MuSEUM

New Muonium Hyperfine Measurement at J-PARC ～MuSEUM Experiment～

S. Nishimura / the University of Tokyo,
for the MuSEUM Collaboration
2017/09/03

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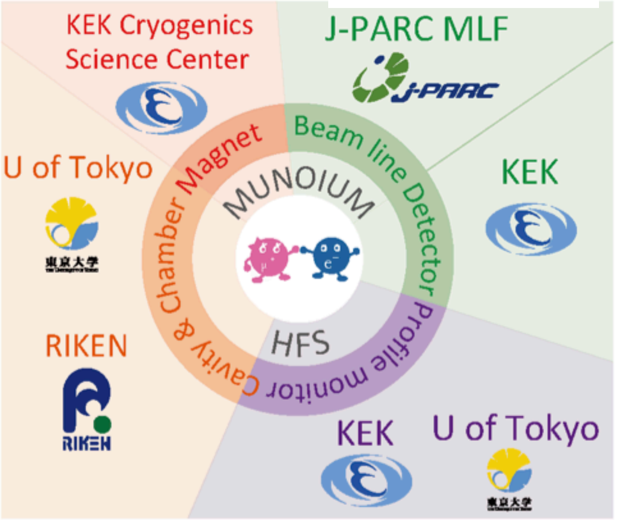

Outline

MuSEUM

- Precision measurement of Mu HFS
- MuSEUM experiment at J-PARC
  - Gas handling system
  - Magnetic shield and field measurement
  - RF cavity
  - Positron detectors
- Resonance search
- Summary and prospects

Muonium Hyperfine Structure

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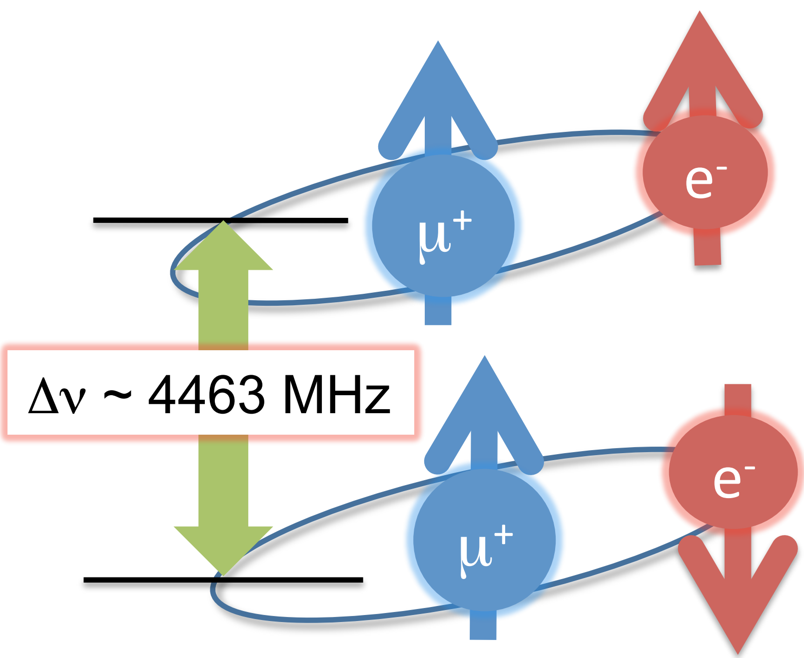
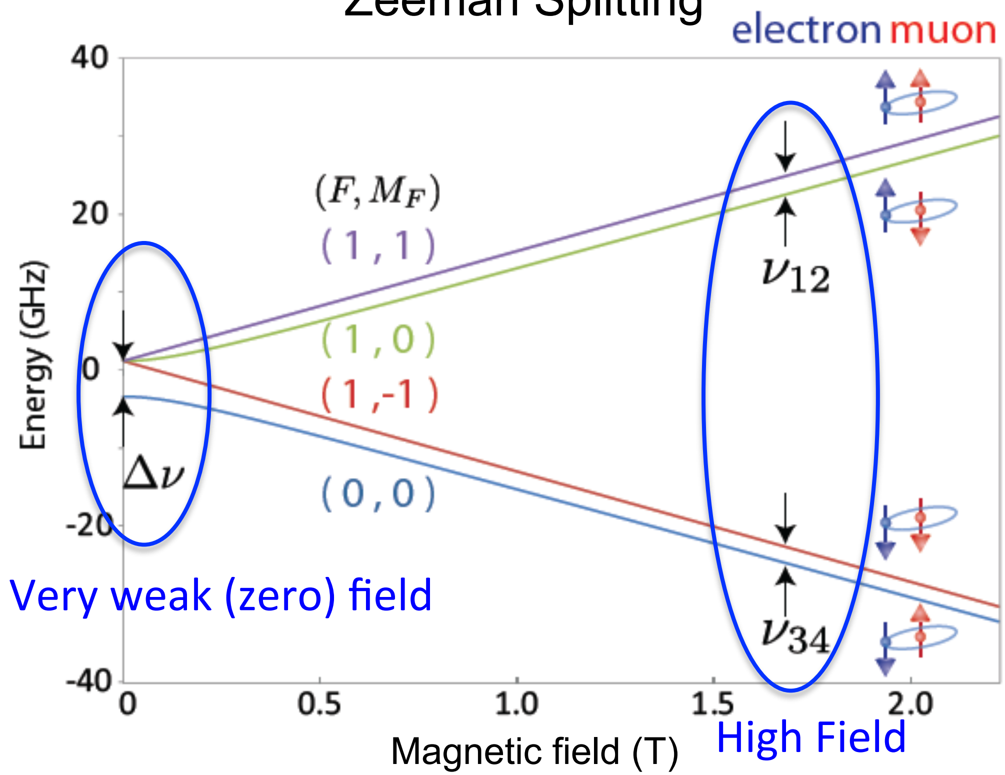
- Hamiltonian of muonium

$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

$\Delta\nu$: Mu Hyperfine Structure



Zeeman Splitting



$\nu_{12}+\nu_{34}=\Delta\nu$ $\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p$

Precise measurement of Mu HFS

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- The most rigorous validation of the bound-state QED

ν_{HFS}(exp) 4463.302 765(53) MHz (12 ppb) LAMPF1999

μ_{μ}/μ_{p} =3.18334524(37) (120ppb)

m_{μ}/m_{e}=206.768277(24) (120ppb)

ν_{HFS}(theory) 4463.302 891 (272) MHz (63 ppb) D. Nomura (2013)

ν_{HFS}(QED) 4463.302 720 (253) (98) (3) MHz(m_{μ}/m_{e}) (QED) (α)

ν_{HFS}(weak) -65 Hz

ν_{HFS}(had v.p) 232(1) Hz

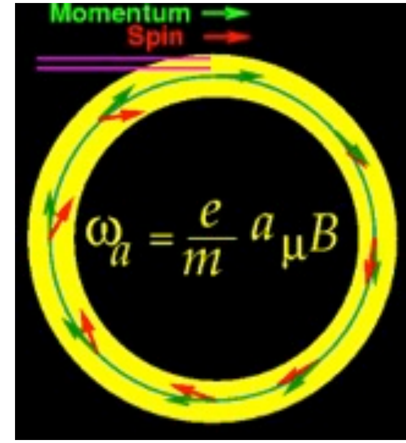
ν_{HFS}(had. h.o) 5 Hz

QED calculation →Effort for 10 Hz is in progress by Eides *et al*.
Phys. Rev. A **86**, 024501 (2012), PRL.. 112, 173004 (2014),
Phys. Rev. D **89**, 014034 (2014)

Precise measurement of Mu HFS

- Strong relationship with muon *g*−2
  - 3σ deviation btw. theory and experiment
  - Angular frequency of spin precession ω

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}} + \frac{\eta}{2}\cancel{\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}\right] \qquad a_\mu = \frac{g-2}{2}$$



  - It is important to measure precise **muon mass** independently

$$\boxed{R \equiv \frac{\omega_a}{\omega_p}} \qquad \boxed{\lambda \equiv \frac{\mu_\mu}{\mu_p}}$$

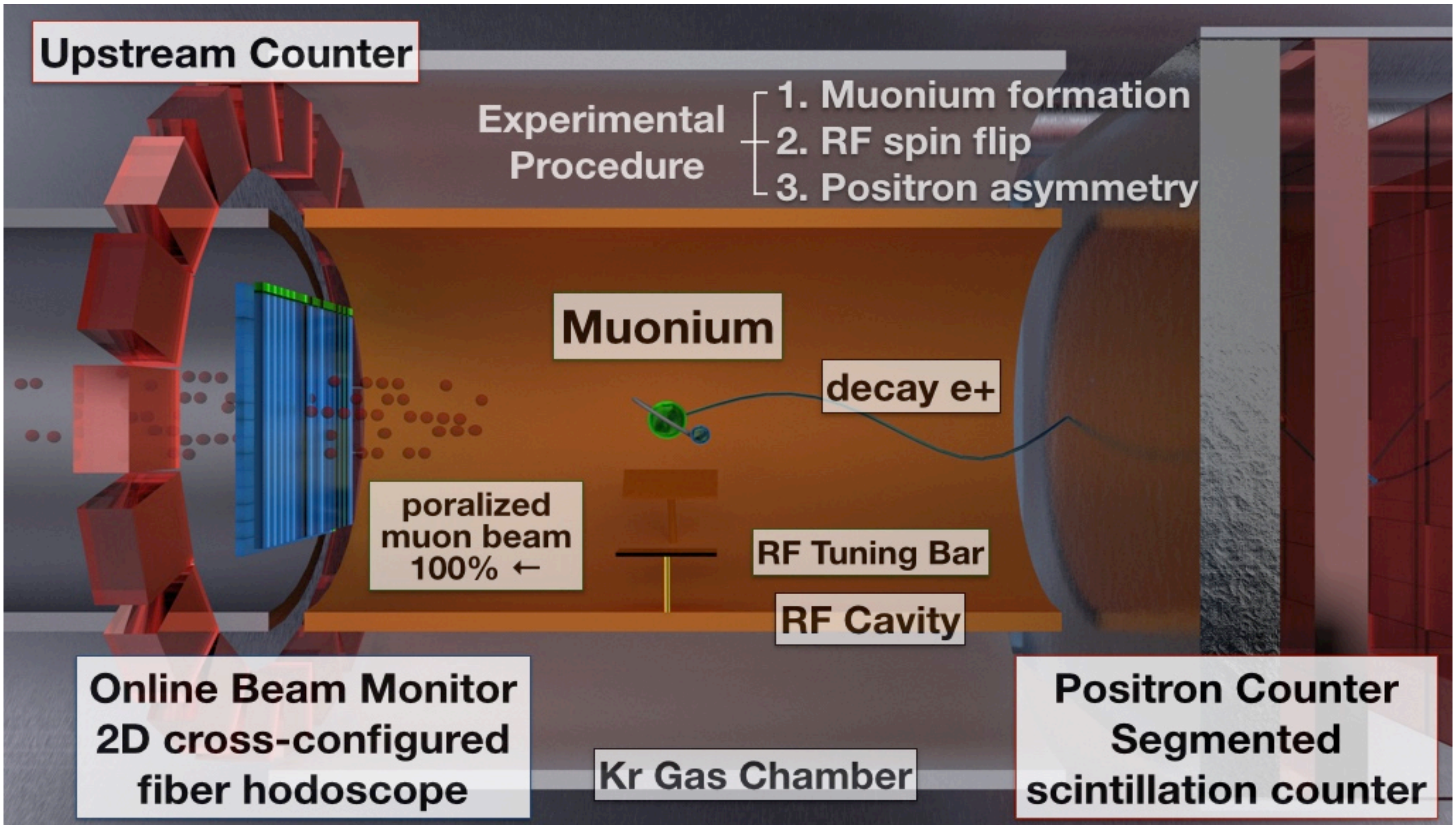
From *g*−2 storage ring — From muonium HFS

  - $a_\mu = \dfrac{R}{\lambda - R}$
  - μ_μ/μ_p accuracy from direct measurement 120ppb

W. Liu *et al., Phys. Rev. Lett.* ***82, 711 (1999).***

MuSEUM Experiment

- High intensity pulse muon beam at J-PARC D-line and H-line

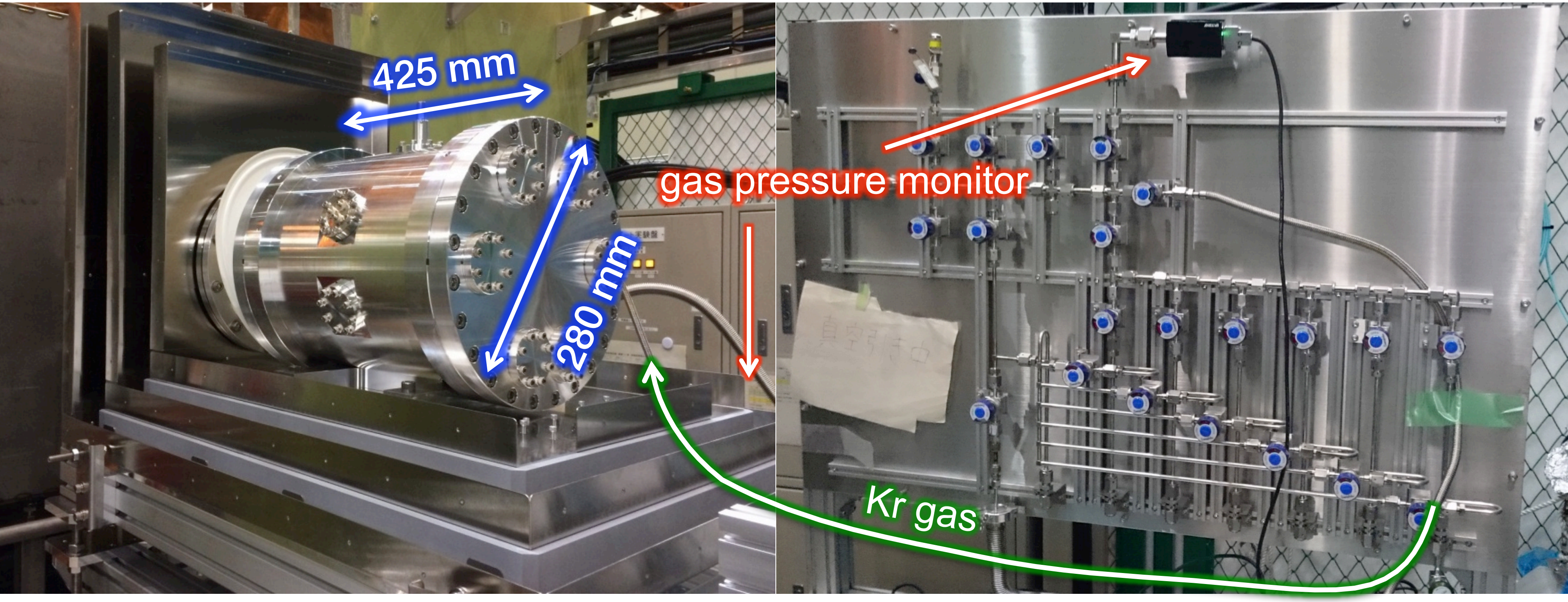


Key Components

for the ZF experiment

- Kr gas chamber and gas handling system
- Permalloy magnetic shield
- Probe for static magnetic field measurement
- Positron detector
- Systematic error study

Gas Handling System



- Gas chamber: 425 mm length, 280 mm diameter, 100 μm Al beam window
- Gas pressure is monitored by a capacitance gauge
- Gas purity is measured by Q-Mass spectrometer

Magnetic Shield and Field Probe

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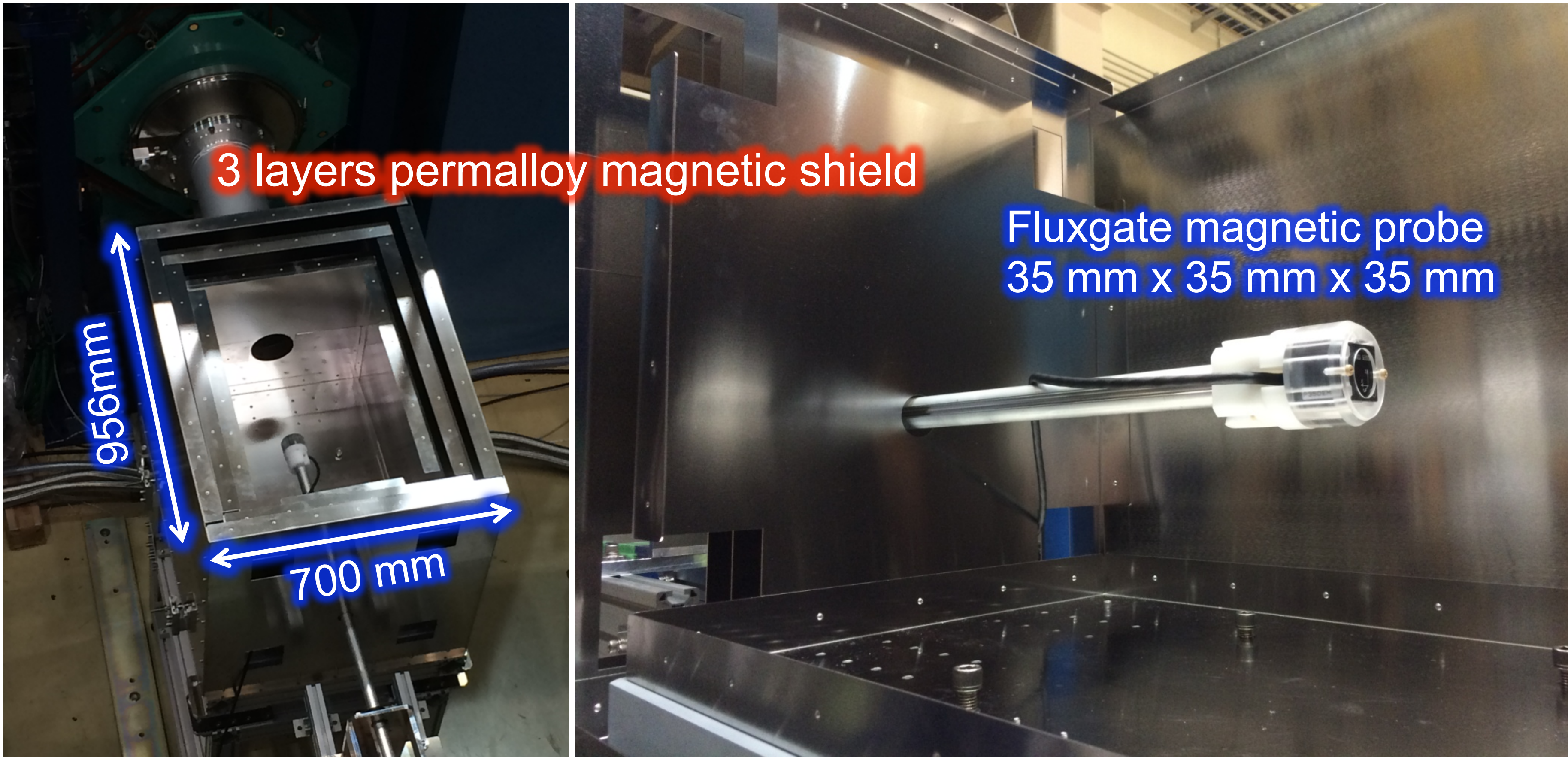

- Magnetic field near beam center area can be measured by the field probe and its moving system
- Good “zero” field condition (~100 nT) was obtained

RF Cavity

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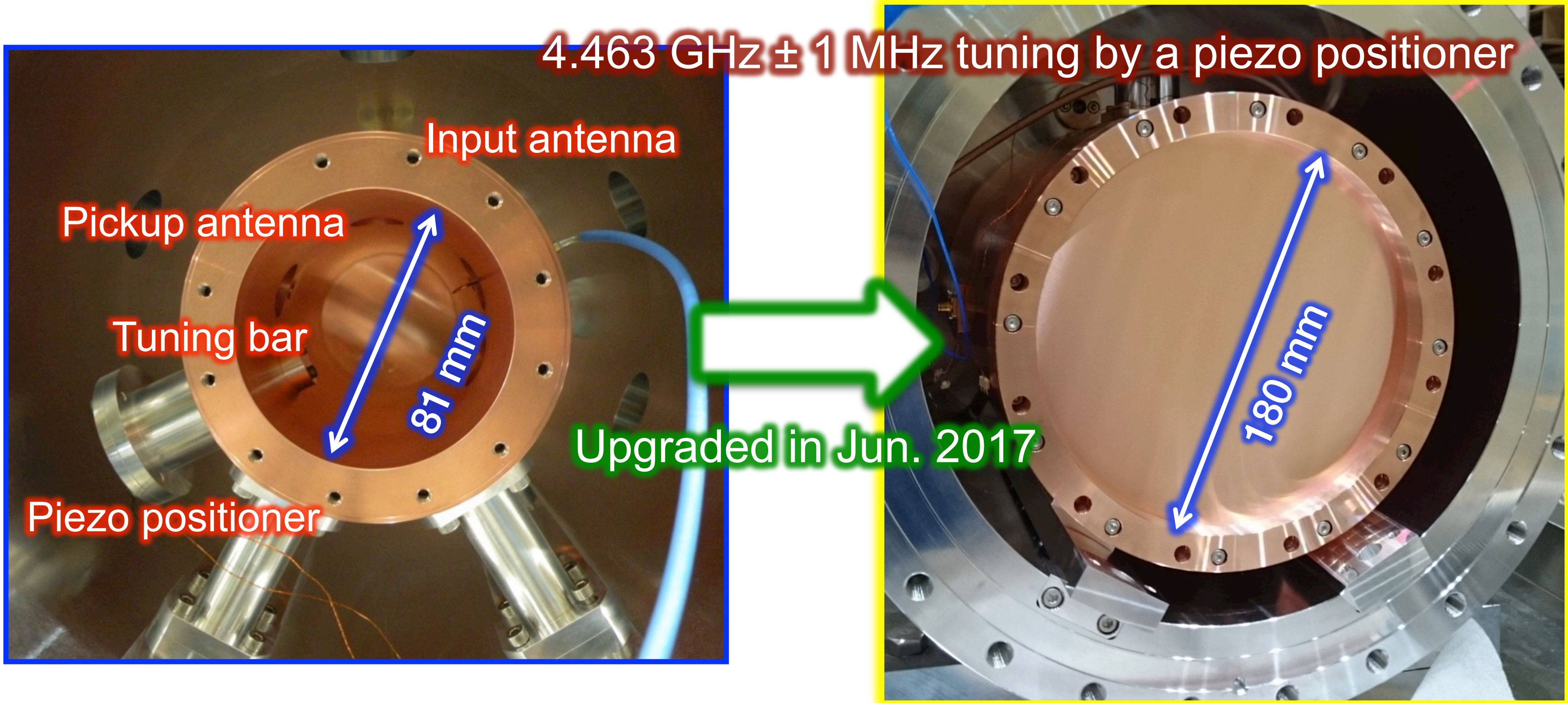
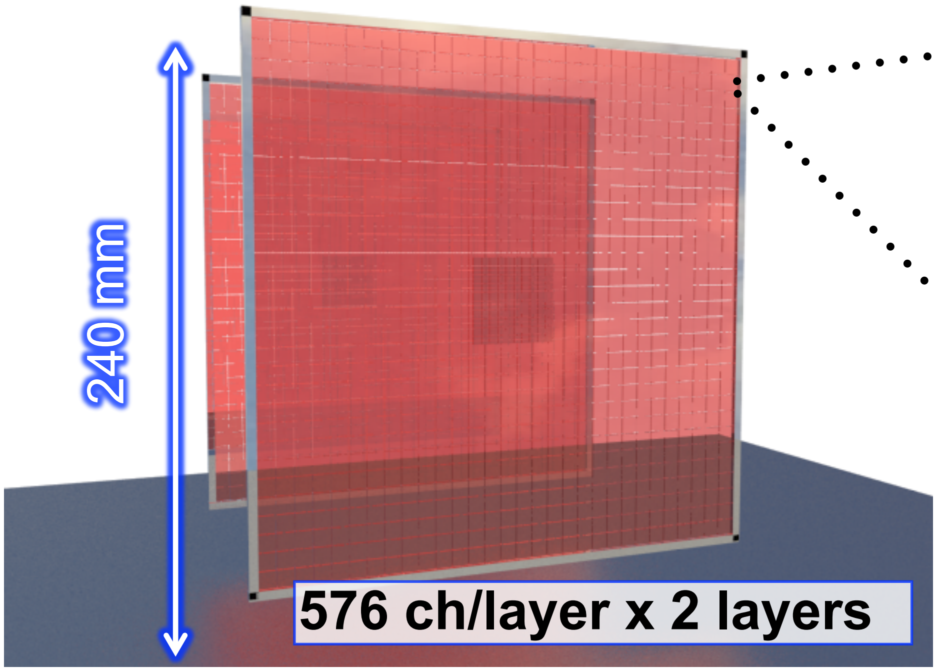
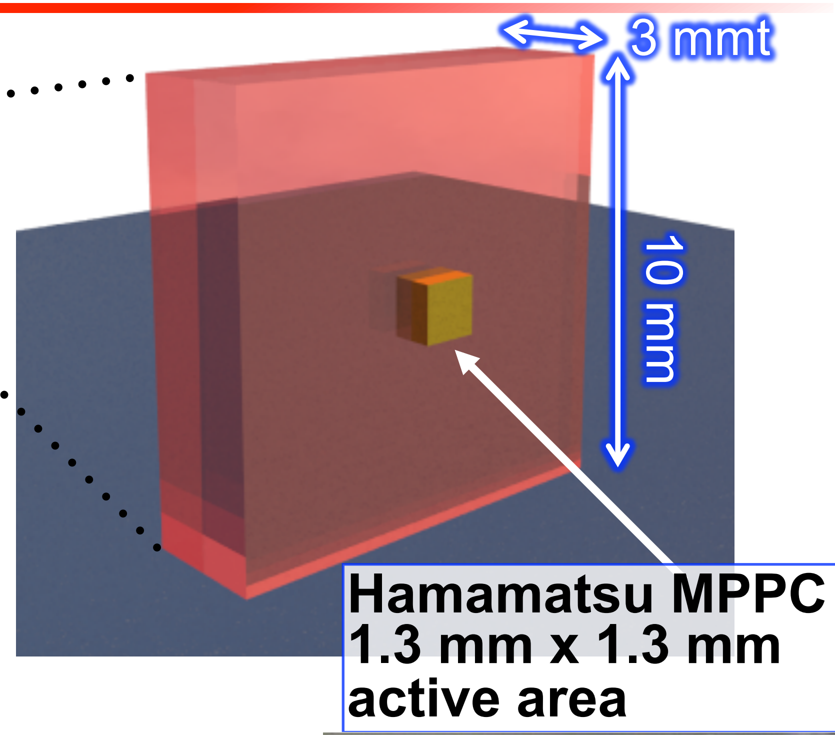


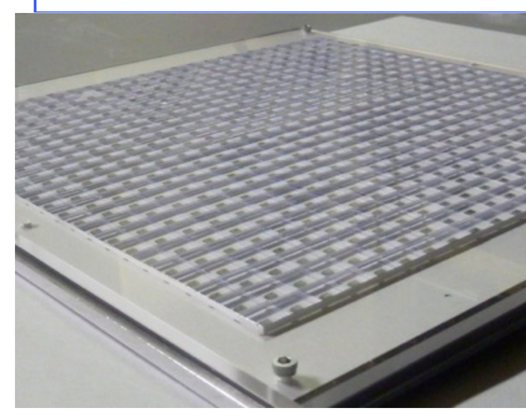
- TM110 Cavity
  - Easy handling
  - Expected Q-value is 10,000
  - Input microwave power is up to 3 W
  - Many muons go outside of the cavity
- TM220 Cavity
  - Larger than TM110
  - More muons stop in the cavity
  - Expected Q-value is 20,000

Segmented Positron Counter





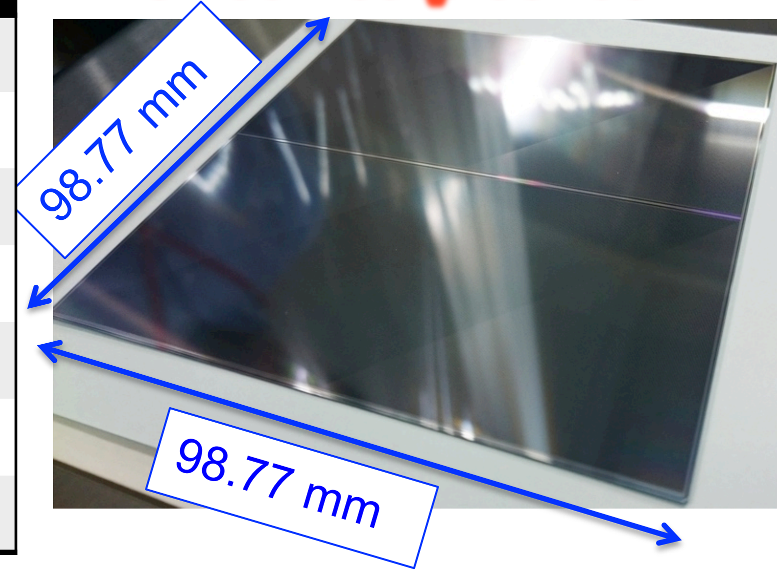
- Segmented scintillation counter with SiPM readout
- Unit cell is 10 mm×10 mm× 3 mmt
- 240 mm× 240 mm area, 1152 ch in total
- High rate capability is required (100 M muon/sec/ch at 1MW)

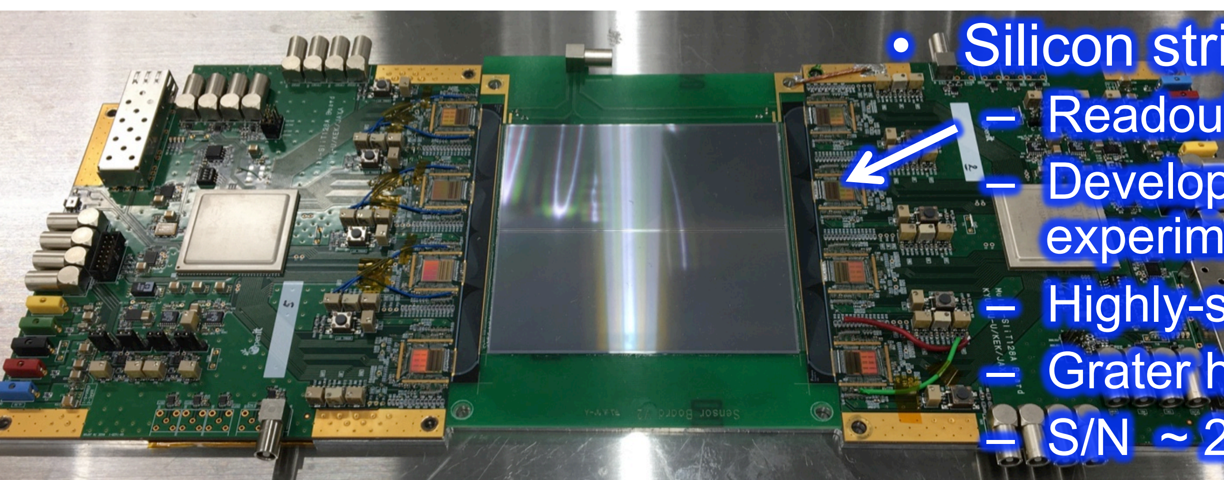


Silicon Strip Detector

Item	Specification
Sensor type	single-sided, p+ on n
Size	98.77 mm × 98.77 mm
Active area	97.28 mm × 97.28 mm
Strip pitch	0.19 mm
Strip length	48.575 mm
# of strips	512 × 2 blocks
Thickness	0.32 mm

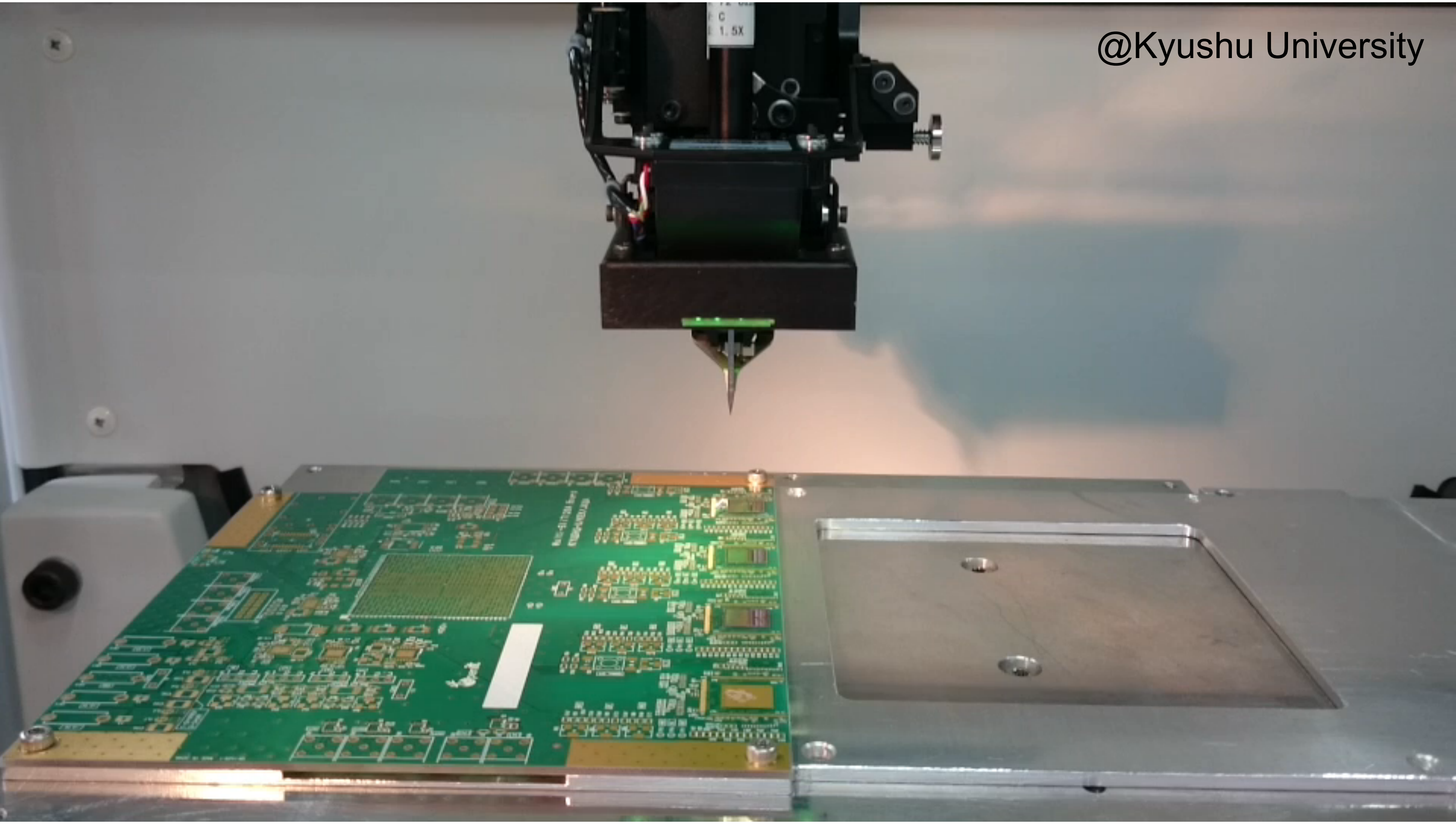
Silicon strip sensor





- Silicon strip detector
  - Readout chips (SliT128A, 128 ch/chip)
  - Developed for J-PARC g−2/EDM experiment
  - Highly-segmented
  - Grater high rate capability
  - S/N ~ 21

Wire Bonding



1^{st} and 2^{nd} Resonance Search

2016. June. 3 (24h)
Beam profile measurement

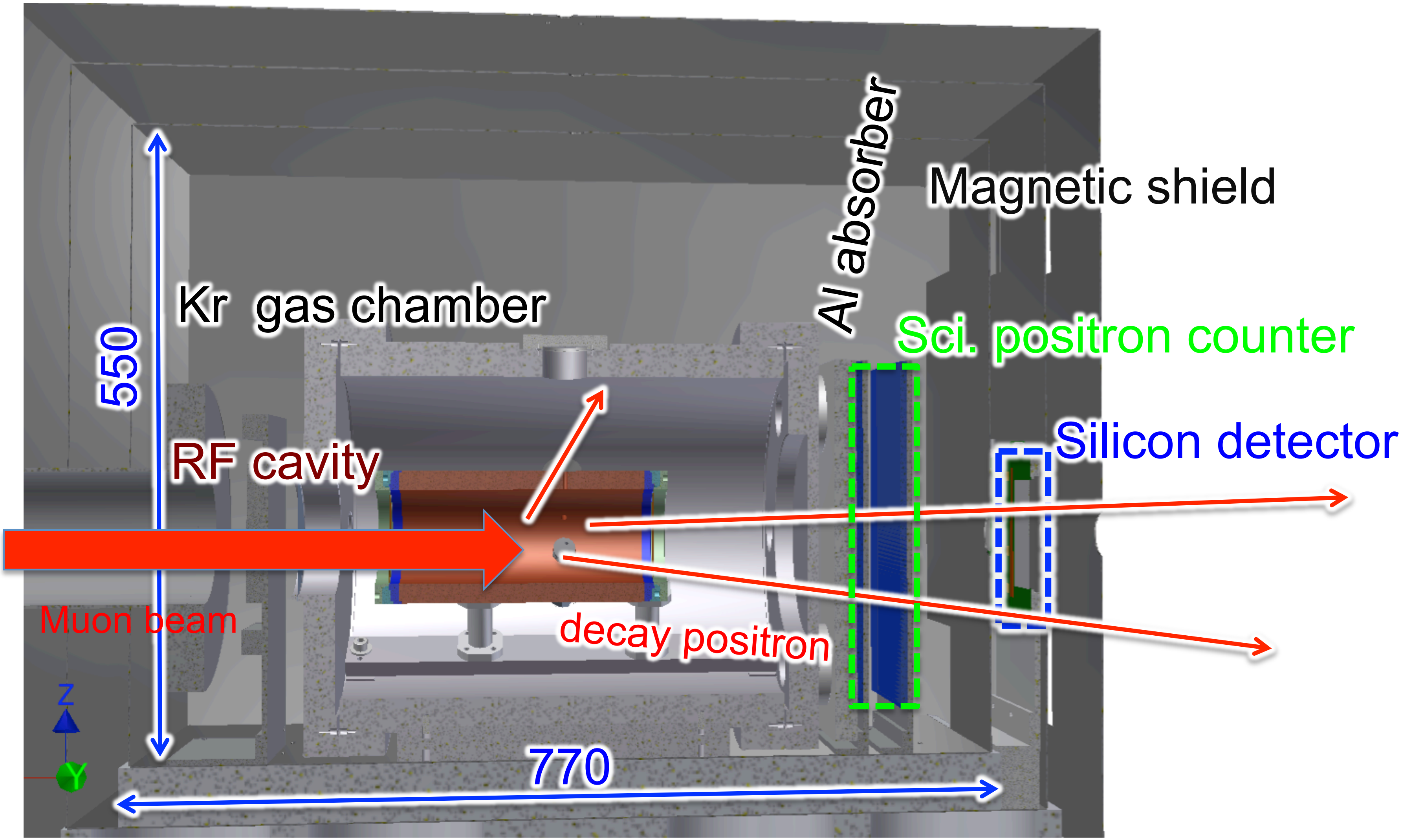
2016. June. 12-14 (60h)
1^{st} Muonium Resonance Search

2017. Feb. 1-4 (96h)
2^{nd} Muonium Resonance Search

- Beam profile was successfully measured
- Enough RF power and cavity Q value were obtained
- All detectors were working properly
- Muonium HFS resonances was obtained

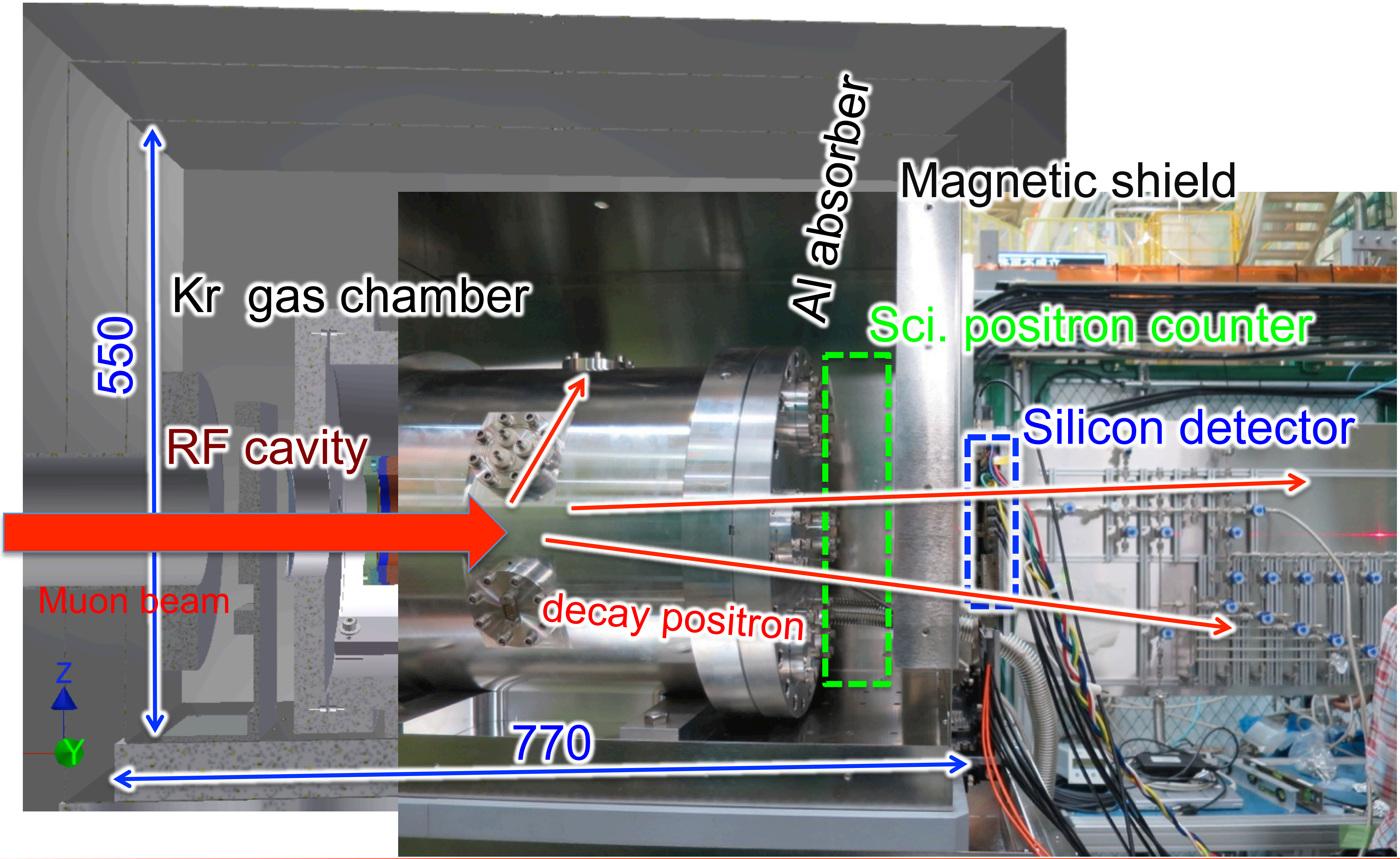
1st and 2nd Resonance Search

MuSEUM



1st and 2nd Resonance Search

MuSEUM



1st Results of Mu Spin Flip Signal

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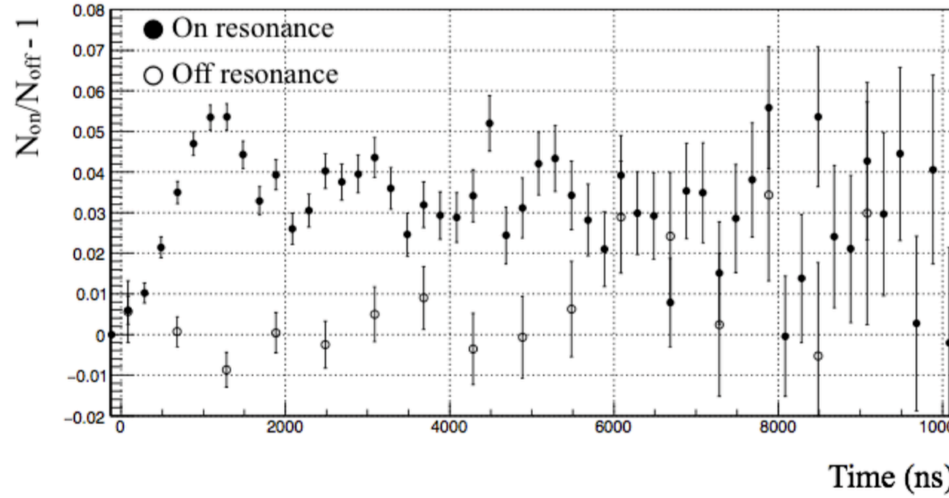
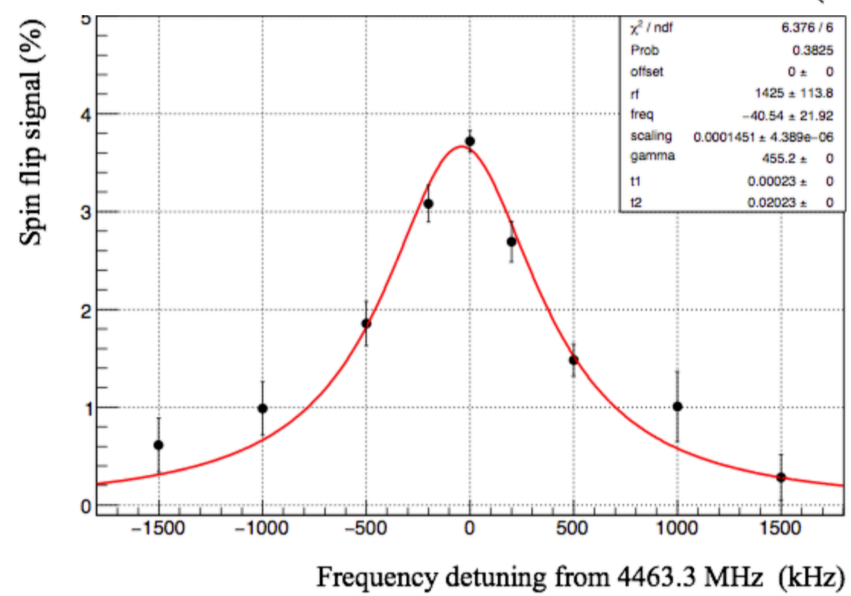
Time dependent spin flip signal
Near at Resonance
4463.3 MHz
RF frequency
1.0 Kr atm
27.4 MeV/c muon



- **Resonance lineshape**
  - HFS resonance was observed
  - Fitted by Lorenzian and freq. center was 4463.26±0.02 MHz
  - Expectation from precursor experiments is 4463.27 MHz



S. Kanda for the MuSEUM Collaboration,
Proseedings of Science, PoS(INPC2016)170, In press

Systematic Error in ZF measurement

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Systematic uncertainties in ZF measurement

Source	Contribution (Hz)	Future upgrade (Hz)
Microwave power drift	26	3
Gas pressure extrapolation	66	7
Gas pressure fluctuation	6	0
Gas impurity	12	1.1
Muon beam intensity	0	0
Muon beam profile	9.8	2.5
Static magnetic field	0	0
Detector pileup	2	2
Total	73	8.3

c.f.) Previous ZF exp. 1,400 Hz

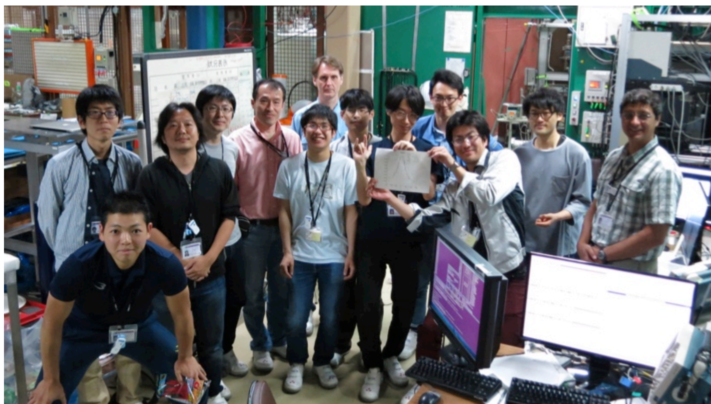
- Expected accuracy ~10 ppb if we have enough muons

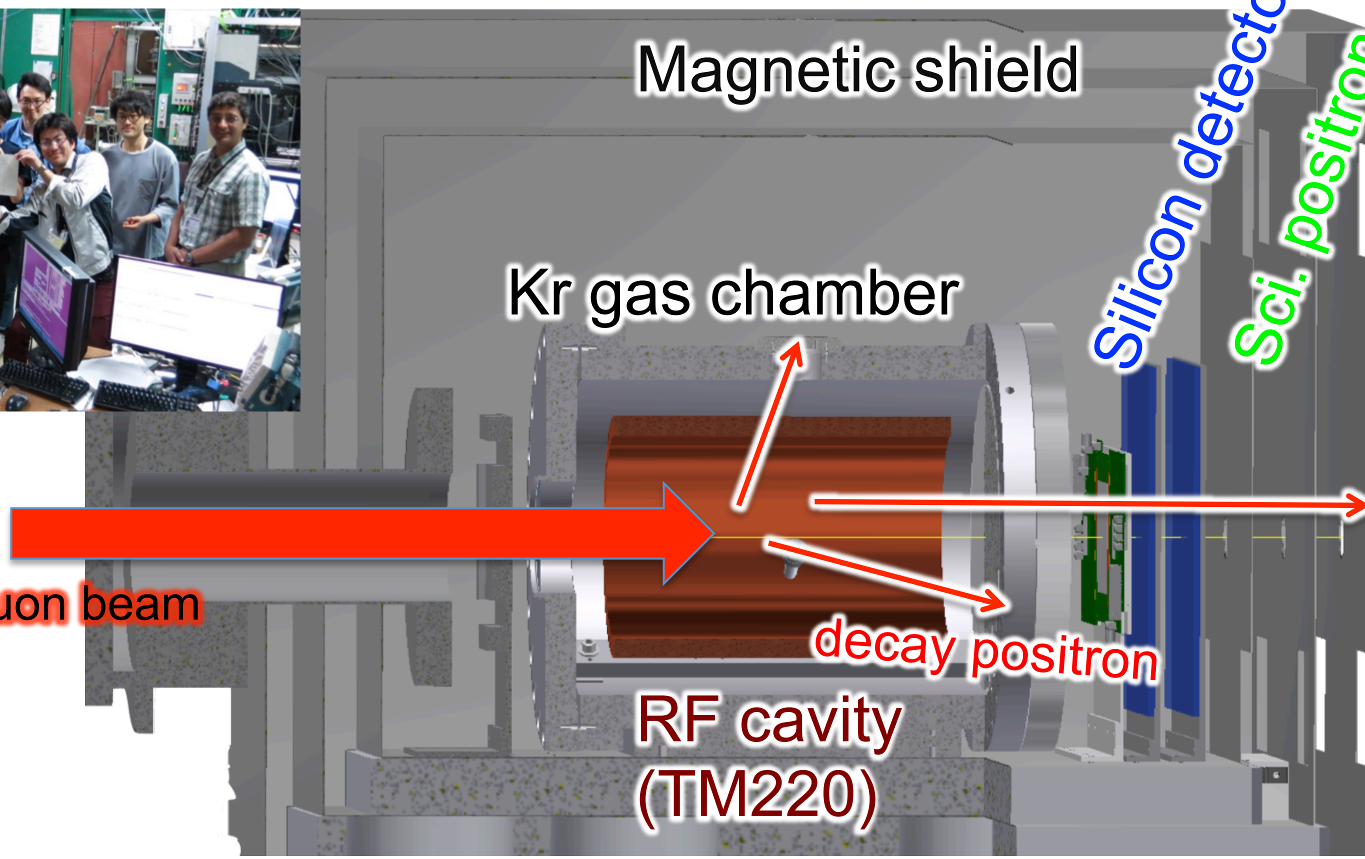
Experiment in Jun. 2017

MuSEUM

- Improvement
  - Large cavity (TM220)
  - Put Silicon Strip Detector at upper stream of Sci. detectors
  - Goal: Δν~1 kHz

2017. June. 13-19 (132h)
3rd Muonium Resonance Search





Experiment in Jun. 2017

MuSEUM

- Improvement
  - Large cavity (TM220)
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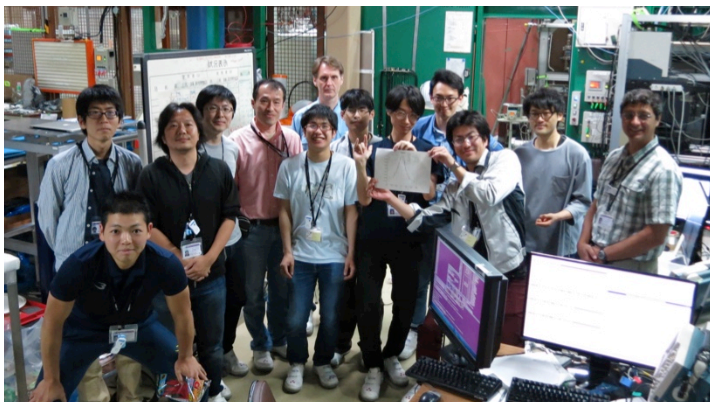
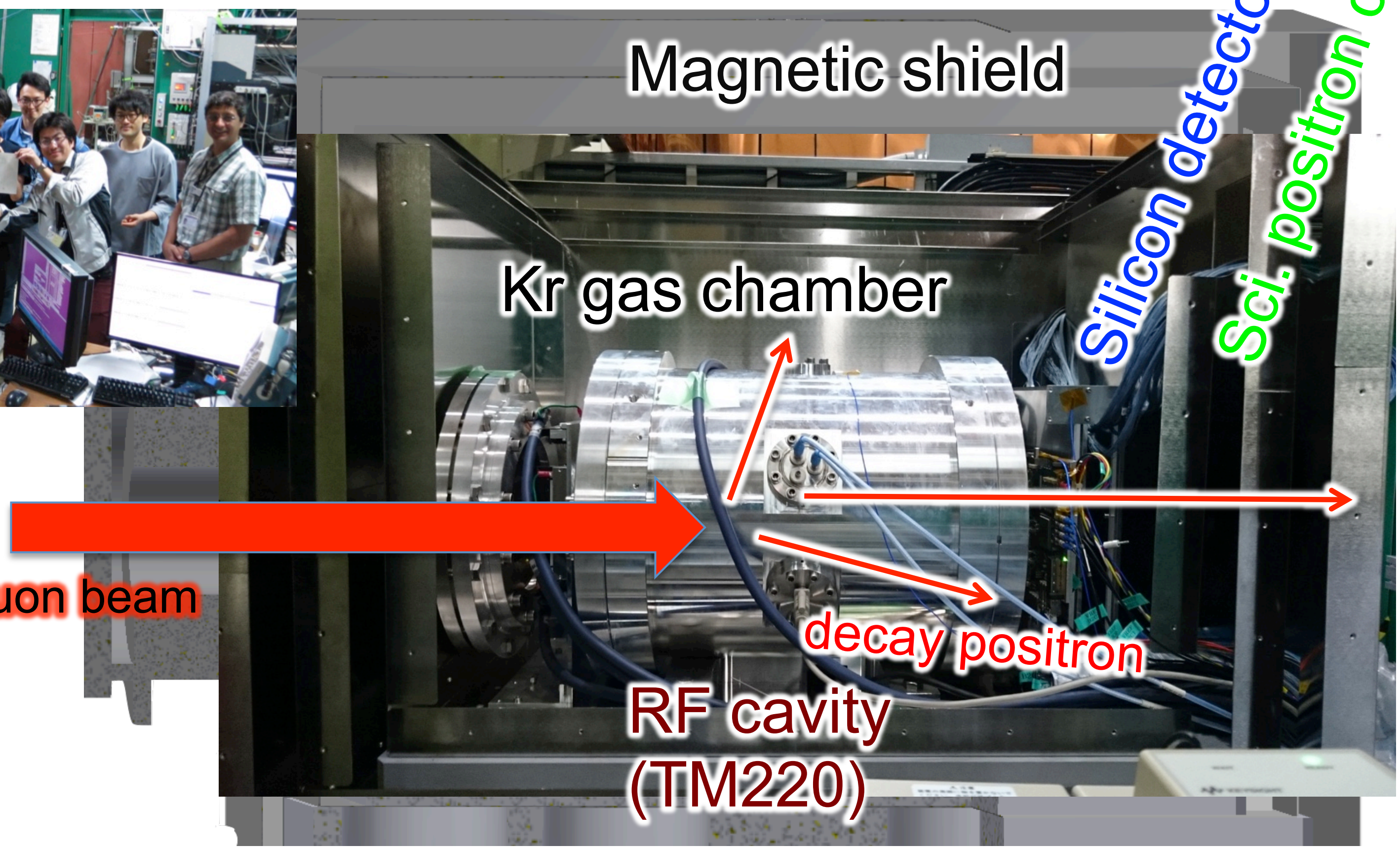
2017. June. 13-19 (132h)
3rd Muonium Resonance Search





Signal of Mu Spin Flip on Resonance

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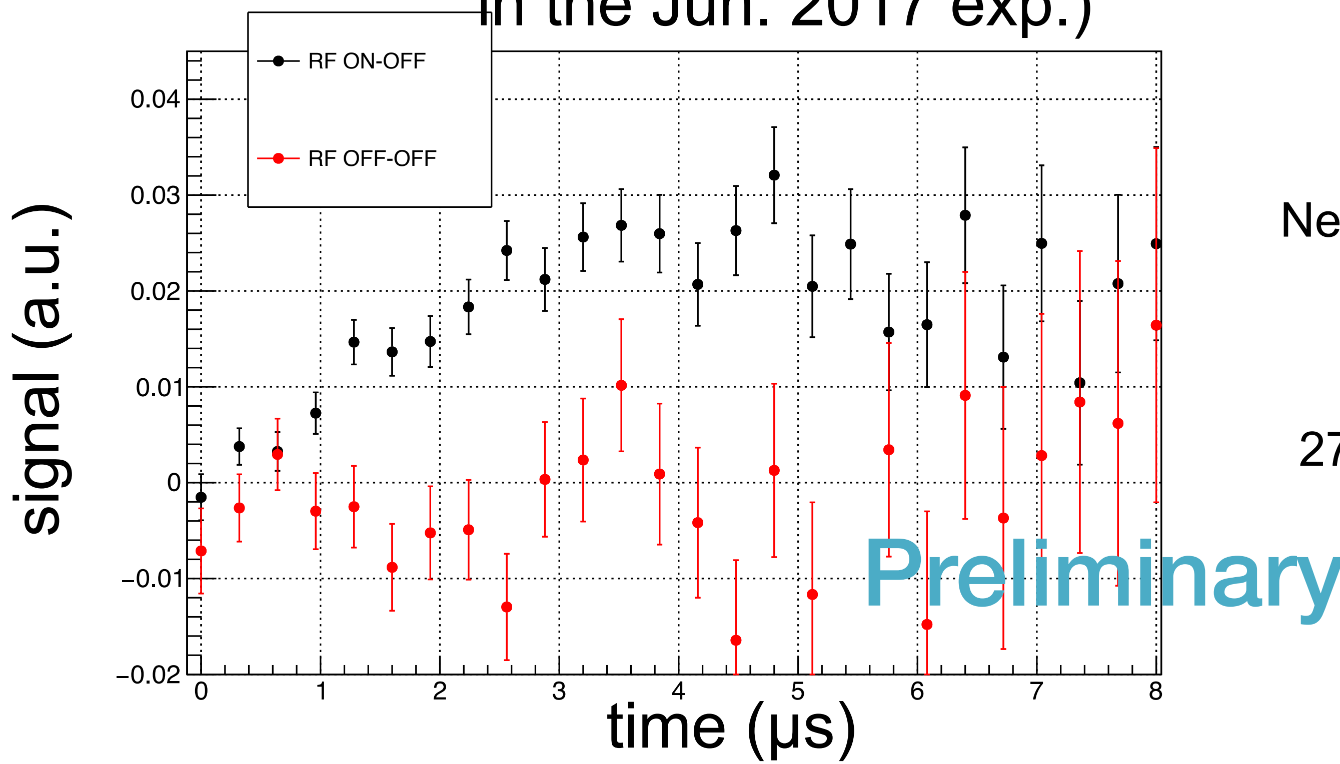
On resonance, time dependent signal
(part of data detected by silicon detector
in the Jun. 2017 exp.)

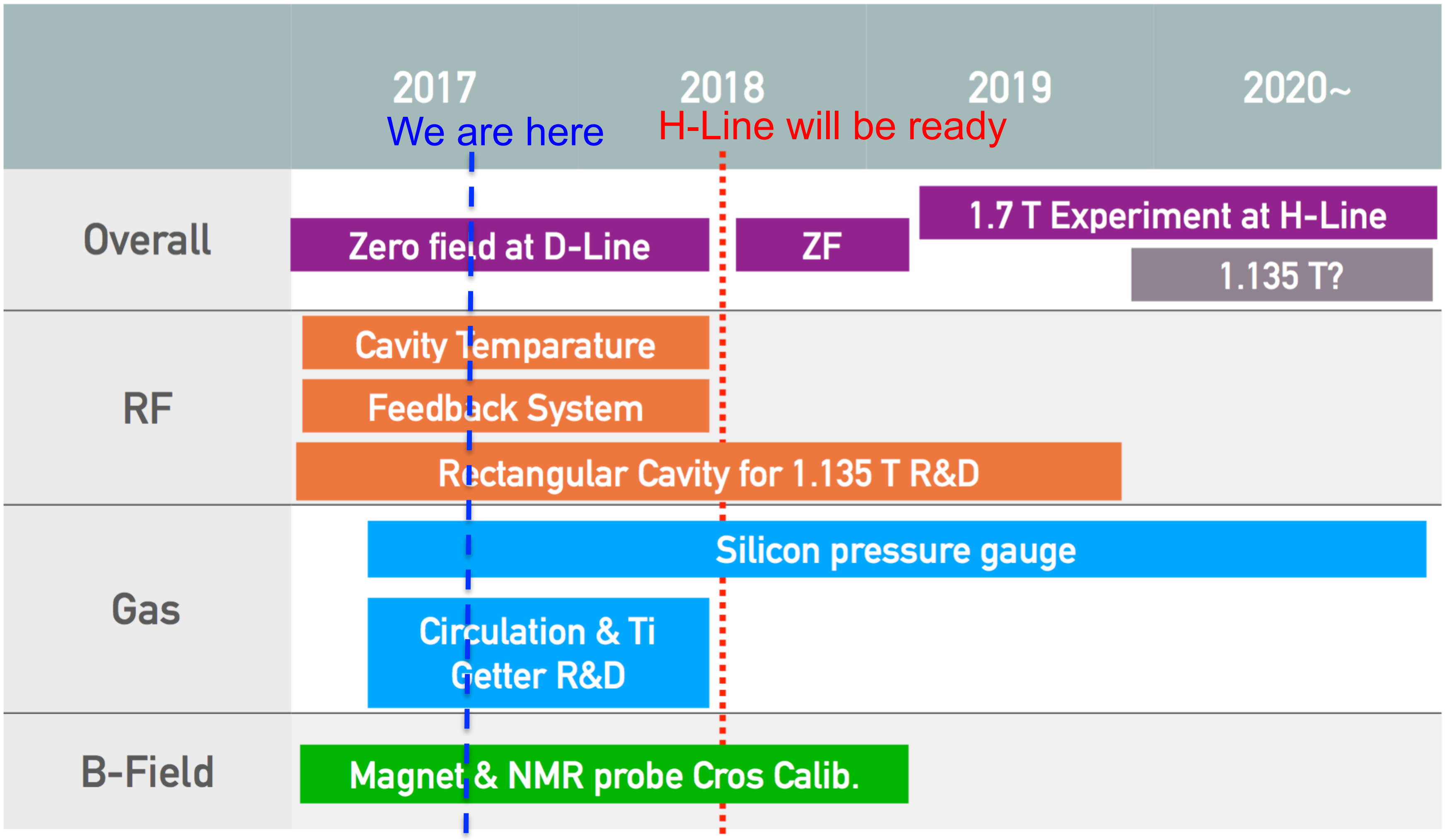


Near at Resonance
4463.3 MHz
RF frequency
1.0 Kr atm
27.4 MeV/c muon

- Mu spin flip signal was observed
- Further analysis is in progress

Future plan

R&D for HF experiment from 2019 is in progress



Summary

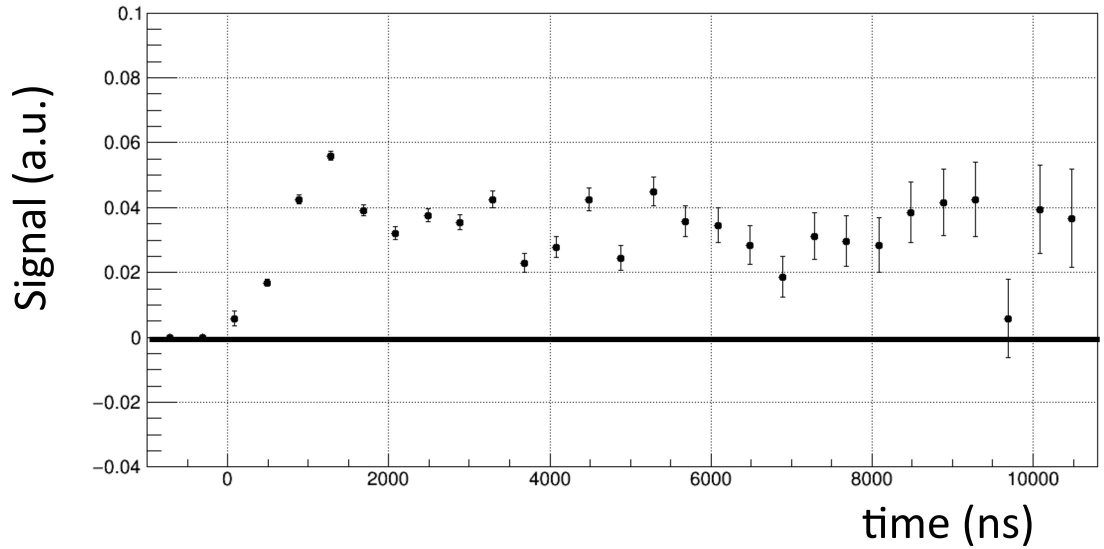
MuSEUM

- Muonium HFS measurement is one of the high sensitivity experiments for beyond SM physics
- Muonium HFS resonance was observed at 1.0 atm Kr gas pressure with 27.4 MeV/c muon beam
- Gas purity, B-field uniformity, and RF stability were good enough
- Data analysis of the 3rd time “zero” field experiment is in progress
- R&D for high field experiment is also ongoing
- High field measurement will start in 2019

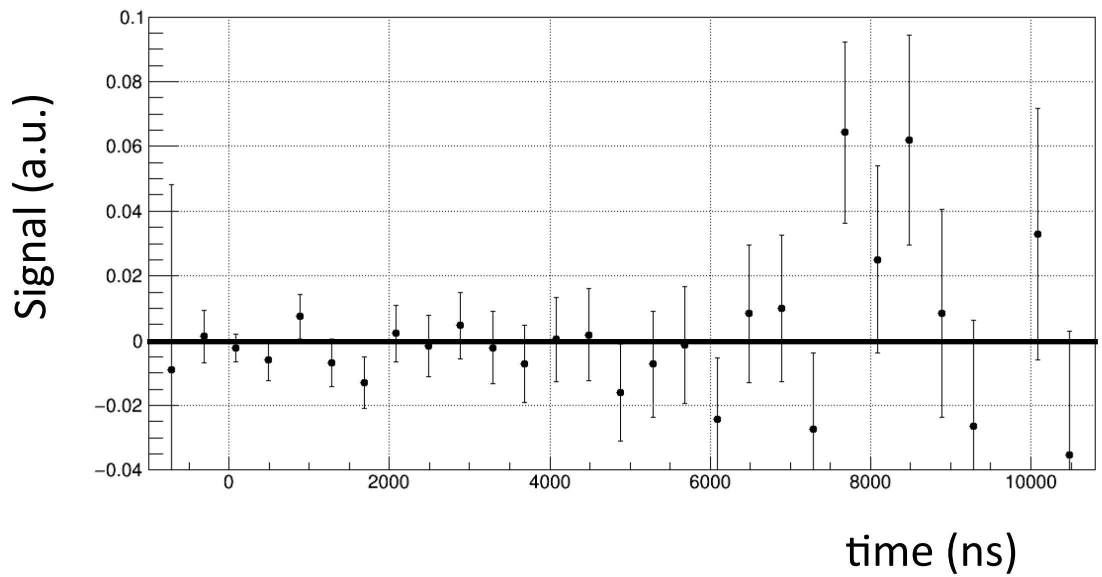
Other Slides

Time Dependent Spin Flip Signal

Near at Resonance
4463.1 MHz
RF frequency
1.0 Kr atm
27.4 MeV/c muon

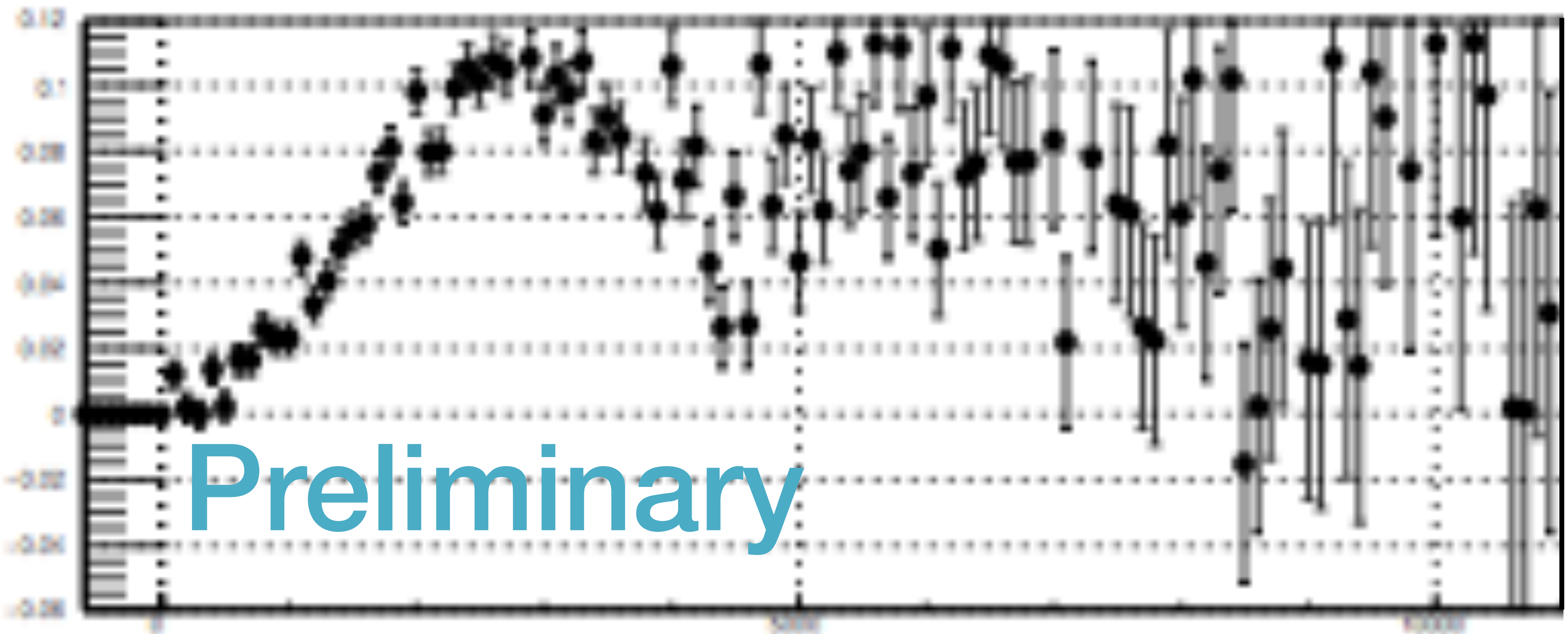


Off-Resonance
RF frequency was far detuned
1.0 Kr atm
27.4 MeV/c muon

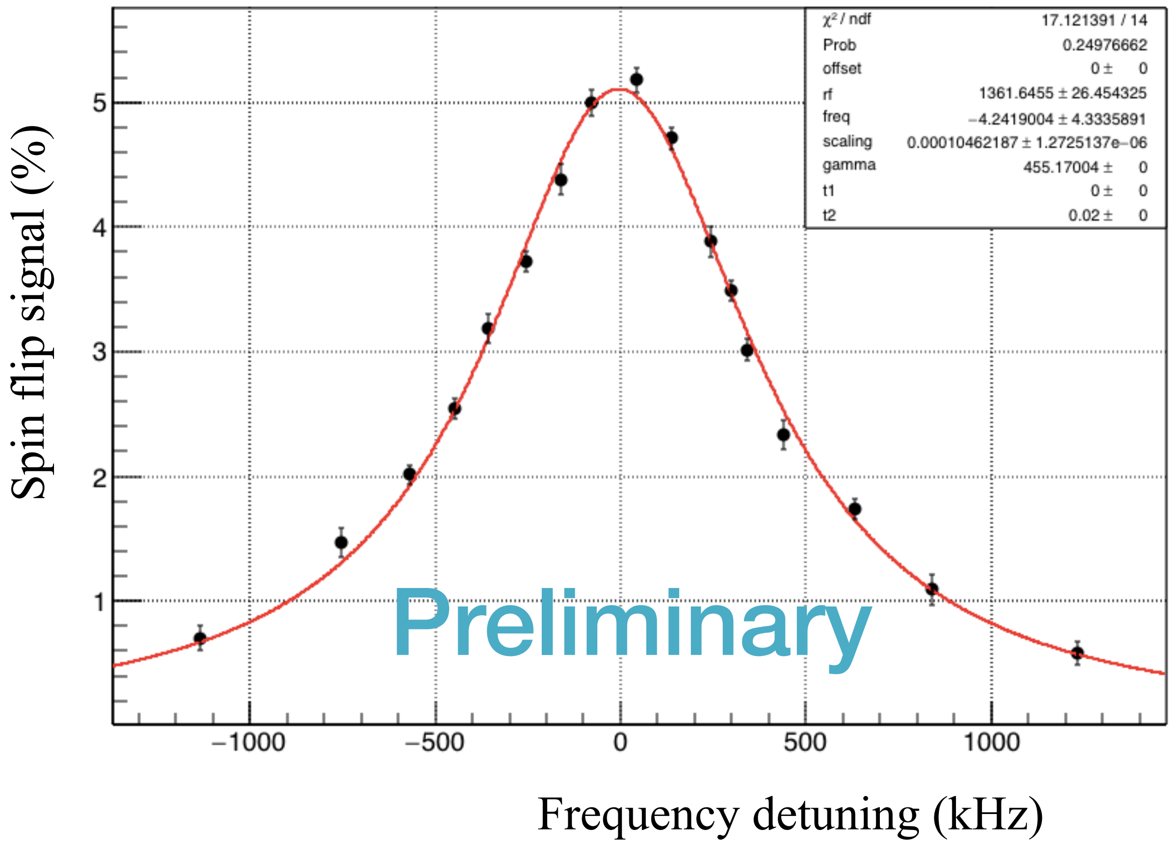


Signal = ON/OFF-1

On resonanse (2nd time)



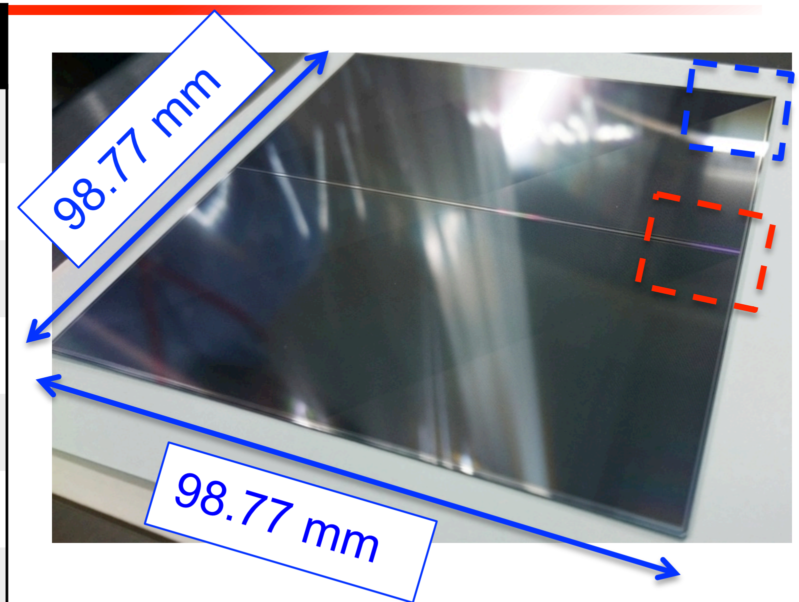
Resonance Lineshape (2017)

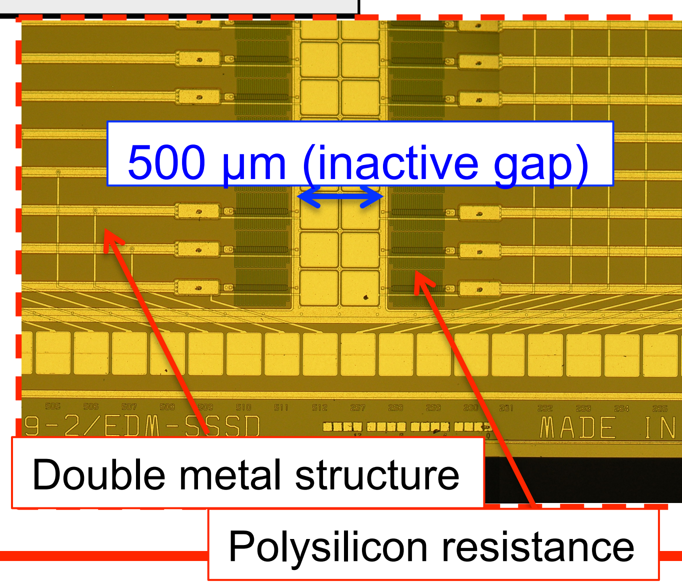


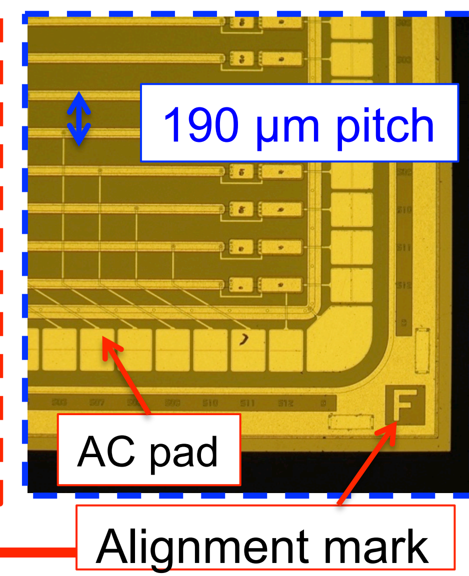
- Statistical uncertainty ~ 4 kHz (x5 improvement)
- Estimation of the systematic uncertainty is in progress

Silicon Strip Detector

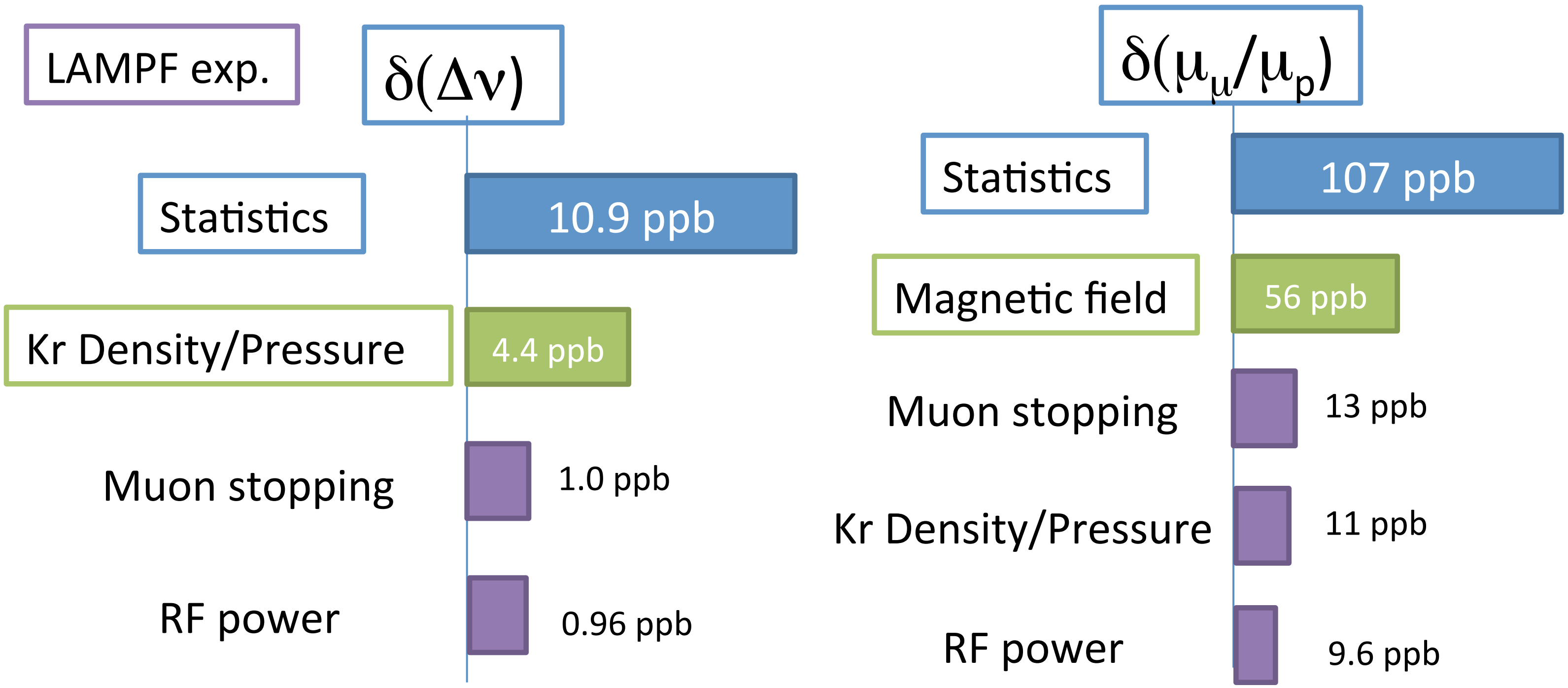
Item	Specification
Sensor type	p+ on n
Size	98.77 mm × 98.77 mm
Active area	97.28 mm × 97.28 mm
Strip pitch	0.19 mm
Strip length	48.575 mm
# of strips	512 × 2 blocks
Thickness	0.32 mm







Uncertainty of the previous measurement



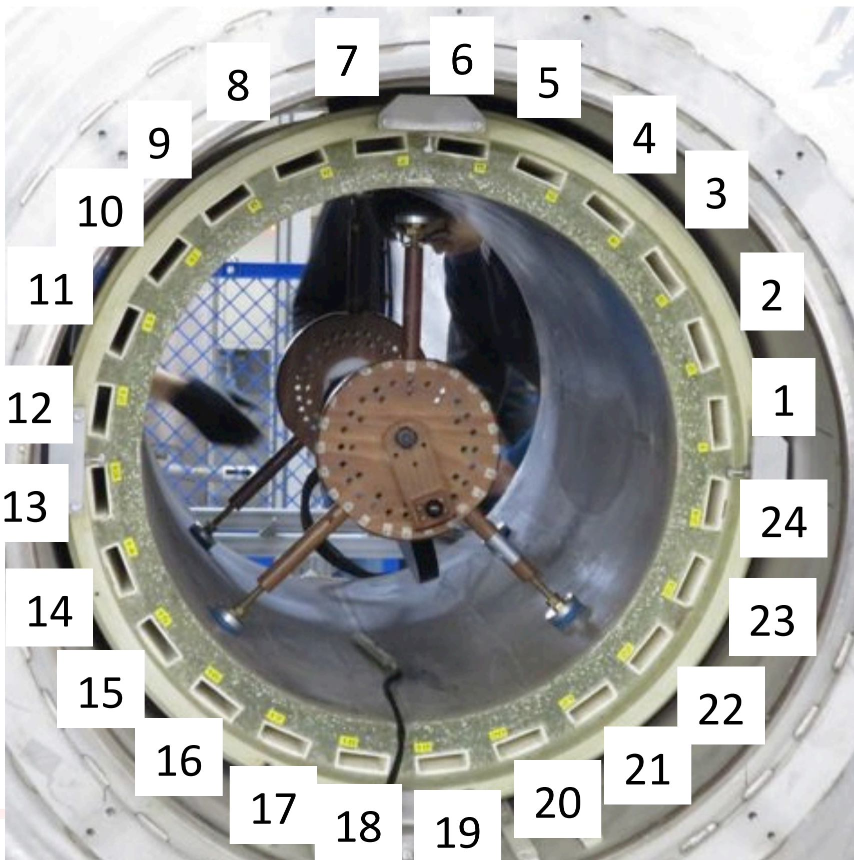
LAMPF DC 10^7 /s
total 10^{13}

x200

J-PARC/MUSE **Pulse 1x10^8** /s
H-Line total 2×10^{15}

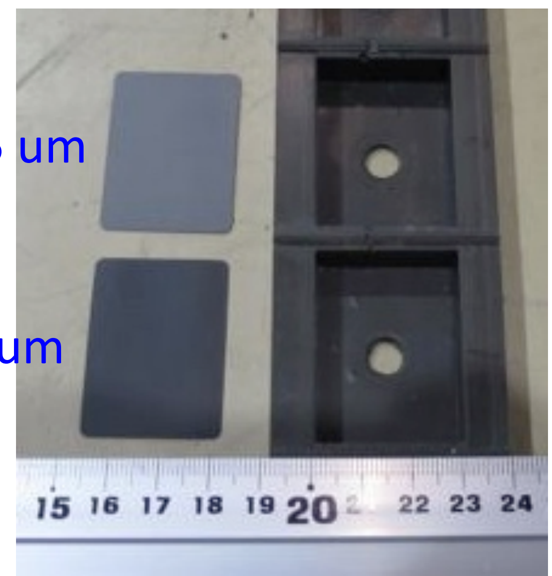
Shim tray, Iron piece

- 24 trays
  - 24 pockets per each tray (576 pockets in total)
- Iron piece
  - W 40 mm, D 30 mm
  - Thick and Thin piece (t : 25 μm, 5 μm)



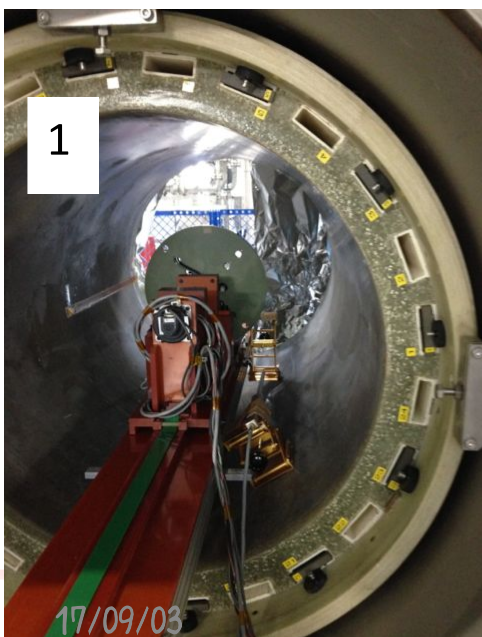
t 5 um

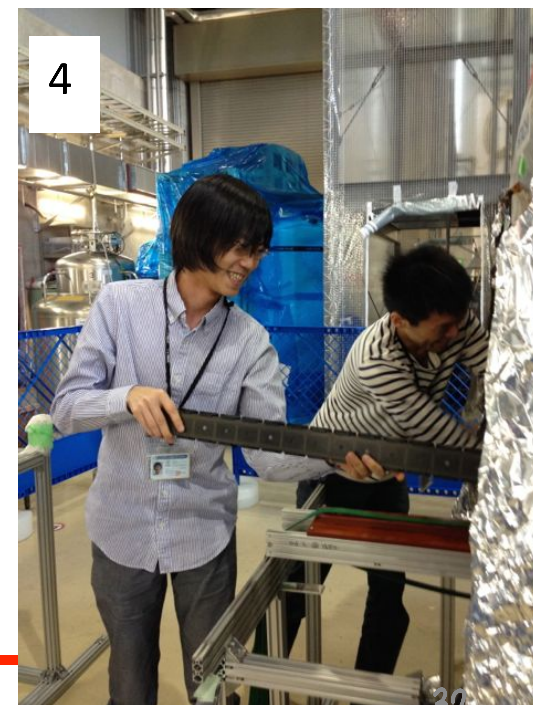
t 25 um



Shimming work

1. Measure magnetic field at 576 points (< 3 hour)
2. Calculate optimum arrangement of iron shim (< 1 hour)
3. Down magnetic field to Zero (~1 hour)
   – don’t need if small amount of iron piece would be installed
4. Put iron pieces into pockets according to calculation results (< 3-4 hours)
5. Excite magnet up to 1. 7 T (~ 1 hour)

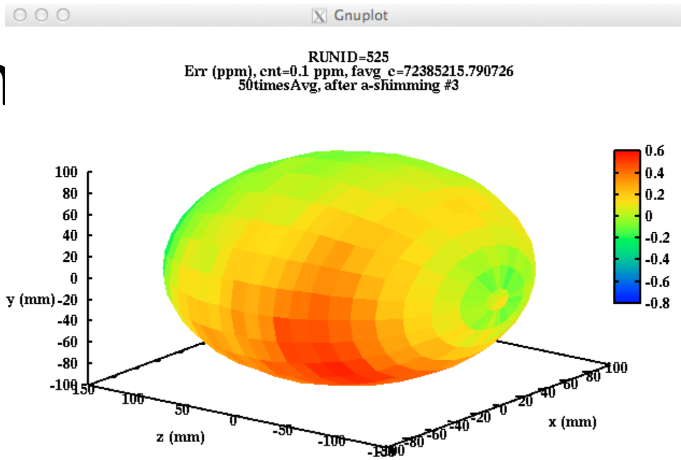


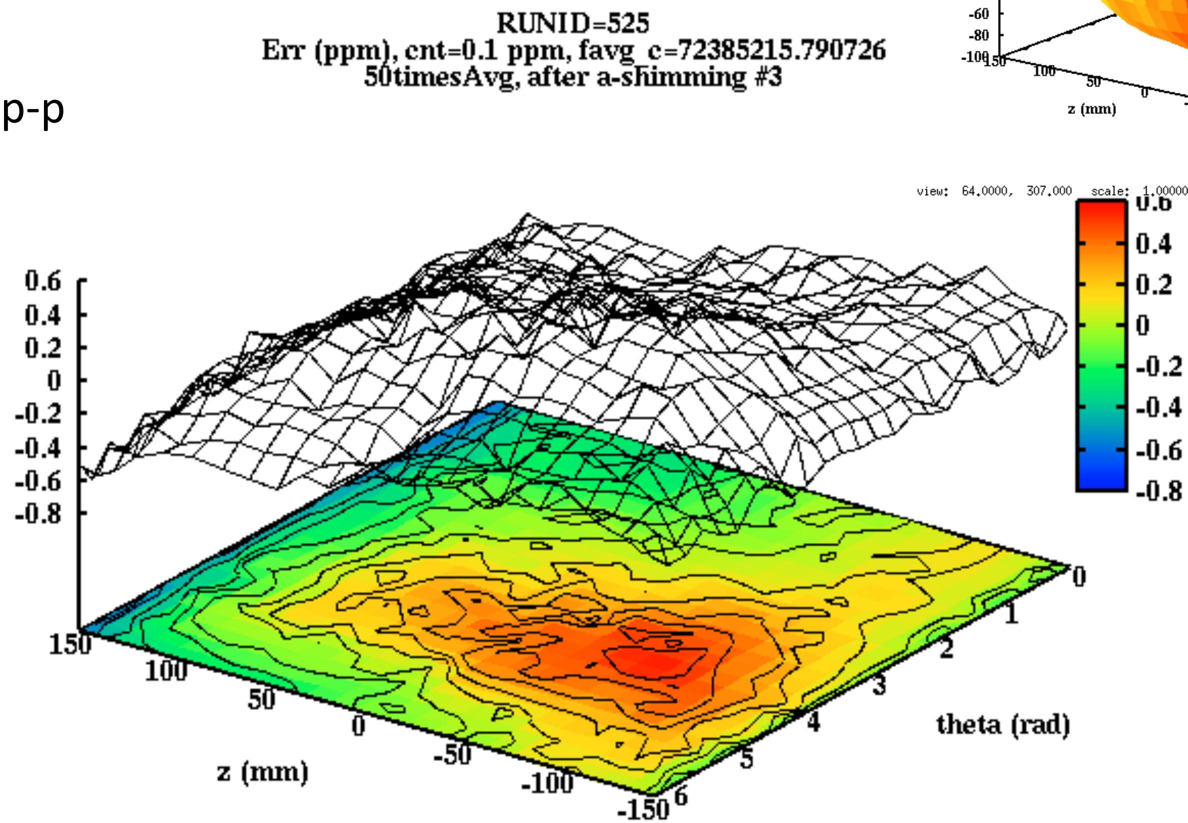


After shimming #3

- Measured by single probe system
  - Spheroid : r=100 mm, z=300 mm

1.4 ppm p-p





NMR field monitoring system

$$\delta_t = \sigma(H_2O) + \delta_b + \delta_p + \delta_s + \delta_e$$

- Analog process + Constant RF
  - Offset caused by voltage threshold
  - Variation of modulation coil field
  - Fluctuation of measured value by circuit noise

- Digital process + RF tuning
  - improve S/N ratio and minimize offset by data-fitting process
  - minimize variation of modulation coil

DAQ process