New Precise Measurement of Muonium Hyperfine Structure at J-PARC

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MuSEUM

Muonium is the bound state of a positive muon and an electron and it is free from the finite-size effect of nucleons, thus the theoretical value of muonium hyperfine splitting(MuHFS) can be detemined precisely[1].
MuSEUM (**Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave) aim **ten-fold improvement of the preceding measurement of MuHFS** both at zero magnetic field(uncertainty: 1.4 kHz)[2] and in high magnetic field(51 Hz)[3].
There are **three major motivation** of this new precise measurement of MuHFS:

1. **Test of bound-state QED(Quantum Electrodynamics)**
2. **Determination of muon mass (and muon magnetic moment)**
3. **Test of CPT and Lorentz invariance**[4]

Fig. 1 illustrates the experimental set up of MuSEUM experiment. Polarized muons are injected into Kr gas and they form muoniums in the gas. RF field induces the HFS resonance and the spin flip of the muon, which is detected by measureing the positron assymmetry.

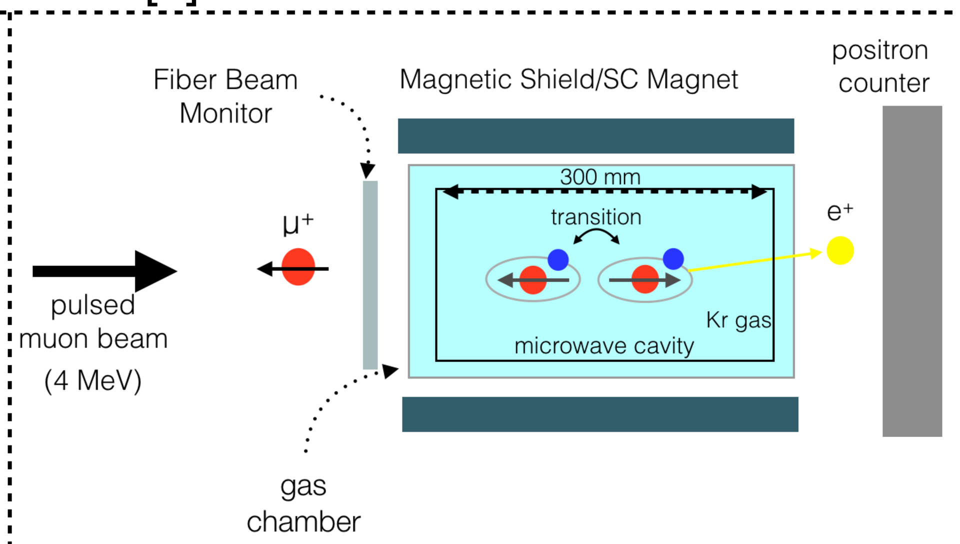


Fig. 1: Schematic drawing of the experimental procedure

RF System

To induce the transition, RF field with frequency 4.4 GHz is applied into the RF resonance cavity through an antenna(Fig. 2). The cavity resonance quality and the coupling of antenna were measured by a vector network analyzer. The typical Q value of the cavity is 12000. The resonance frequency is tuned by changing the position of the aluminum bar inserted in the cavity.
Another small antenna was utilized for picking up a small portion of RF power and monitoring the power stability. The fluctuation of RF power can distrort the resonance line and may shift the resonance center. **The systematic uncertainty from the power stability was evalueted to be 10 Hz**.

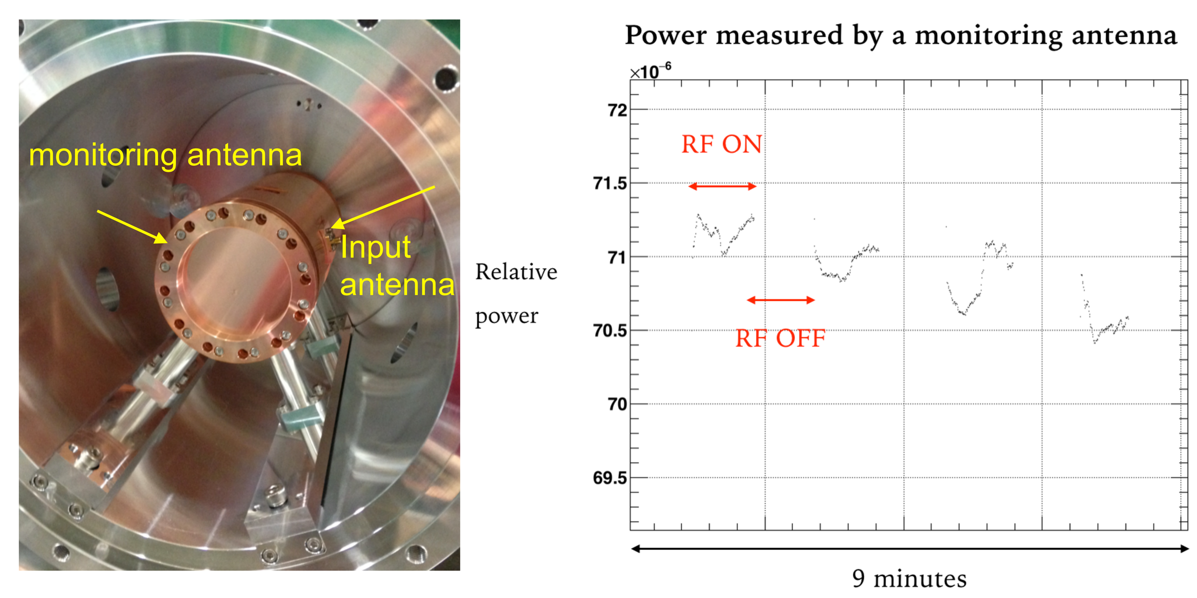


Fig. 2: The RF cavity and the monitored power. The power stability was monitored by a monitoring-dedicated small antenna. The monitored power is used for calibrating the resonance signal.

Magnetic Shield

Magnetic field is concerned beacause (1) the field may broaden the resonance line by the Zeeman effect and (2) the field may reduce the signal by rotating the muon spin in the gas chamber. The magnetic shield made of permalloy(Fig. 3) was employed to suppress the magnetic field. The field inside the RF cavity was measured using a flux-gate probe(Fig. 4) and the field is less than 100 nT. **The resonance broadening** caused by the 100 nT field **is less than 10 Hz**, and **the signal reduction** due to the spin rotation **is negligible**.

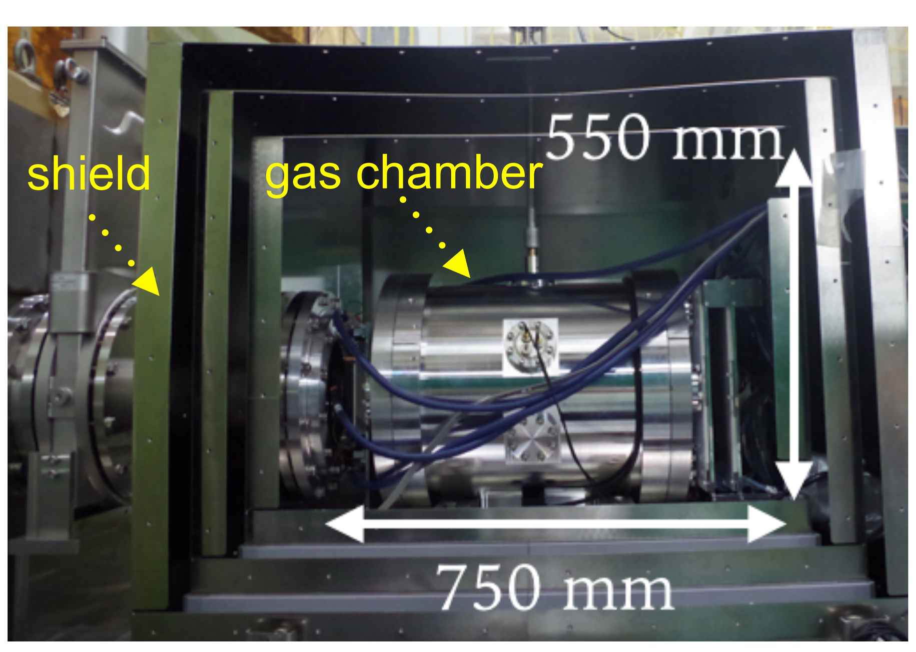


Fig. 3: Magnetic shield and the gas chamber. The shield is made of three layers of permalloy box.

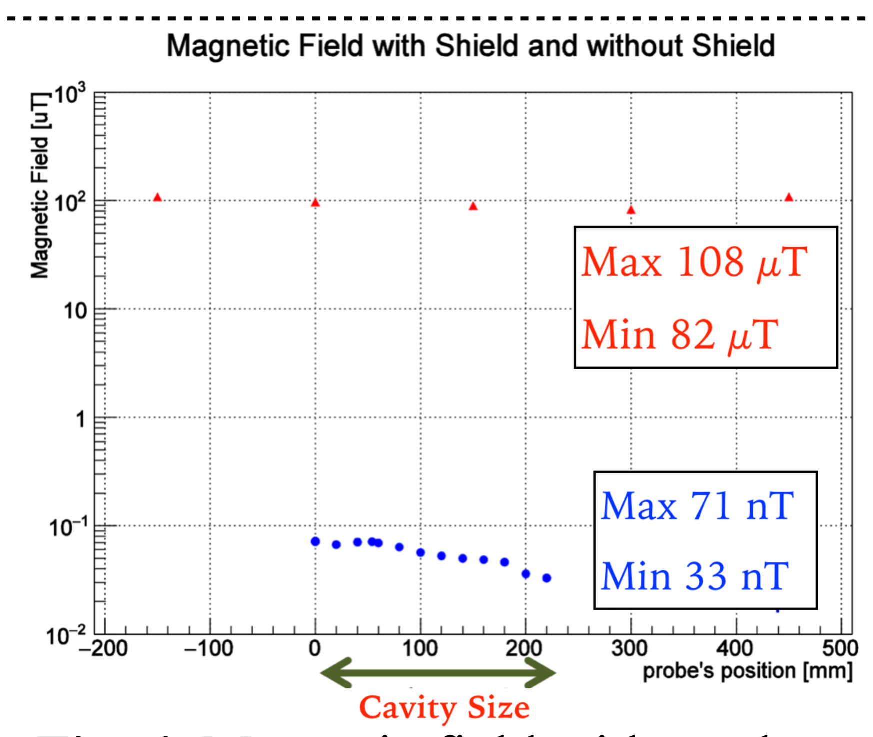


Fig. 4: Magnetic field without the magnetic shield(Red) and with the shield(Blue). The field is suppressed by a factor of 1000.

Other Apparatuses

MuSEUM have developed a 3D muon beam monitoring system called Target Beam Profile Monitor(TBPM) based on a beam monitor system for mu-SR[5]. Fig. 2 shows how TBPM measures the 3D distribution of muon. Typical 2D image of muon beam is also shown in the figure. The systematic unceretainties from the spatial distribution of RF field or static magnetic field were estimated based on the 3D muonium distribution. The latter is explained with the magnetic shield in the left box. **The uncertainty related to RF and Muonium distribution is 6 Hz**.

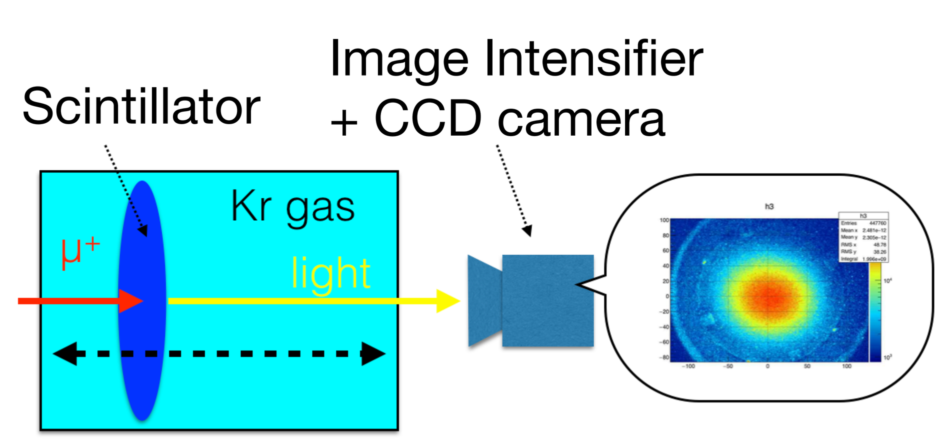


Fig. 5: Schematic drawing of the 3D muon beam profile monitor. Muons are stopped in a scintillator and the scintillation light is captured by a CCD camera as a cross-sectional 2D image. From the images with different scintillator positions, the longitudinal distribution of muon is obtained.

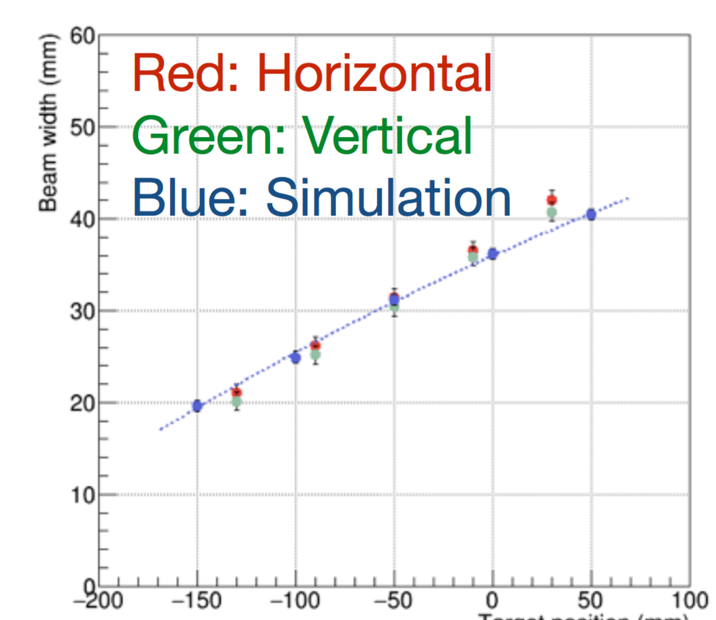


Fig. 6: The beam width measured by the beam monitor and simulated by MC. The measured values and simulated values are in good agreement.

Resonance Observed

During the beam time in June 2016, there was the difference of the signal with RF on-resonance and off-resonance(Fig. 7). Based on the data taken in 6 hours, **the resonance line was observed(Fig. 8)**. Further analysis is underway.
We anticipate that we can exceed the record with further data-taking (about 100 hours) since the systematic uncertainty is small enough (see summary section).

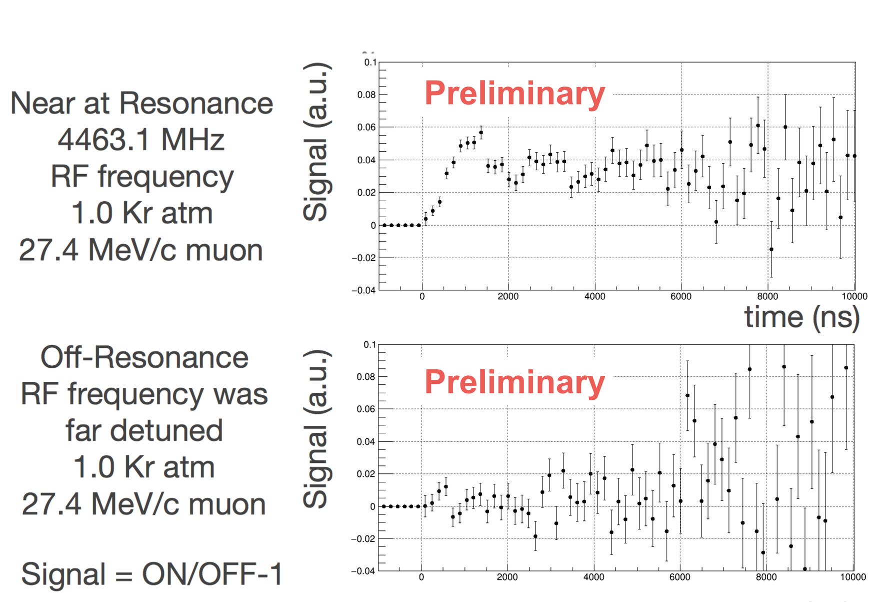


Fig. 7: The time-dependent signal with on-resonance RF(upper) and off-resonance RF(lower).

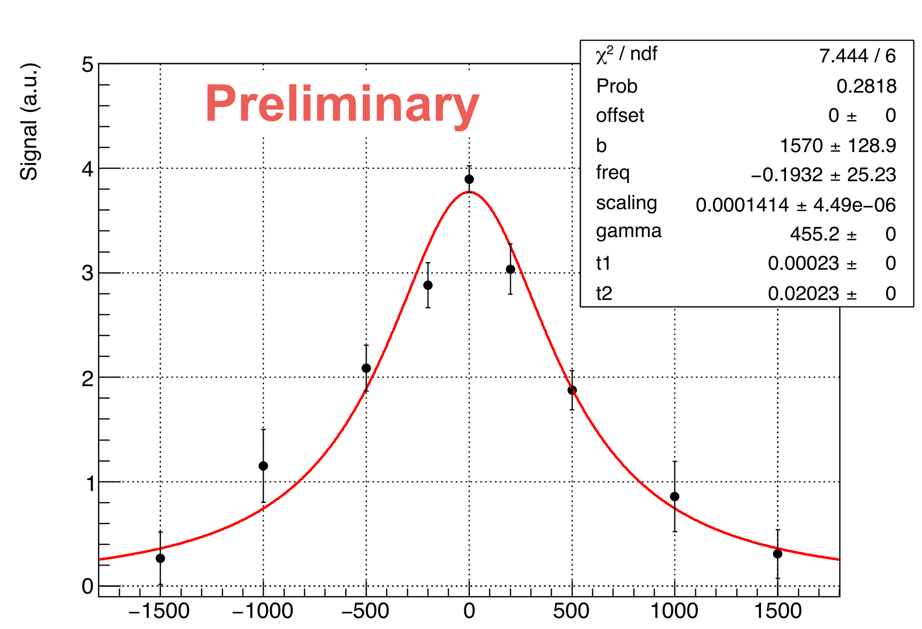


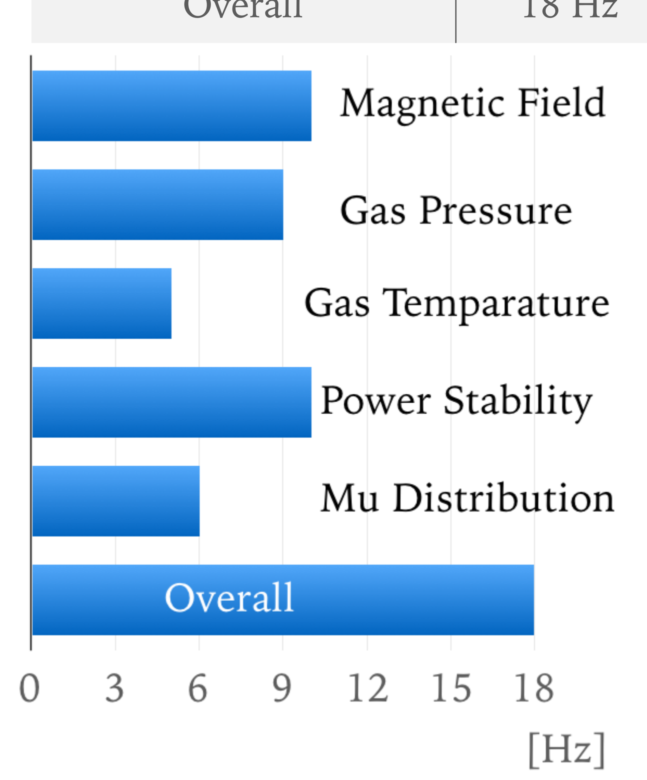
Fig. 8: The resonance signal from the data in 6 hours(Kr gas 1 atm). Further analysis is ongoing.

Summary

- **MuSEUM collaboration aim ten-fold improvement of the experimental value of MuHFS.**
- **First resonance signal was observed during the beam time in 2016 June.**
- **Analysis and evaluation of the systematic uncertainties are ongoing**
- **Preliminary systematic table is shown**
- **We expect further beam time in 2017**

Preliminary Uncertainty Table

Magnetic Field	10 Hz*
Gas Pressure	9 Hz
Gas Temparature	5 Hz
RF Power Stability	10 Hz
Muonium Distribution	6 Hz
Overall	18 Hz



[1]: D. Nomura and T. Teubner, Nucl. Phys. B 867 236 (2013)
[2]: D. E. Casperson, *et al*., Phys. Lett. 59B 4 (1975)
[3]: W. Liu, *et al*., PRL. 82, 711 (1999)
[4]: A. H. Gomes, *et al*., PRD 90 076009 (2014)
[5]: T. U. Ito, *et al*., NIM A 754 (2014)