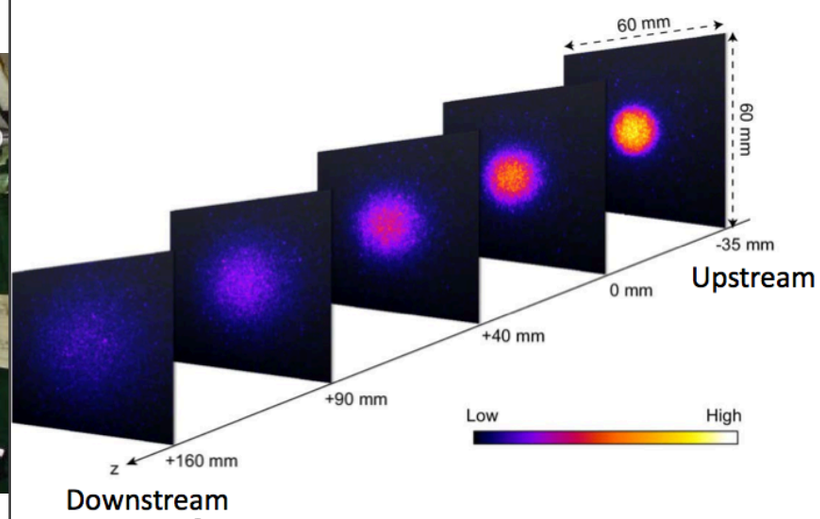




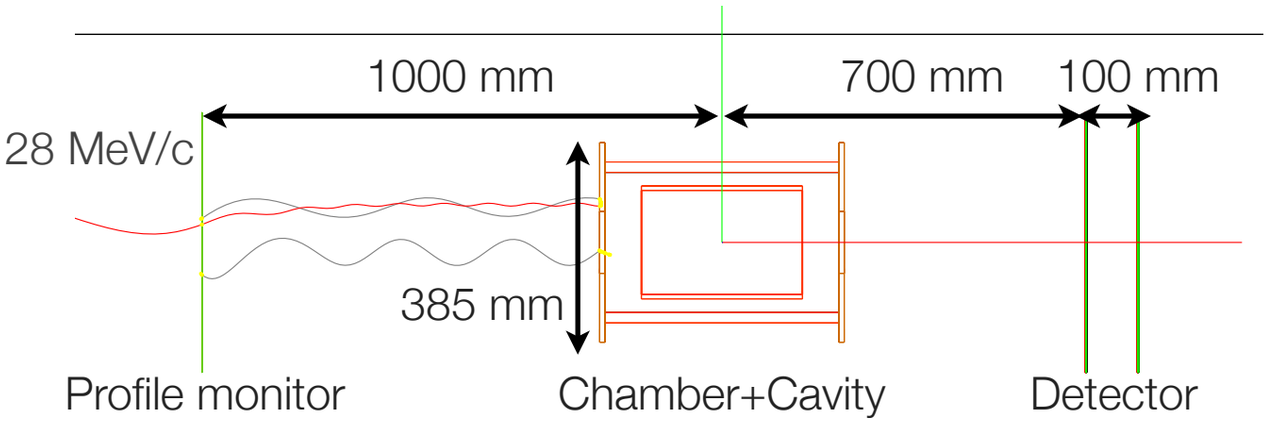


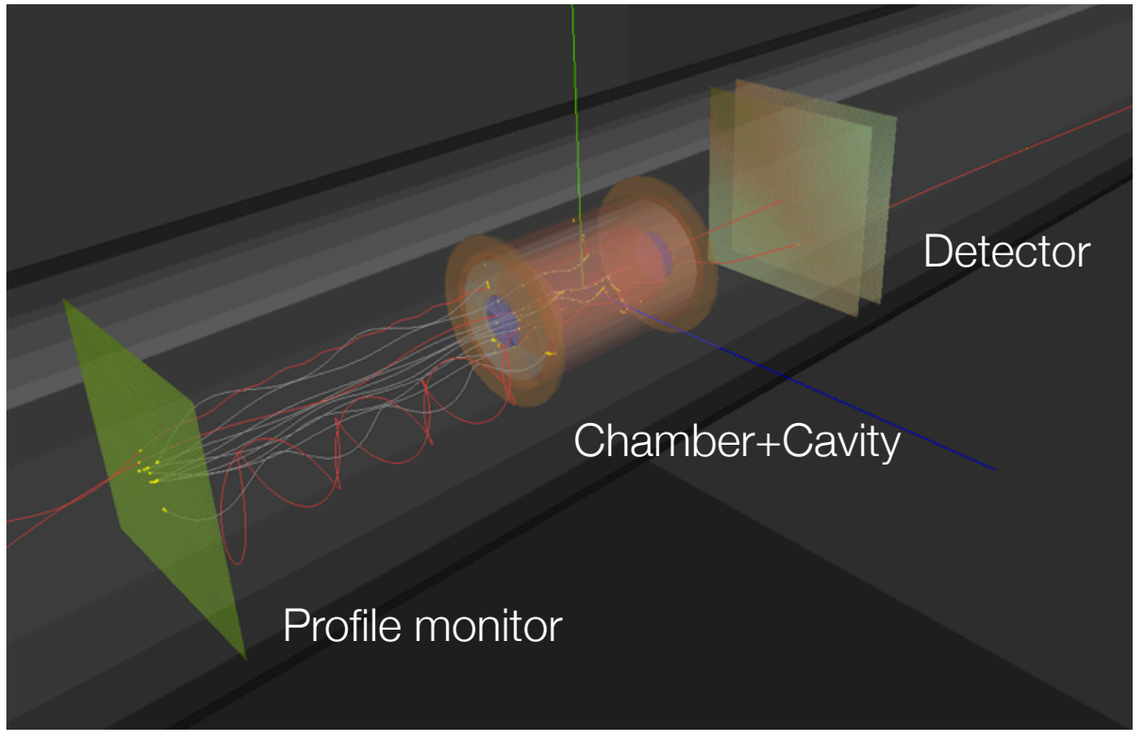
Additional Materials

Profile monitor R&D

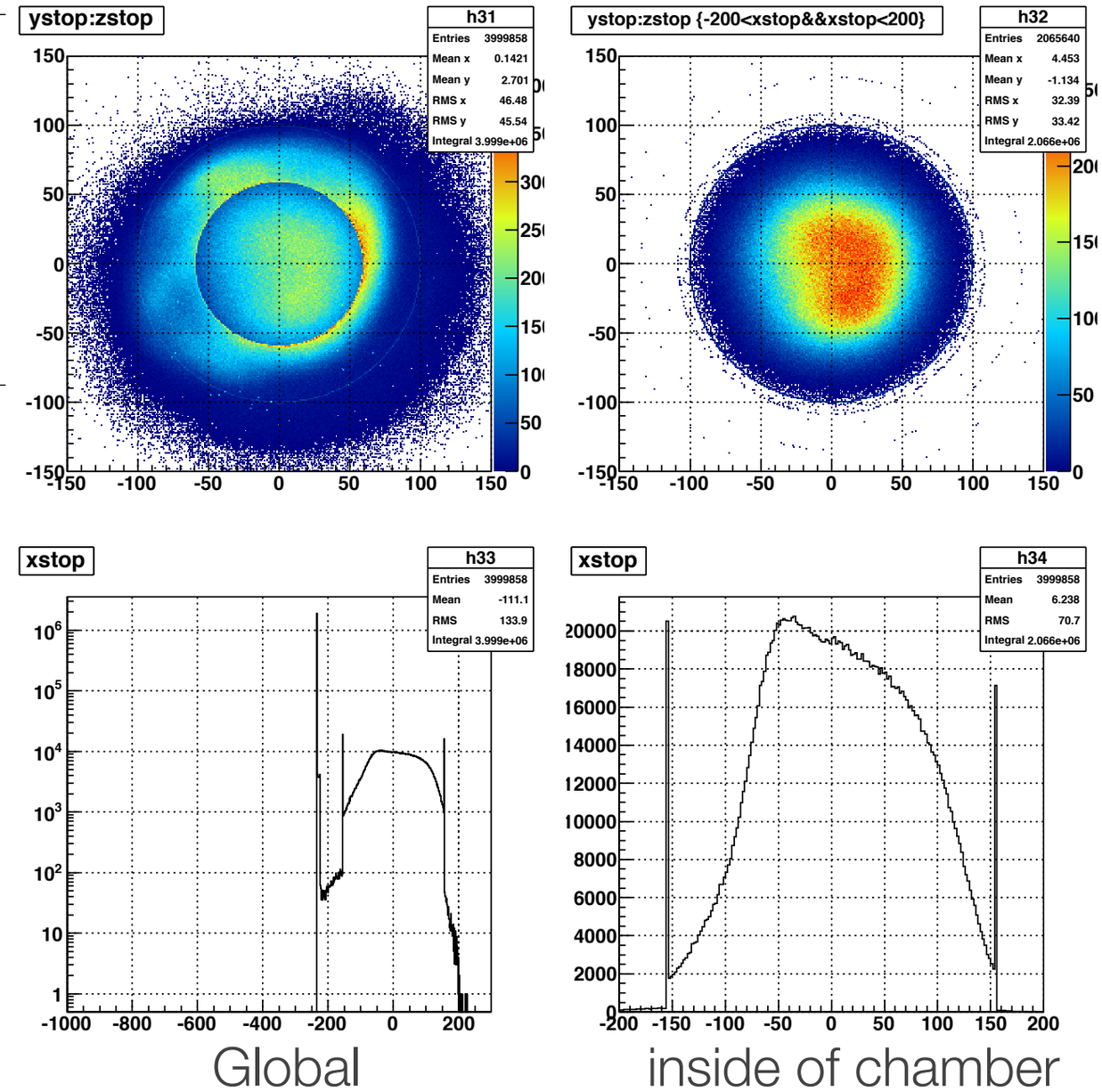
Online beam profile monitor M. Tajima *et al*, Japan Phys. Soc. Ann. Meeting (2013)	 Prototype	 Obtained beam profile at J-PARC
Offline beam profile monitor T. U. Ito *et al*, USM2013 (2013)	 Prototype	 Obtained beam profile at J-PARC

Simulation Study





Simulation geometry



Global

inside of chamber

Muon stopping distribution

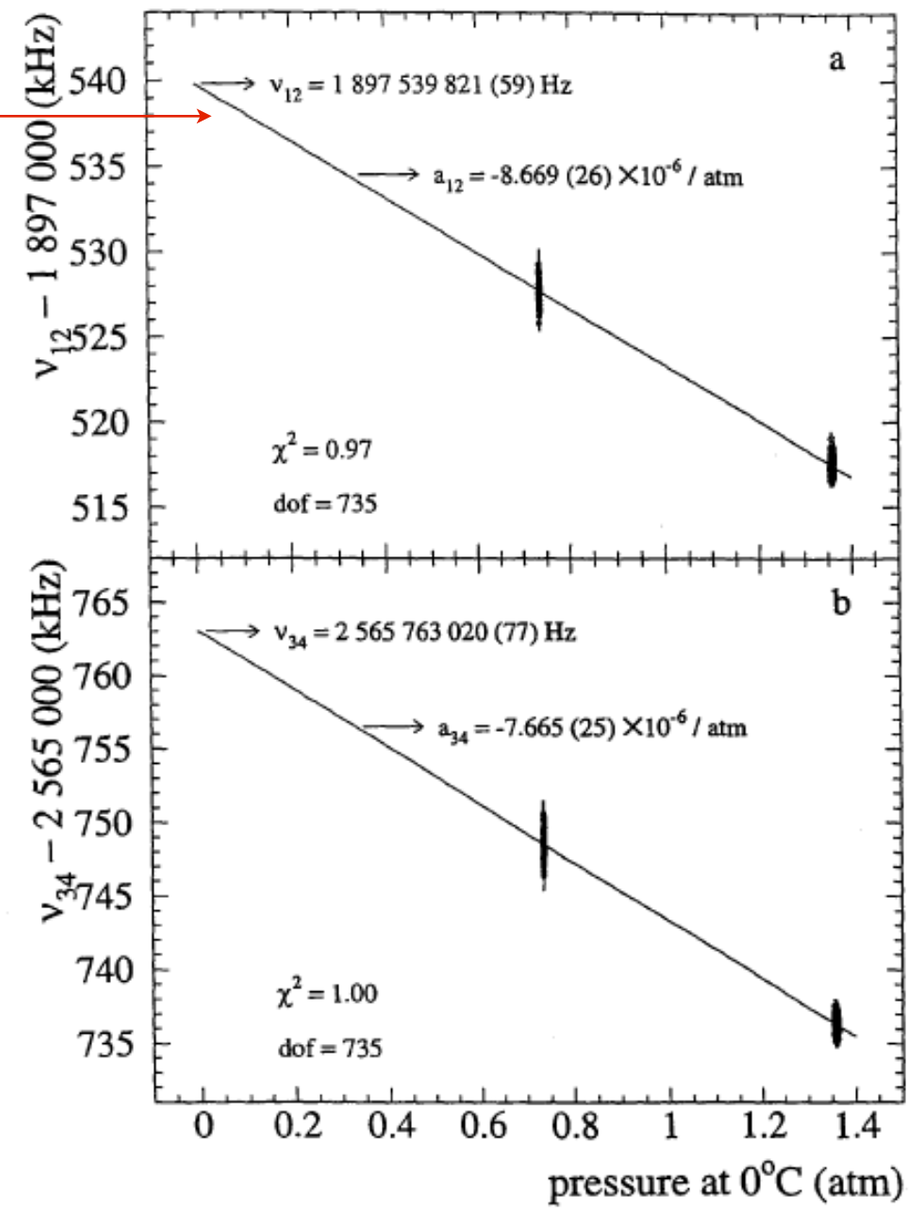
Gas Density Extrapolation

Extrapolation to Gas pressure=0

Los Alamos Experiment
only 2 pressure data points
->Extrapolation uncertainty

More data points is important for the
improvement of precision
(Especially lower gas density)

->J-PARC new experiment uses longer
cavity (lower gas density is achievable)

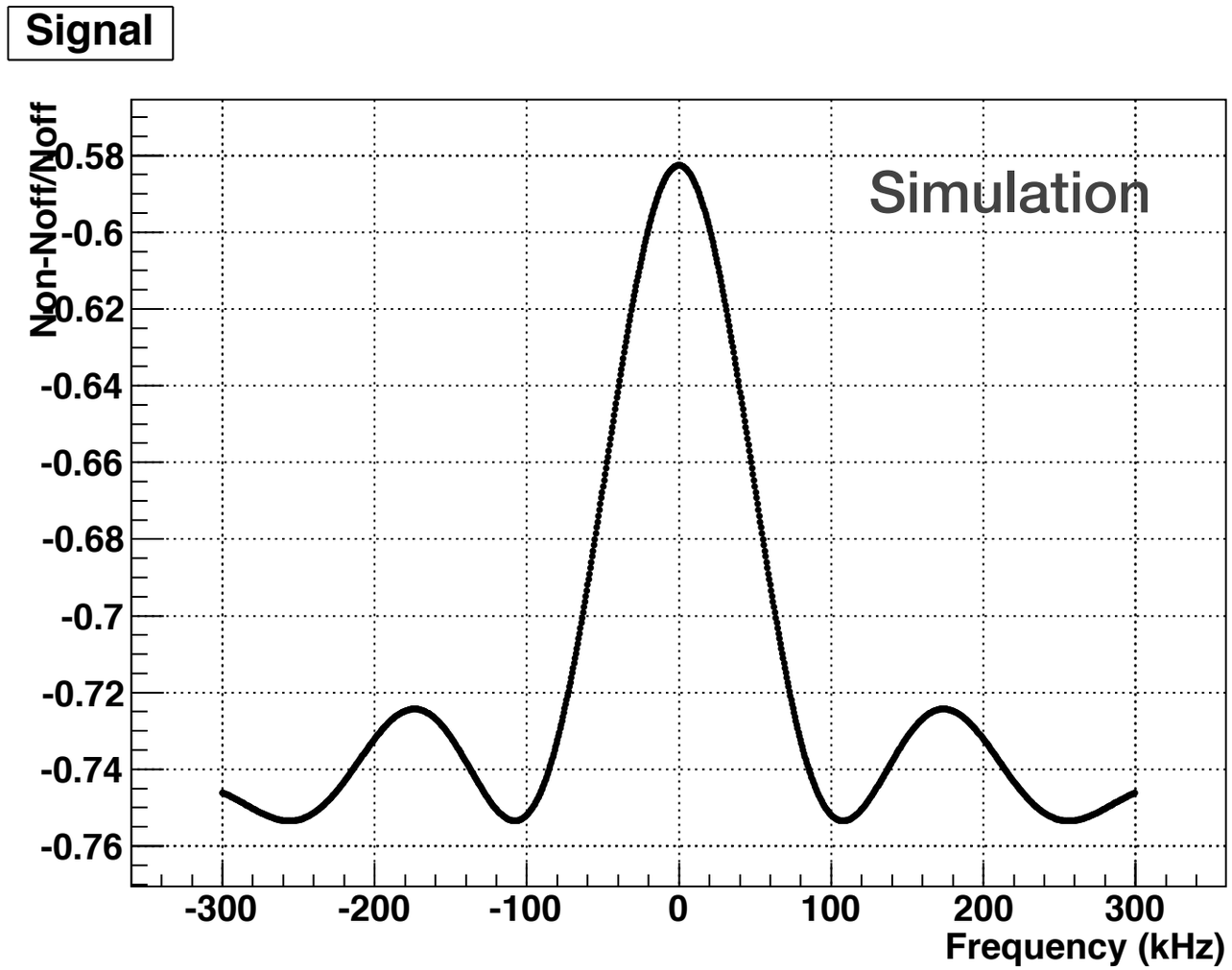


W. Liu, PhD Thesis (1997)

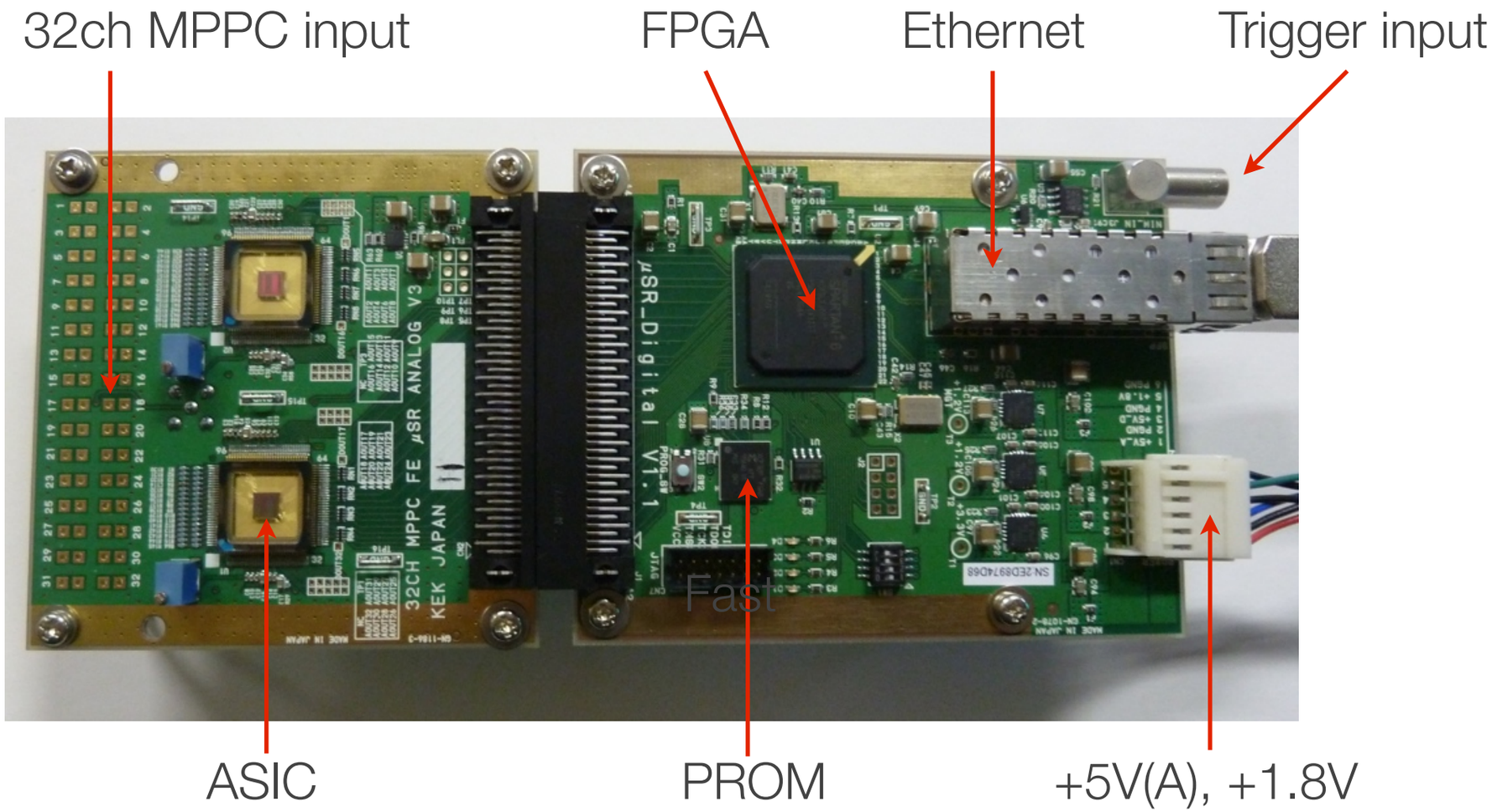
Resonance Line Shape

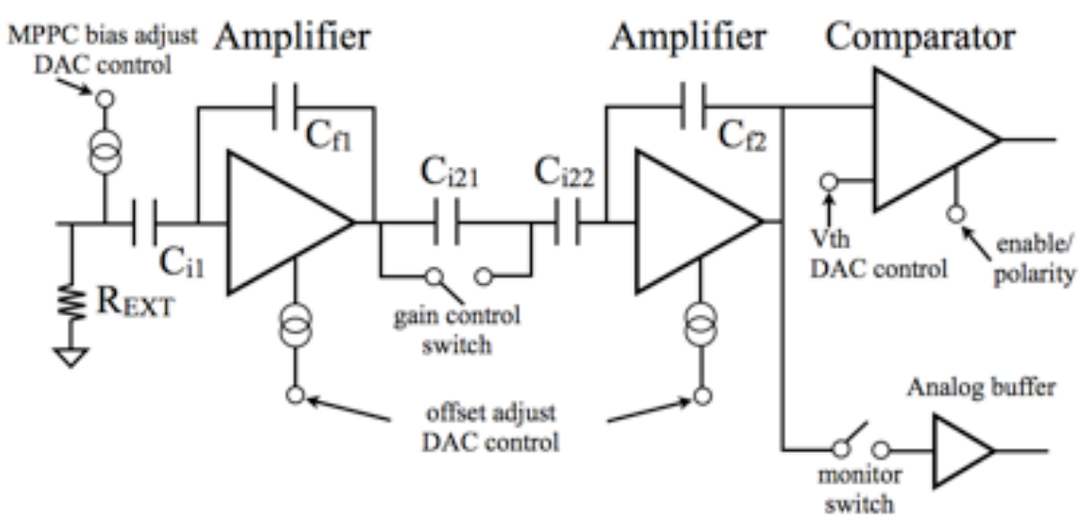
Calculation procedure

1. Hamiltonian of muonium
2. Wave function of muonium
3. State amplitude/probability
4. Muon stopping distribution
5. Muon polarization
6. Decay positron asymmetry
7. Positron detection
8. Frequency sweep
9. Difference between RF on/off



Readout Electronics

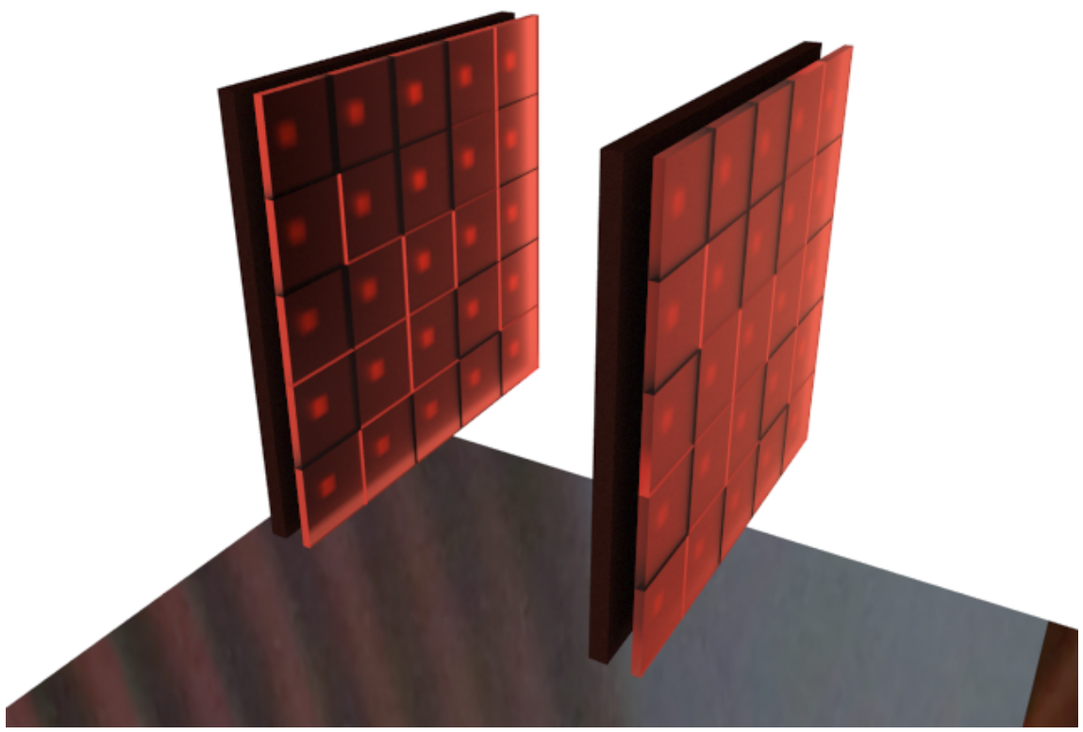




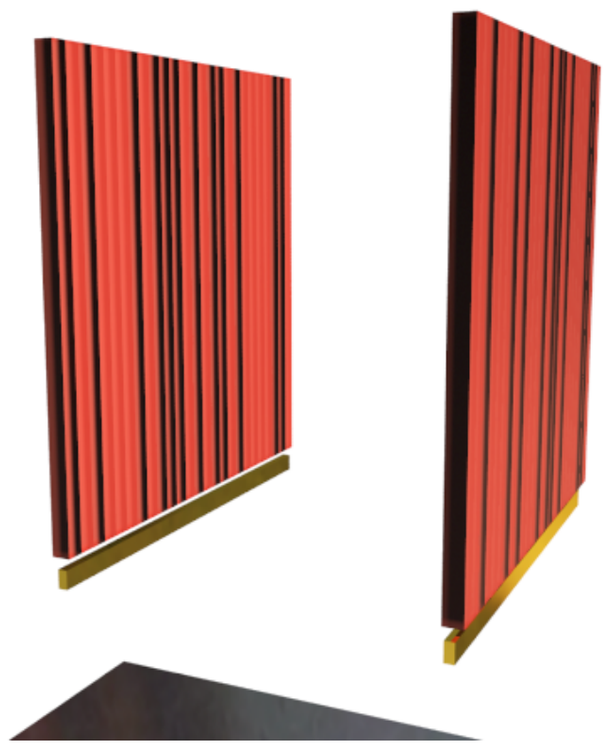
M. Tanaka, K. M. Kojima, T. Murakami, S. Kanda, C de la Taille and A. Koda (to be published)

Detector Options

2D Tiled Pixel



1D Fiber Array



and hybrid of them