Precision measurement of muonium hyperfine structure at J-PARC

2021/09/08 PANIC2021

Hiroki Tada (Nagoya University)
For MuSEUM collaboration

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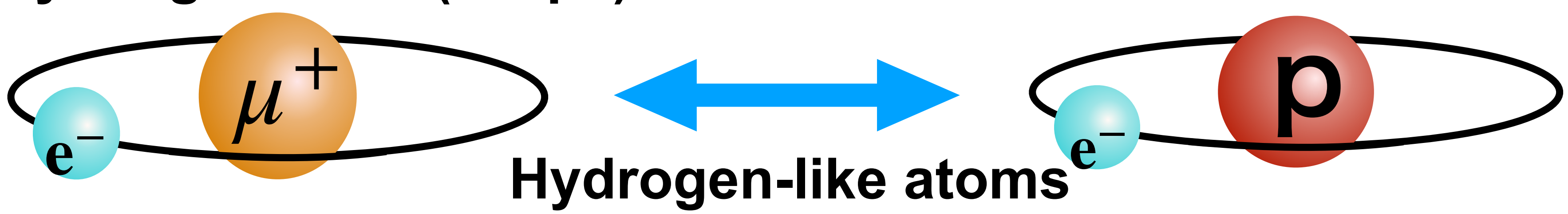
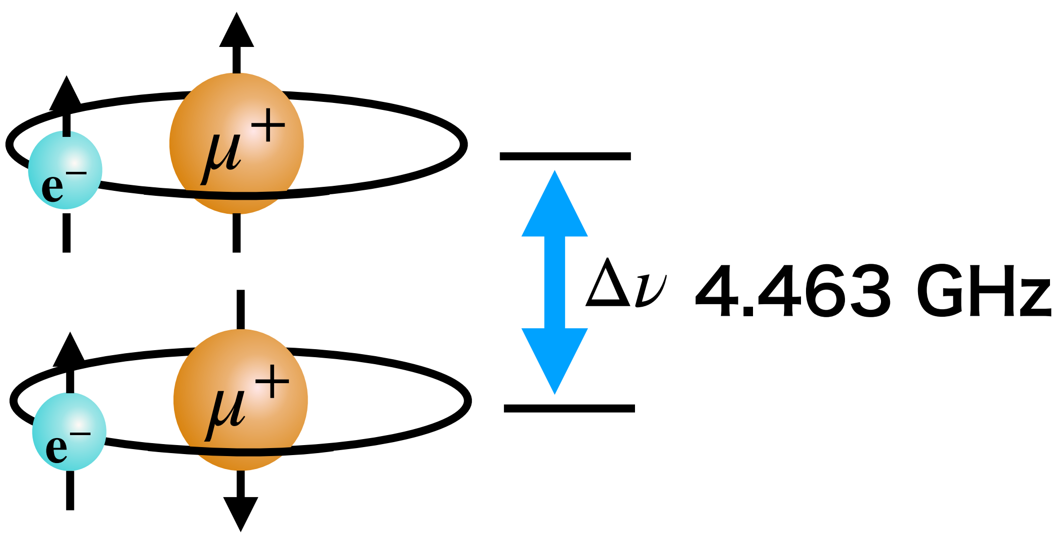
Muonium Hyperfine Structure

Muonium

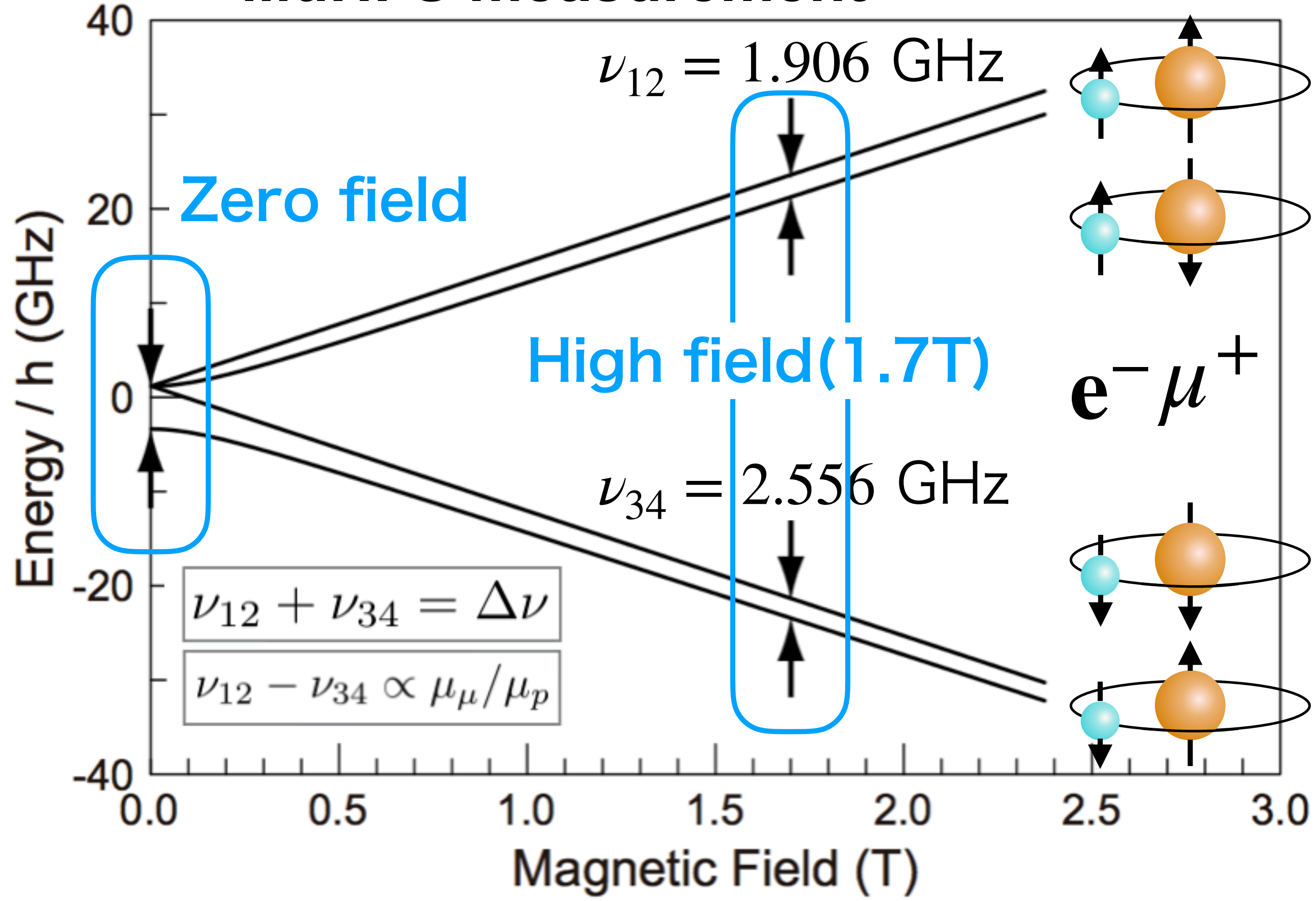
- **The bound state of μ^+ and e^-**
- **No internal structure**
- **Relatively long lifetime (2.2 μs)**



- **Muonium Hyperfine Structure (MuHFS: $\Delta\nu$)**



- **Two independent methods for the MuHFS measurement**



Goal of MuSEUM

- **Theoretical prediction**

$\Delta\nu^{th}_{HFS}$**=4 463 302 872(515) Hz (115 ppb)**

$$\Delta\nu^{th}_{HFS} = \frac{16}{3} Z^4 \alpha^2 c R_\infty \frac{m_e}{m_\mu} \left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \Delta\nu_{QED} + \Delta\nu_{QCD} + \Delta\nu_{weak}$$

$\Delta\nu_{QCD}$: 237 Hz, $\Delta\nu_{weak}$: 65 Hz

M.I. Eides, Phys. Lett. B 795, 113(2019).

- **Experimental result @LAMPF**

$\Delta\nu$**(ZF) = 4.463 302 2 (14) GHz (300 ppb)**

D. E. Casperson, *et al*., Phys. Lett. 59B 397 (1975).

$\Delta\nu$**(HF) = 4.463 302 765 (51)(17) GHz (12 ppb)** ←**Statistical uncertainty is dominant**

Sta Sys **(Hz)**

μ_μ/μ_p **= 3.183 345 13 (39) (120 ppb)**

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

↓ **With J-PARC beam power and new developments**

- **MuSEUM's Goal : ten-fold improvement**

A ten-fold improvement in precision allows us to see the contribution of weak interactions.

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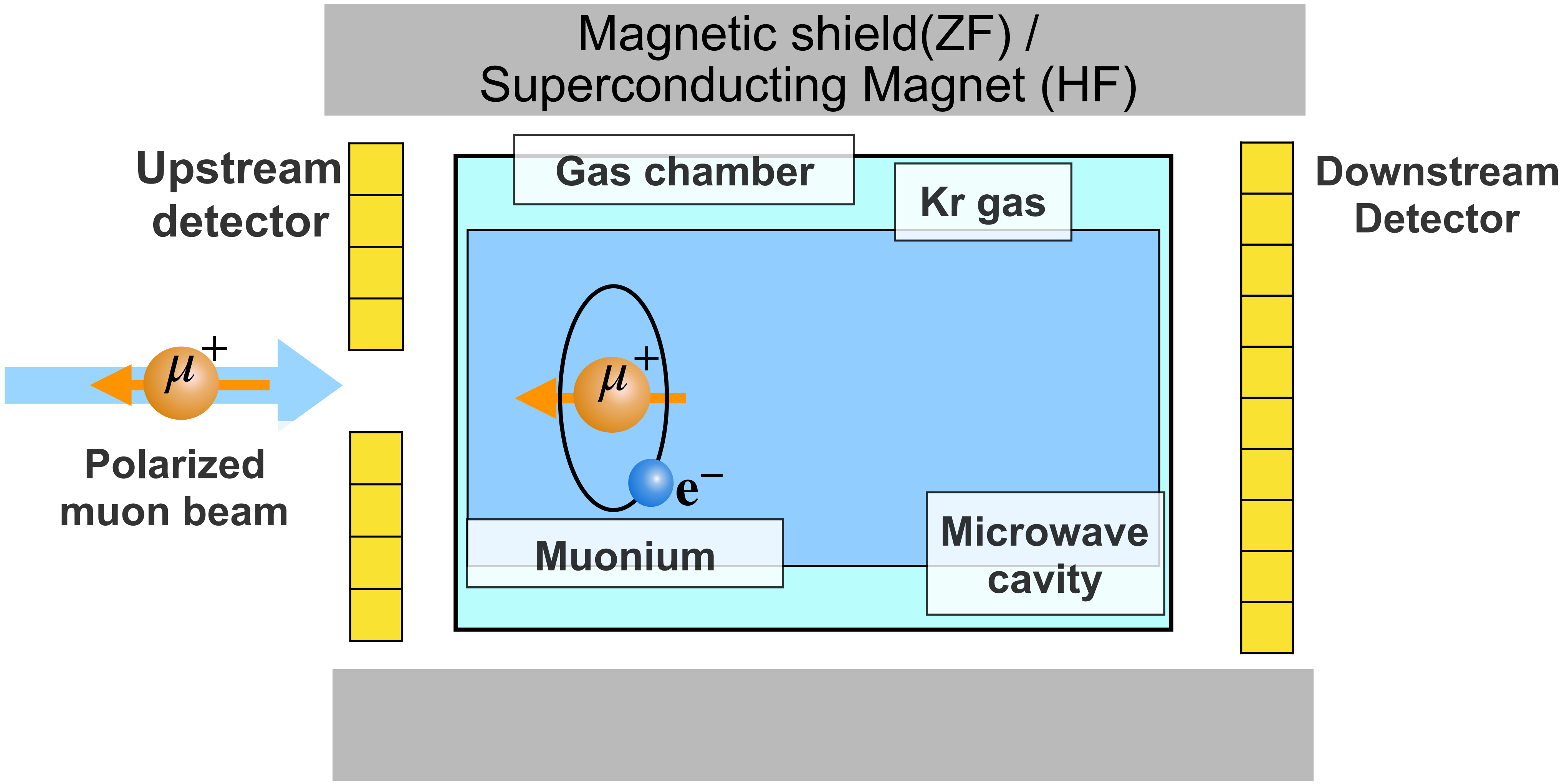
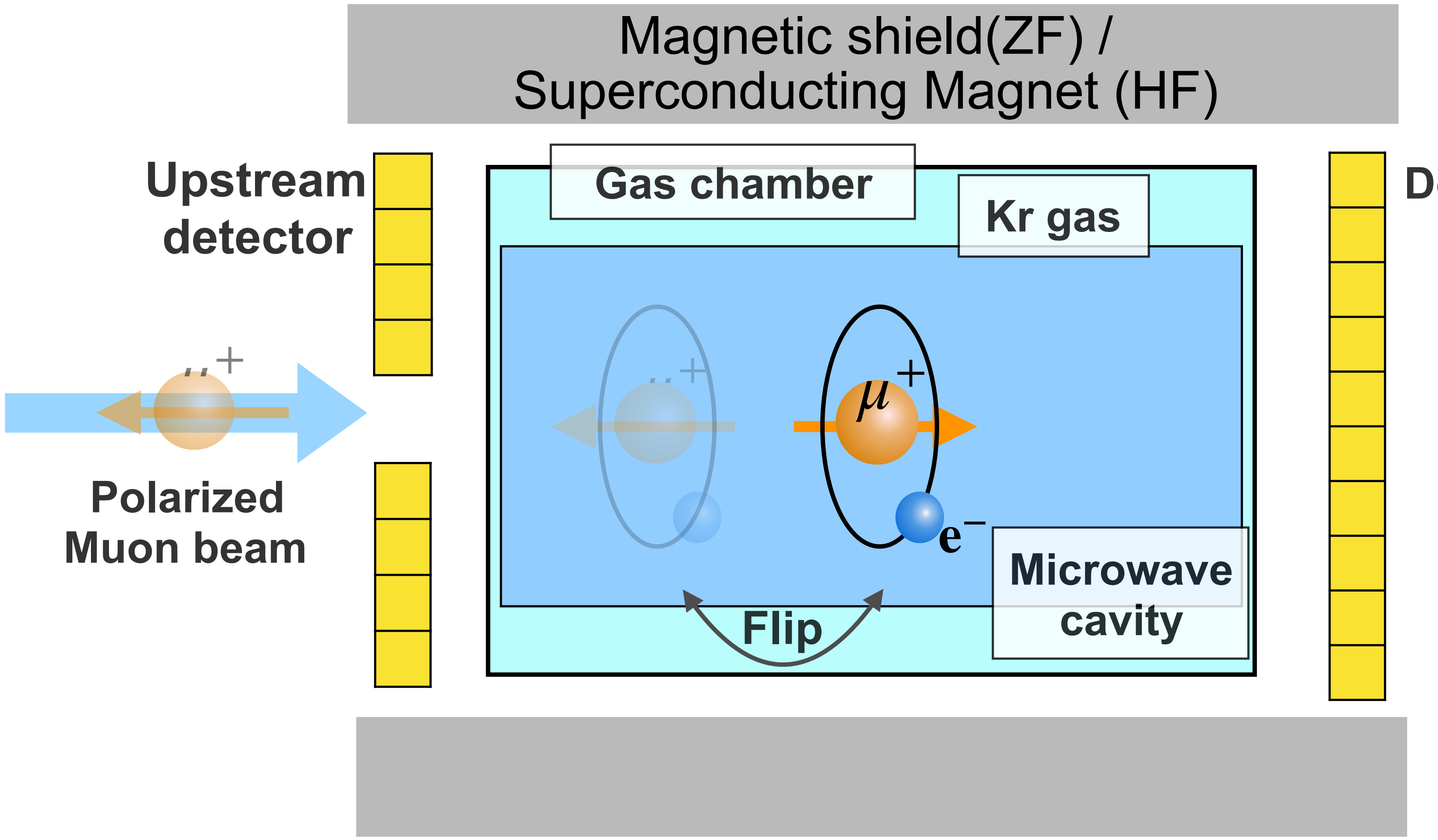
Experiment Procedure



- Muon captures electron from Kr to become muonium
- Muon spin flips when the microwaves frequency is on-resonance
- The muons are more likely to emit positrons in the spin direction
- MuHFS is determined from the relationship between microwave frequency and the number of positrons detected.

Experiment Procedure



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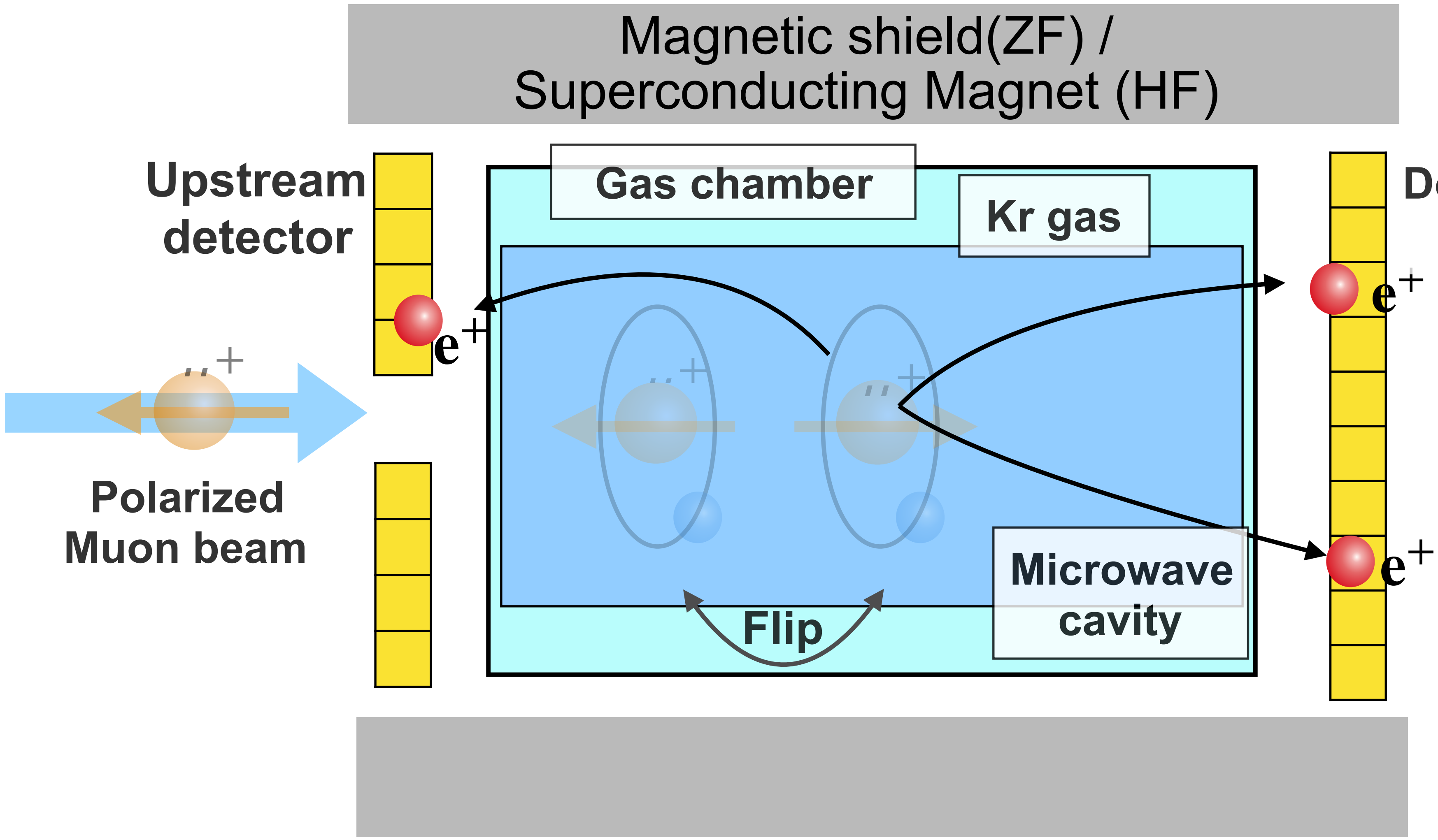

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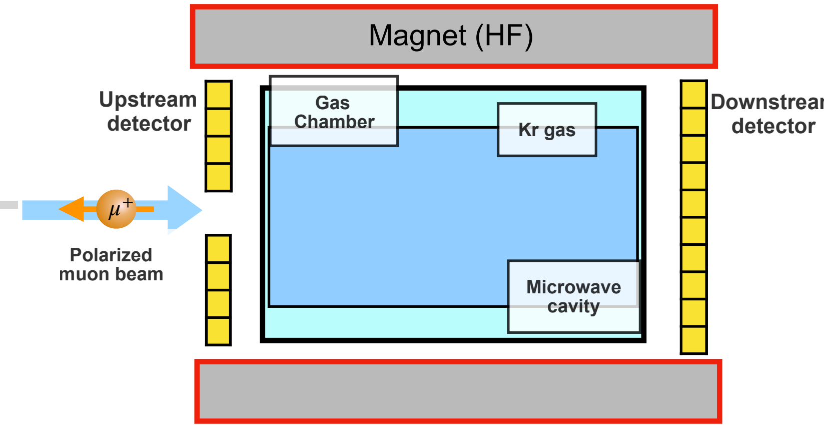
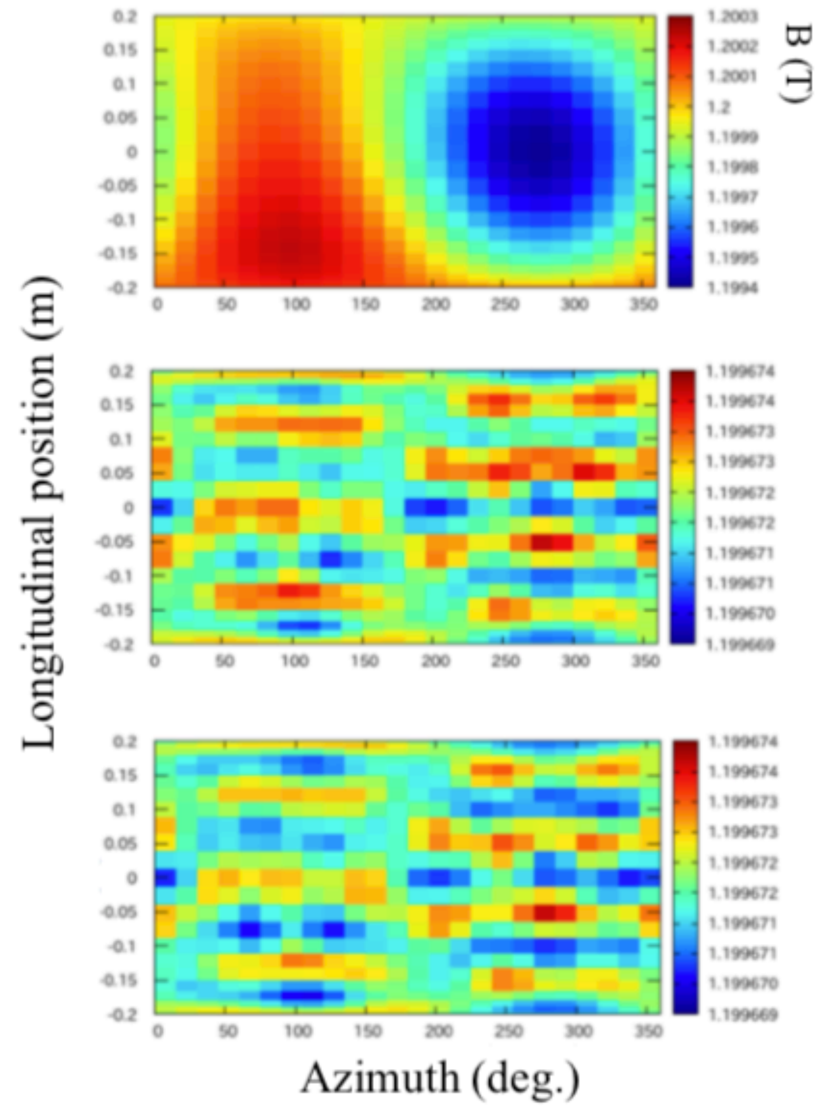
Magnet & Passive Shimming



Superconducting Magnetic field : 1.7T

Requirements for the field are

- **0.2 ppm (peak-to-peak) uniformity in a spheroidal volume with z=30 cm, r=10 cm.**
- **±0.1 ppm stability during measurement.**



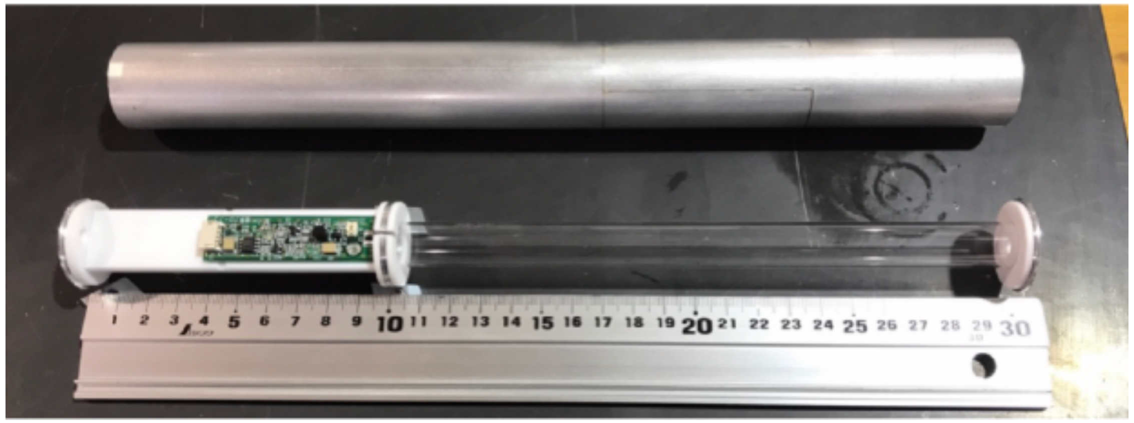
Iron shim plates 341 ppm (p-p)

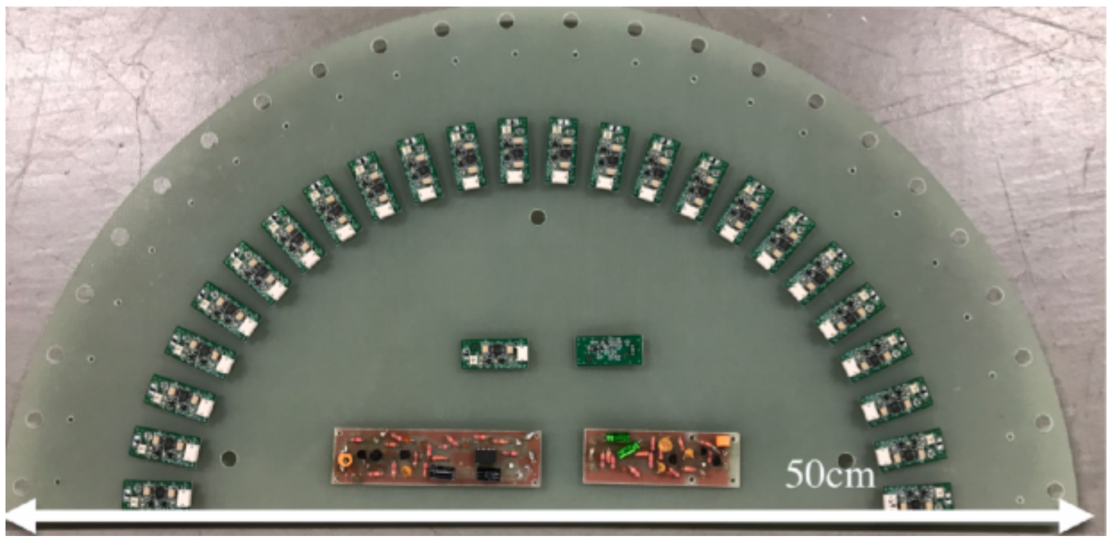
Nickel films 0.28 ppm (p-p)

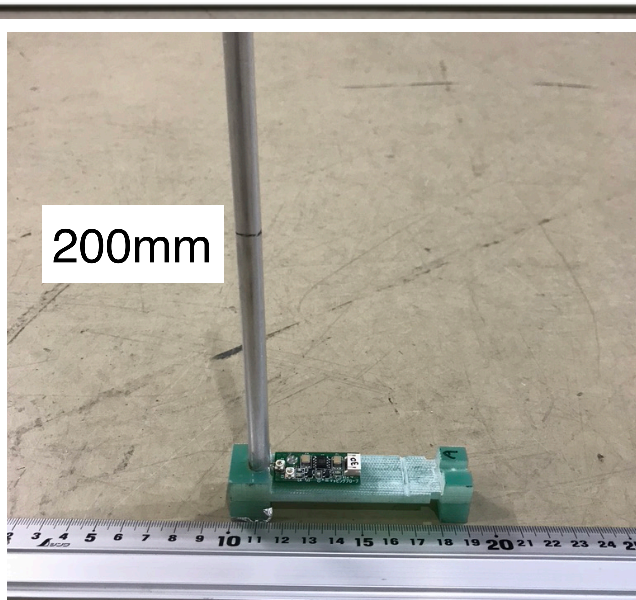
Magnetic putty. 0.17 ppm (p-p)

M. Abe, magn. reson. med. sci., vol. 16, no.4, Oct. Pp. 284-296,2017.

NMR Probes







Three types of probes

A) Standard probe (Almost finished)

- **A high-precision NMR probe to calibrate others.**
- **An accuracy of 15 ppb has been achieved.**
- **Cross-calibration is underway in a joint research project between Japan and the US.**

B) Field camera (in progress)

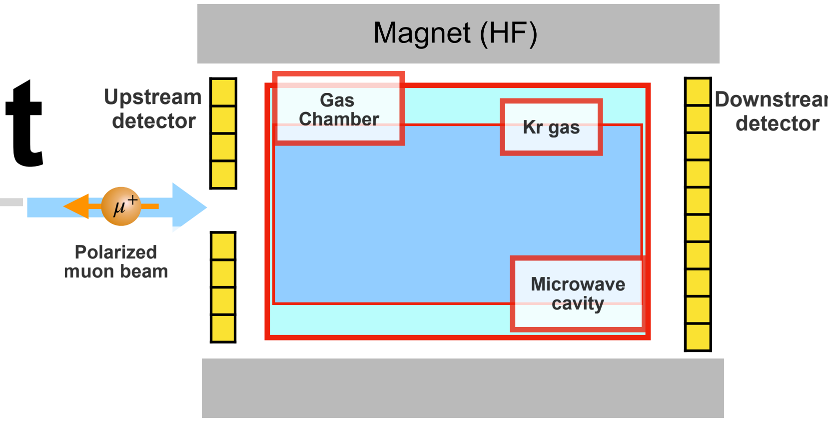
- **A 24-channel rotating NMR probe that maps magnetic fields.**
- **Used for shimming**

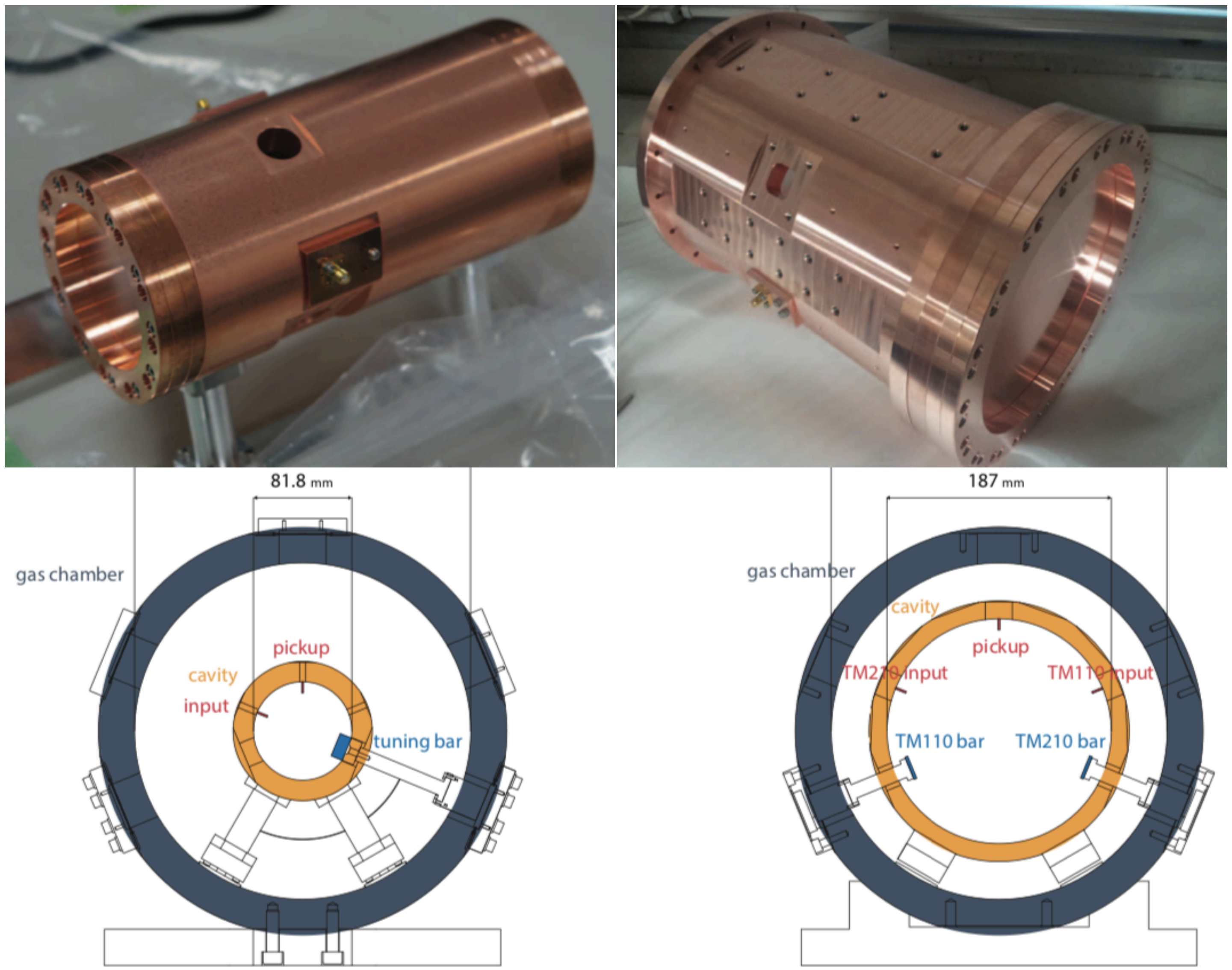
C) Fixed probe (in progress)

- **A compact probe to monitor magnetic field stability during experiment.**

H. Yamaguchi, IEEE Trans. Appl. Supercond. Vol. 29, no. 5, Aug. 2019, Art. no. 9000904

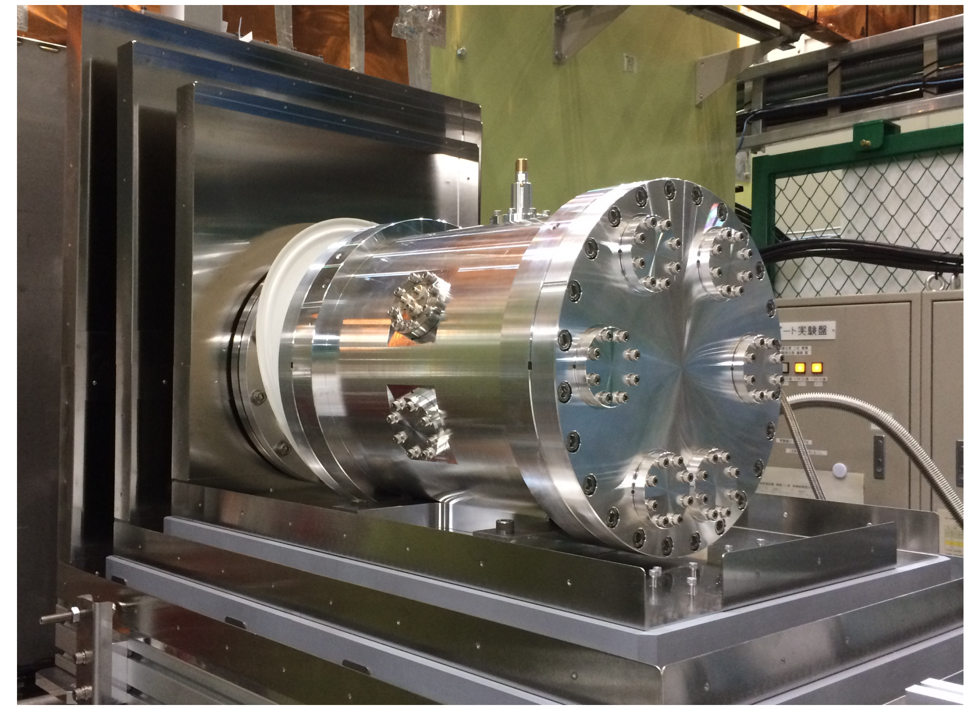
Microwave Cavity & Gas Target





- A cylindrical microwave cavity resonates at

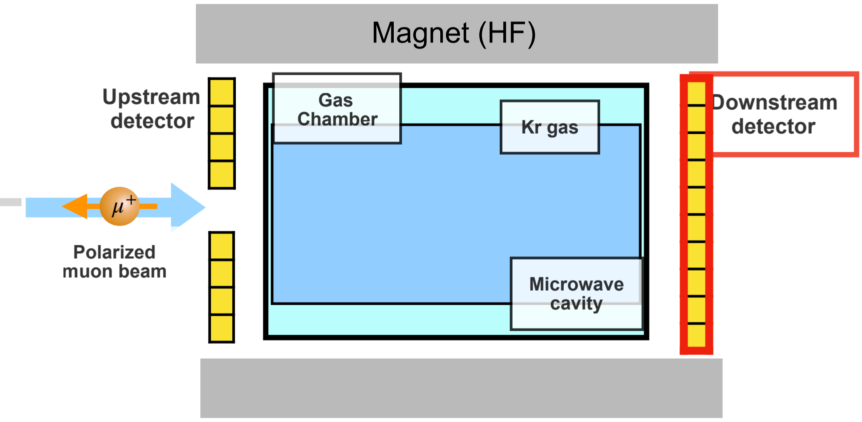
ZF : 4.46 GHz (TM110)
HF : 1.95 GHz (TM110) and 2.65 GHz (TM210)

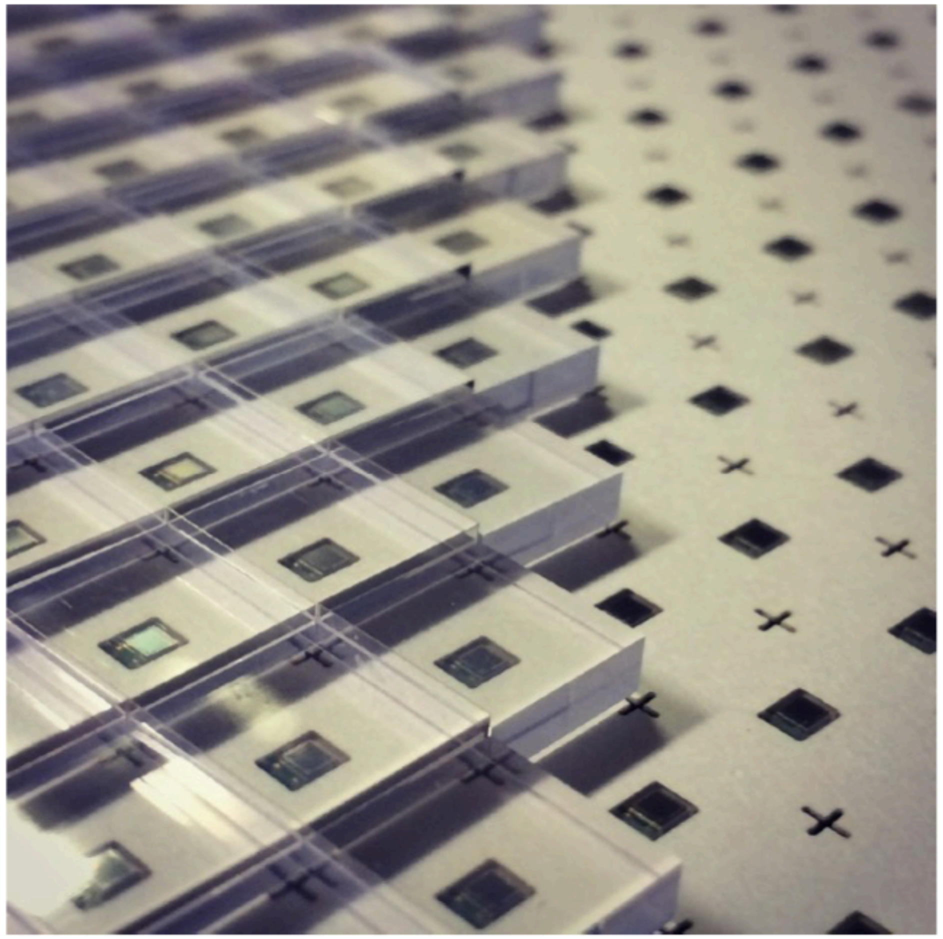


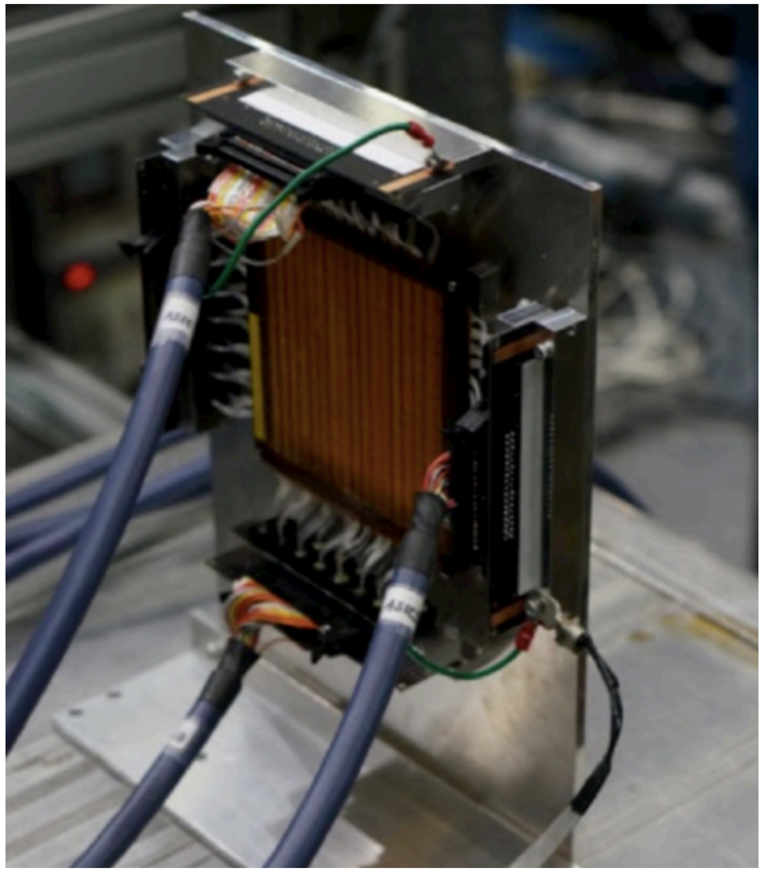
- A cylindrical aluminum vessel with almost no magnetism.
- Target is Kr gas
- Muon stopping with a low-density of 0.3 atm.
- precise gas density monitoring with 0.02% accuracy.

K S Tanaka, et al., PTEP, Volume 2021, Issue 5, May 2021, 053C01.

Positron & Muon Detectors







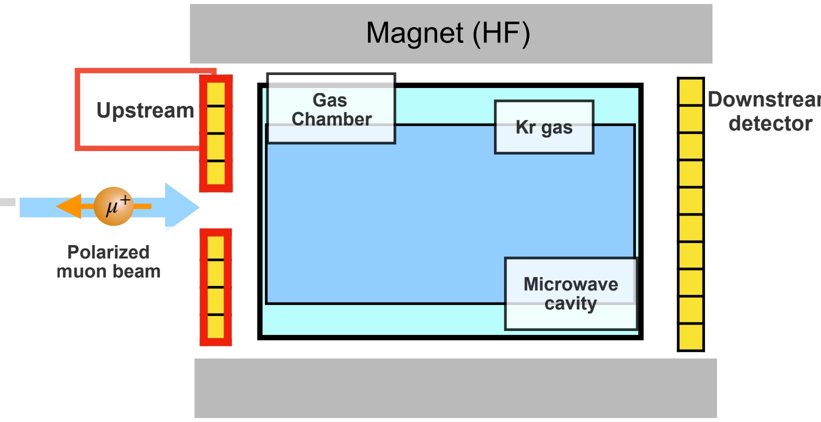
Positron counter

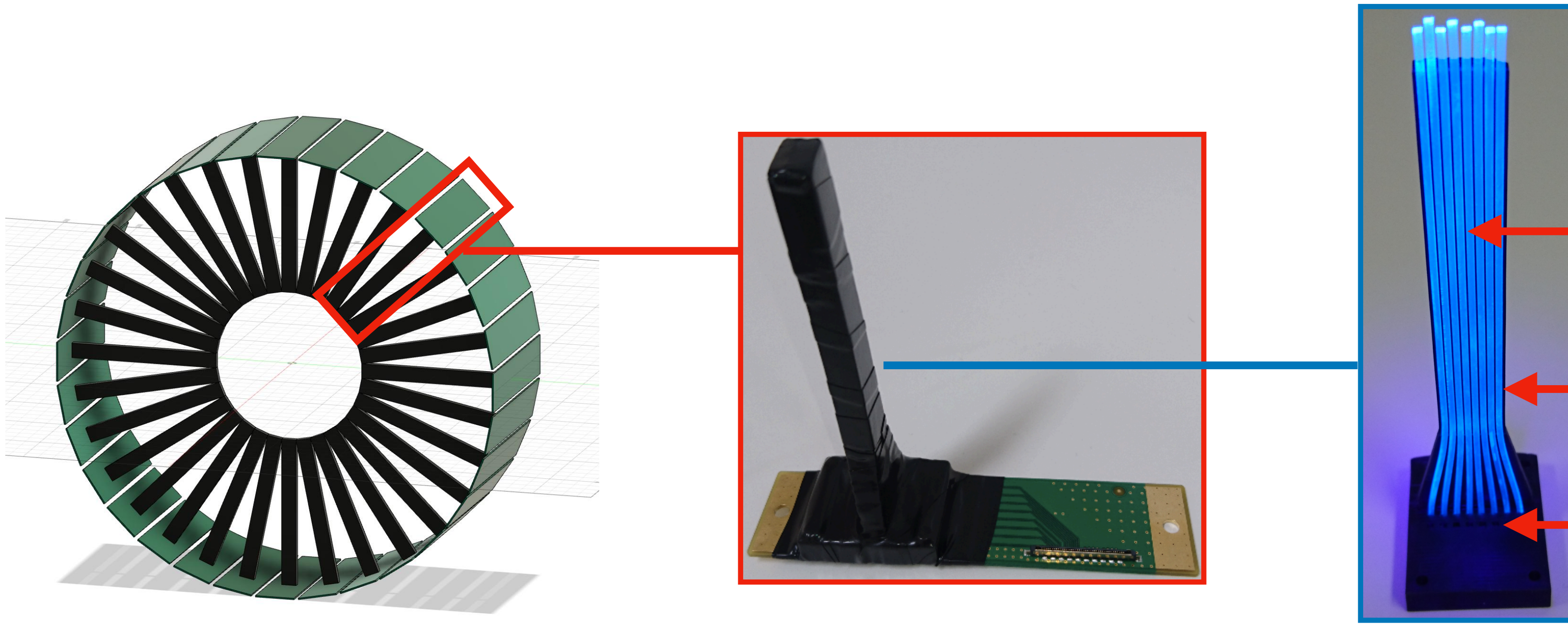
- High-rate capable, segmented positron counter with 1152 channels.
- The scintillator size is 1×1 cm
- Consists of scintillator and SiPM.
  - S. Kanda, et al., PoS(PhotoDet16)039 (2016).

Muon beam profile monitors

- Extremely thin online beam profile monitor having a thickness of 300 μm.
- Cross-configured fiber hodoscope with SiPM readout.
  - S. Kanda, RIKEN APR 48, 278 (2016).

Additional Positron Detector

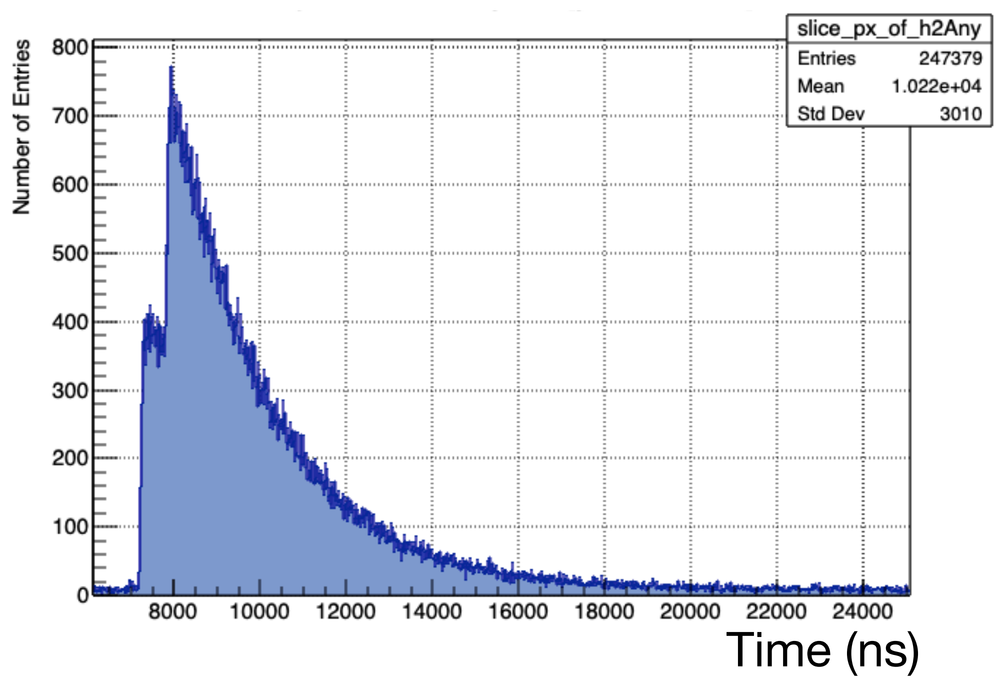




Scintillating fiber

Frame modeled with a 3D printer

SiPM on PCB



- **Upstream Detector (Additional positron counter)**
- **Increase of statistics and measurement of forward/backward asymmetry to study systematic uncertainties.**
- **Development and testing Prototype**
- **Improved and scheduled for mass production**

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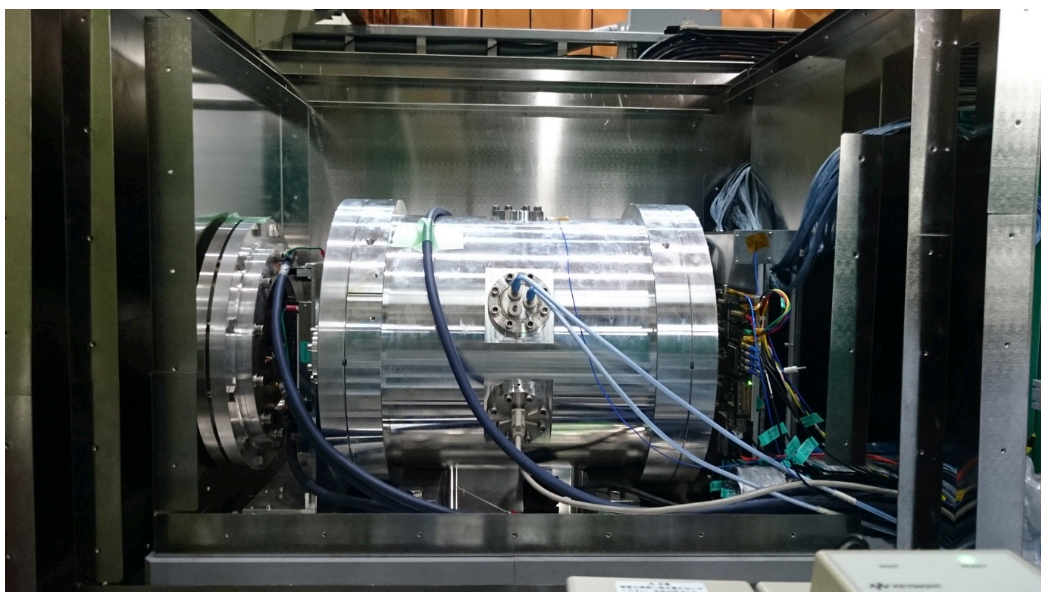
Status of MuSEUM (2014 - 21)

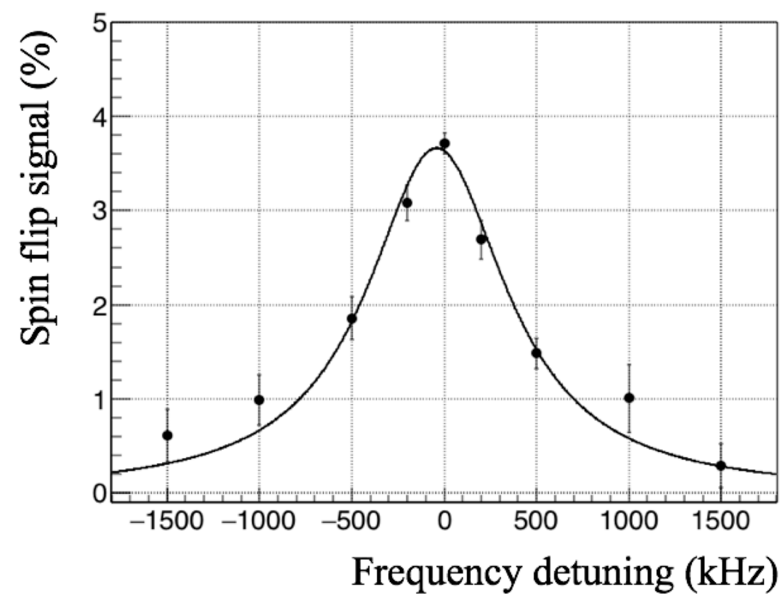
2011 2013 2015 2017 2019 2021

ZF: R&D | 1st | 2nd | 3rd | 4th | 5th

HF: Proposal Submitted | R&D | New Beamline Construction | 1st?



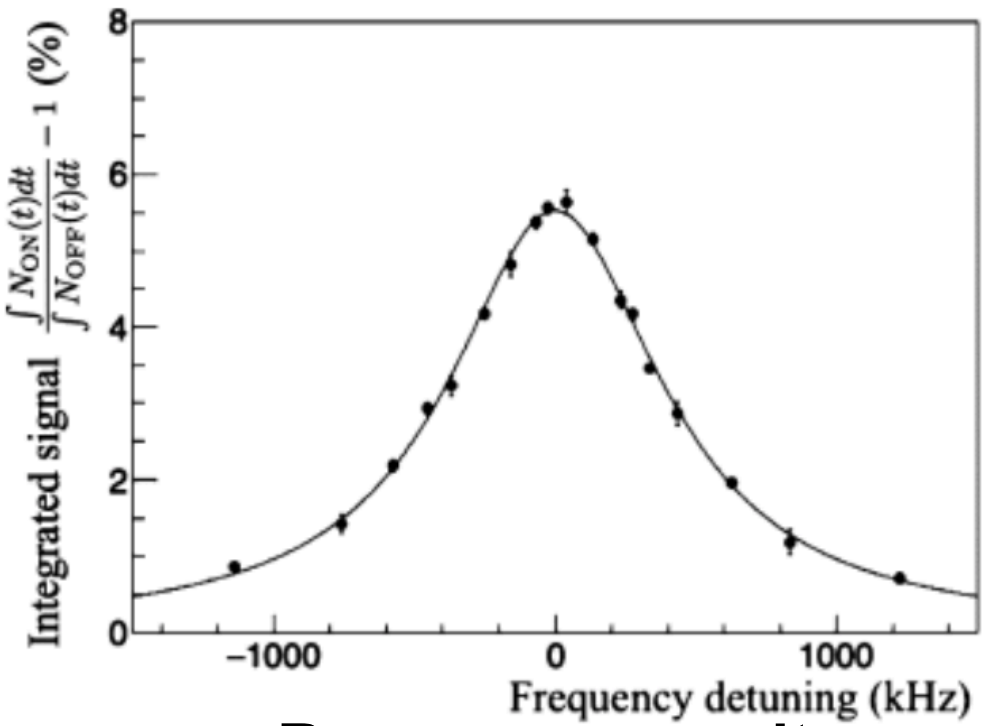
Experimental setup



First resonance result(in 2016)

- Until the construction of the HF beamline, ZF experiments were conducted at the existing beamline to verify the principle.
- We are preparing for the first HF experiment.

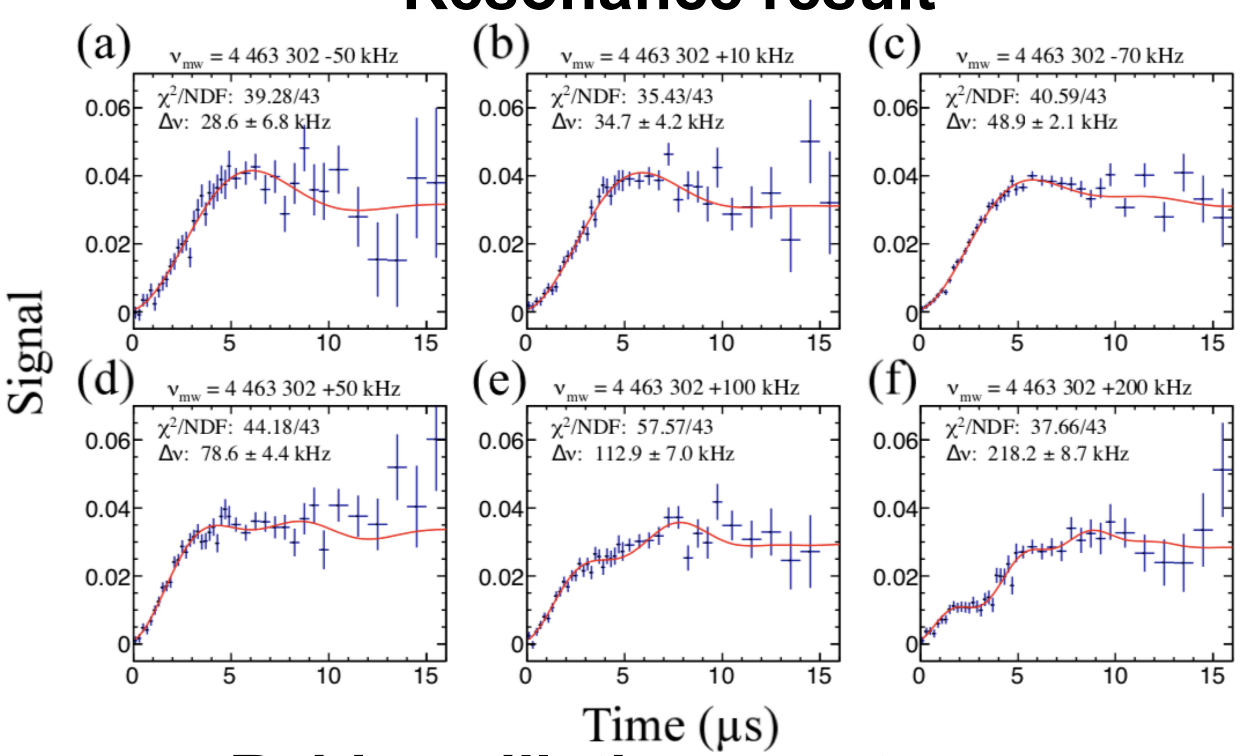
Achievements of Zero-field experiments



Resonance result

- **First result using a pulsed muon beam.**
- **relative precision of 0.9 ppm from Lorentzian fit of resonance curve**

S. Kanda et al., Physics Letters B 815 (2021) 136154.

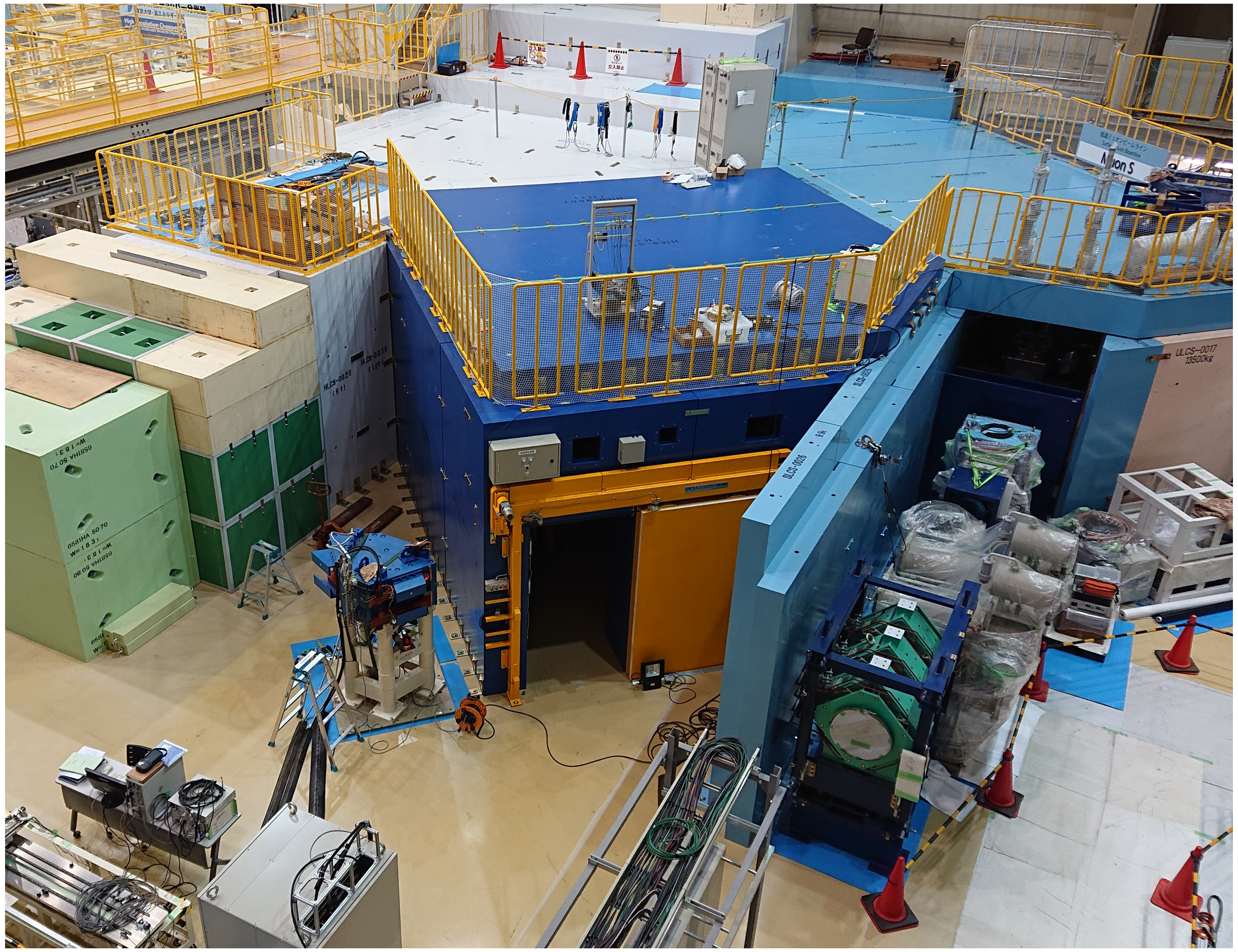


Rabi-oscillation spectroscopy

- **relative precision of 160 ppb from Rabi-oscillation spectroscopy**
  world record for zero-field experiments!

S. Nishimura et al., Phys. Rev. A 104 (2021) 020801

New Muon Beamline



- T. Yamazaki, N. Kawamura, A. Toyoda (KEK).
- A. Toyoda et al., "J-PARC MUSE H-Line optimization for the g-2 and MuHFS experiments", J. Phys.: Conf. Ser. 408 012073 (2013).
- N. Kawamura, et al., "New concept for a large-acceptance general-purpose muon beamline", PTEP 113G01 (2018).

- **A high-intensity beamline is under construction that can provide beams of $1 \times 10^8\ \mu^+/\mathrm{s}$ or more.**

LAMPF : $2 \times 10^6\ \mu^+/\mathrm{s}$
J-PARC D Line : $5 \times 10^6\ \mu^+/\mathrm{s}$
(MuSEUM ZF)

- **In the earliest case, the beam will be provided from early 2022.**

- **In high field experiments, the statistical accuracy reaches 5 Hz (1.2 ppb) after 40 days of measurements.**

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Expected Precision

Systematic uncertainty in zero-field

Source	Contribution (Hz)
Gas density measurement	46
Microwave power drift	37
Detector pileup	19
Gas temperature fluctuation	6
Static magnetic field	negligible
Gas impurity buildup	12
Muon beam intensity	negligible
Muon beam profile	negligible
Total	63

S. Kanda *et al.*, Physics Letters B 815 (2021) 136154.

Improvements for high field experiments

- **Gas : 46Hz→3Hz by using a new high-precision silicon gauge.**
- **Power drift : 37Hz→less than 1Hz by power and temperature control.**
- **Pileup : 19Hz→2Hz by improvement in segmentation and front-end electronics.**
- **Impurity : 12Hz→less than 1Hz by improvement in Q-Mass monitoring.**
- **B-Field and NMR probe accuracy will give an uncertainty of 8 ppb in the magnetic moment ratio μ_μ/μ_p.**

We are aiming for a precision of 5 Hz, a ten-fold improvement from the 53 Hz of the previous experiment.

Summary

- Muonium spectroscopy deepens our understanding of the Standard Model.
- MuSEUM collaboration is preparing for measurements of the muonium HFS.
- We have finished demonstrating the principle by experiments at zero-field.
- To achieve the highest precision, an experiment in high-field is in preparation.
- We are aiming for a high-field experiment in early 2022.

MuSEUM collaboration

Muonium Spectroscopy Experiment Using Microwave

- **Collaborators**

KEK, JAEA, J-PARC: M. Abe, Y. Fukao, Y. Ikedo, T.Ito, R. Kadono, N. Kawamura, A. Koda, N. Kurosawa, T. Mibe, Y. Miyake, K. Nagamine, S. Nishimura, T. Ogitsu, N. Saito, K. Sasaki, Y. Sato, K. Shimomura, P. Strasser, M. Sugano, A. Toyoda, K. Ueno, H. Yamaguchi, S. Kanda, A. Yamamoto, T. Yamazaki, M. Yoshida

東京大学 THE UNIVERSITY OF TOKYO: Y. Matsuda, S. Seo, T. Tanaka, H. A. Torii, H. Yamauchi, H. Yasuda F. Yoshizu, S. Oyama

九州大学 KYUSHU UNIVERSITY: K. Kawagoe, J. Tojo, T. Yamanaka, T. Yoshioka

RIKEN: K. Ishida, M. Iwasaki, O. Kamigaito, Y. Ueno

名古屋大学 NAGOYA UNIVERSITY: S. Fukumura, M. Kitaguchi, H. Tada

TOHOKU: K. S. Tanaka

大阪大学 OSAKA UNIVERSITY: M. Aoki, D. Tomono

ICU 国際基督教大学 Expanding Potential: M. K. Kubo

TRIUMF: K. M. Kojima

山梨大学 UNIVERSITY OF YAMANASHI: E. Torikai

茨城大学 Ibaraki University: H. Iinuma

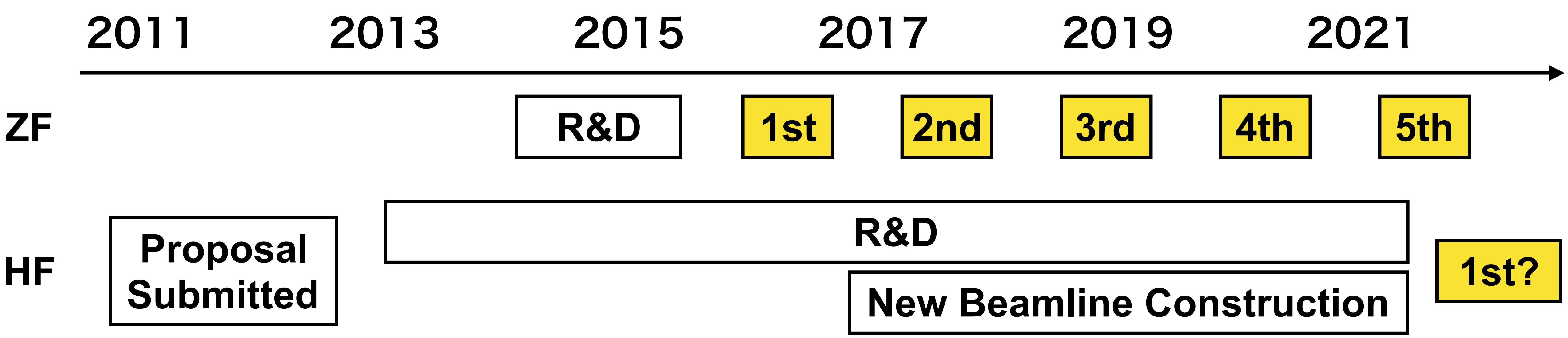
S. Choi, C. Park

University of Massachusetts Amherst: D. Kawall

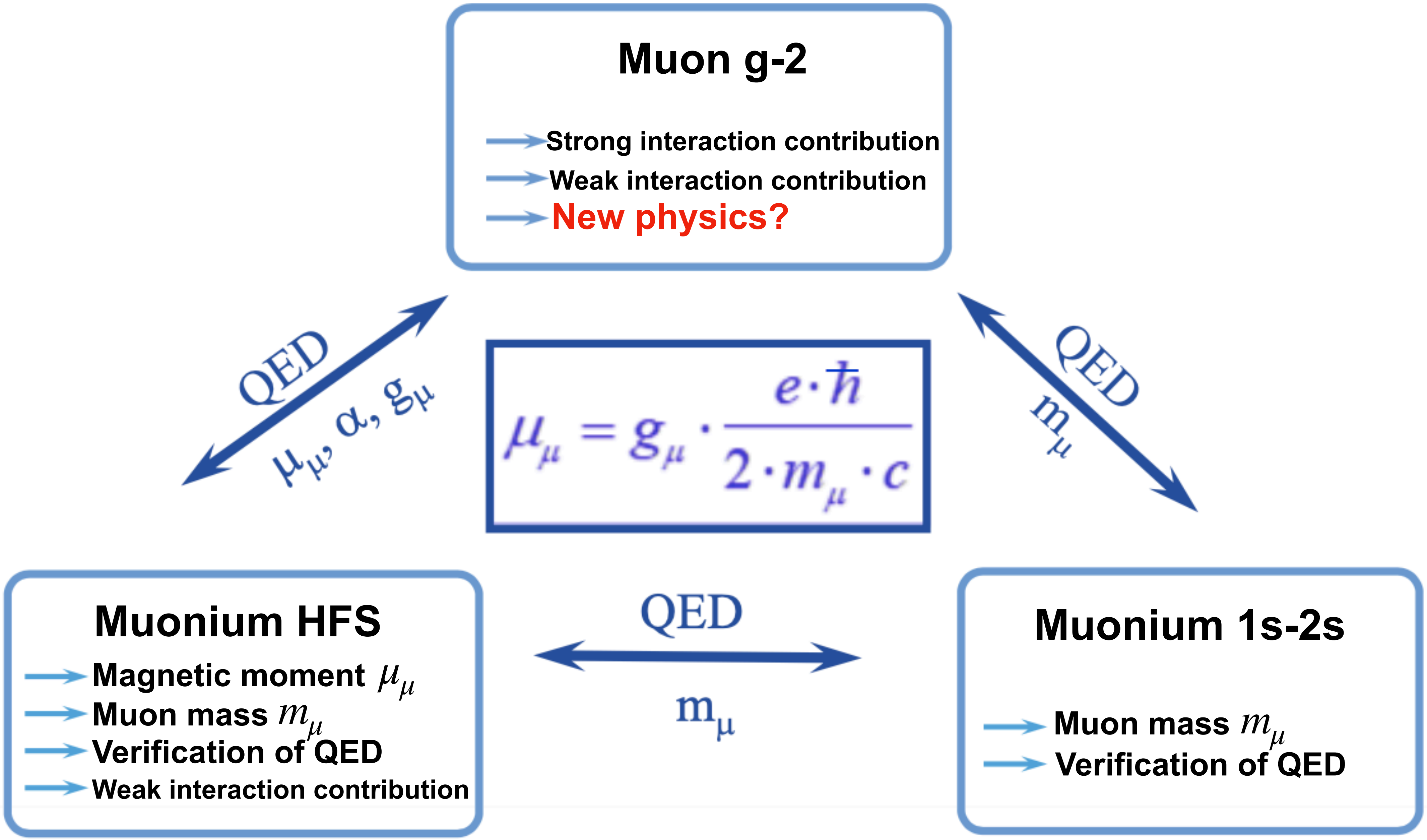
Back up

Status of MuSEUM

- **Zero field : Demonstration at existing beamline**
  - 1st Beamtime: First observation
  - 2nd Beamtime: Development of a new analysis method
  - 3st Beamtime: Gas pressure dependence was studied
  - 4th & 5th Beamtime: Compensation of gas density shift by Kr/ He gas mixture.
- **High field : Highest precision experiment**
  - We are preparing for the first HF experiment.



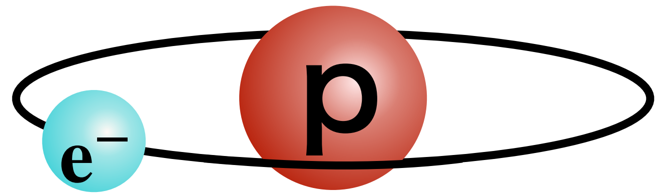
Relation with other experiments

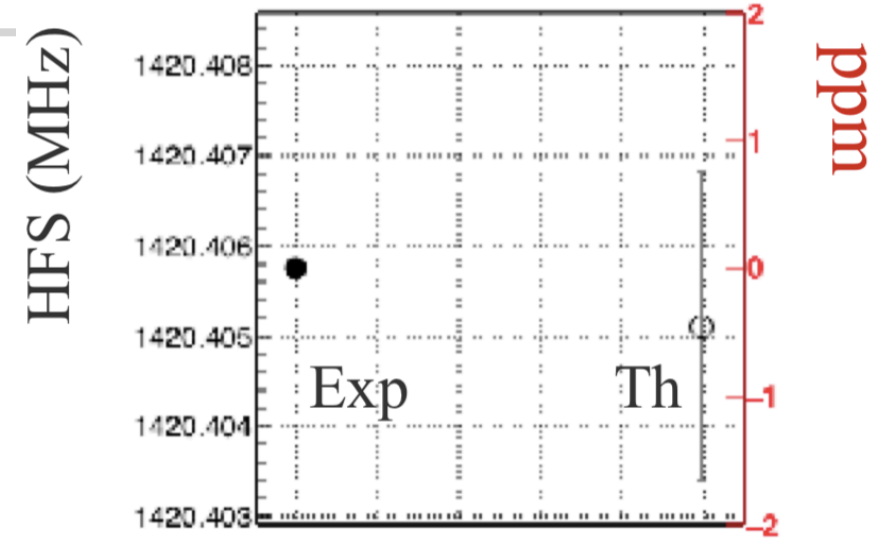


Combining MuSEUM, Muon g-2 measurement and Muon mass measurement, perfome the validation of SM and the bound-state QED.

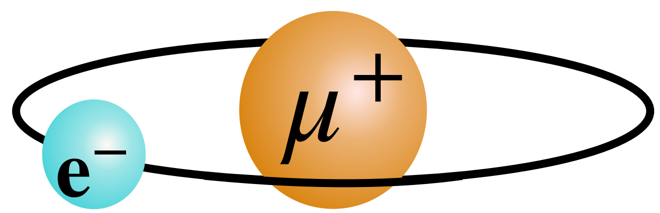
水素様原子のHFS

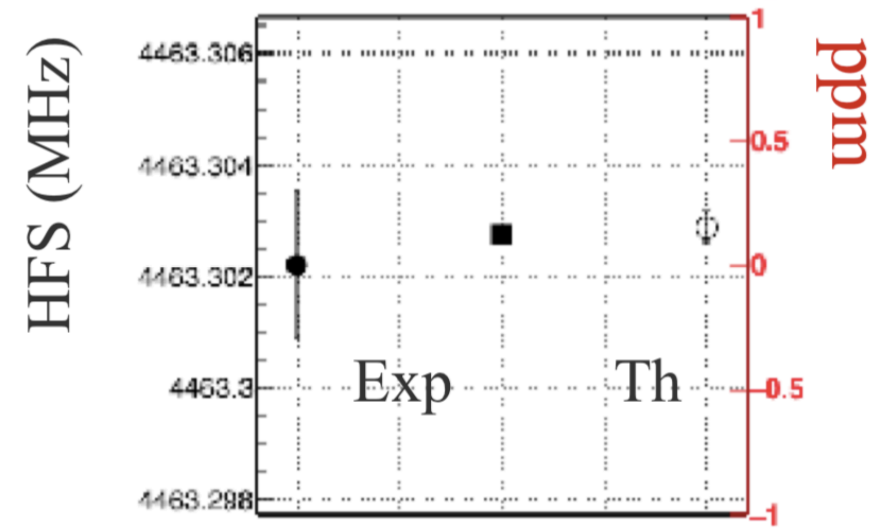
- 水素
- 1420 MHz
- 水素原子メーザー



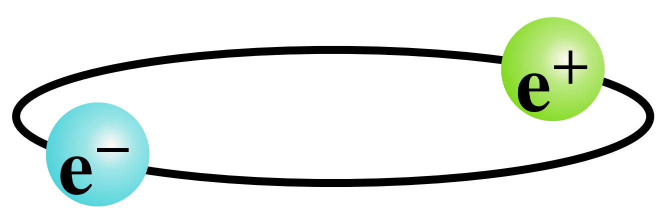


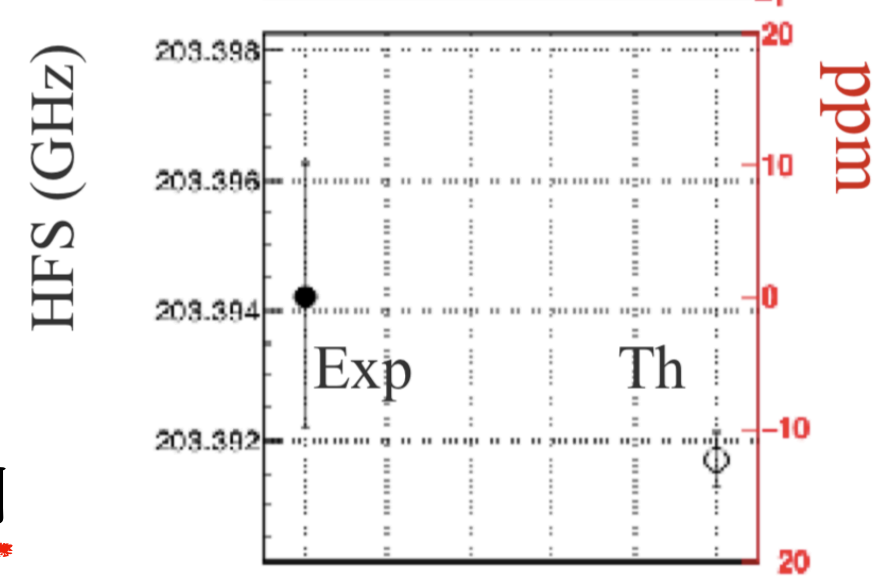
- ミュオニウム
- 4464 MHz
- 崩壊陽電子の非対称度





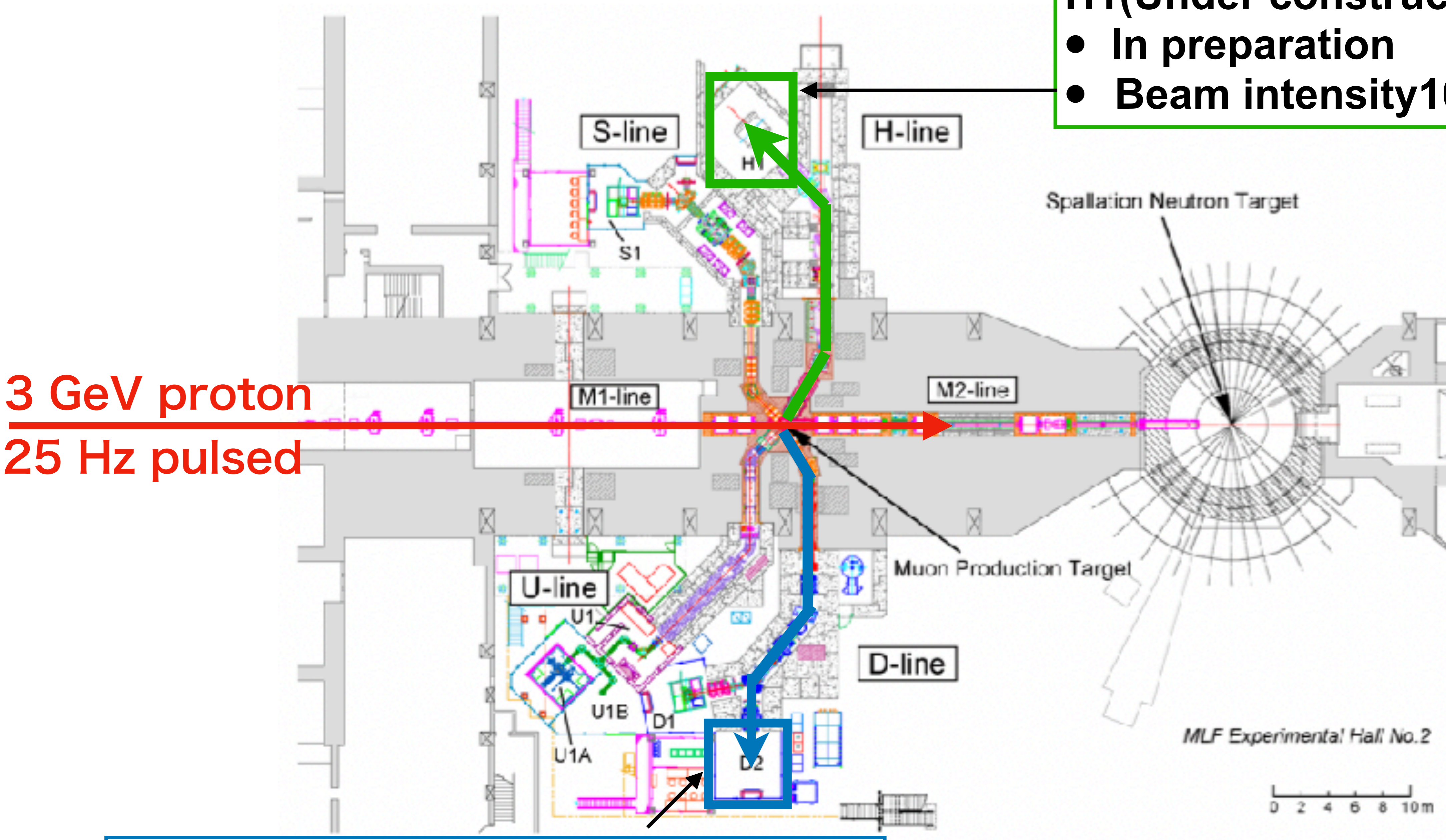
- ポジトロニウム
- 203 GHz
- 対消滅γ線





▶ミュオニウムは理論と実験の比較において最も有利

Beam Line @J-PARC MLF MUSE



H1(Under construction)

- **In preparation**
- **Beam intensity10^8 μ⁺/s**

D2

- **End**
- **Beam intensity 6×10^6 μ⁺/s (0.6 MW)**

N. Kawamura et al., PTEP 2018 (2018). doi: 10.1093/ptep/pty116, 113G01.
W. Higemoto, *Quantum Beam Sci*. **1** (2017) 11.