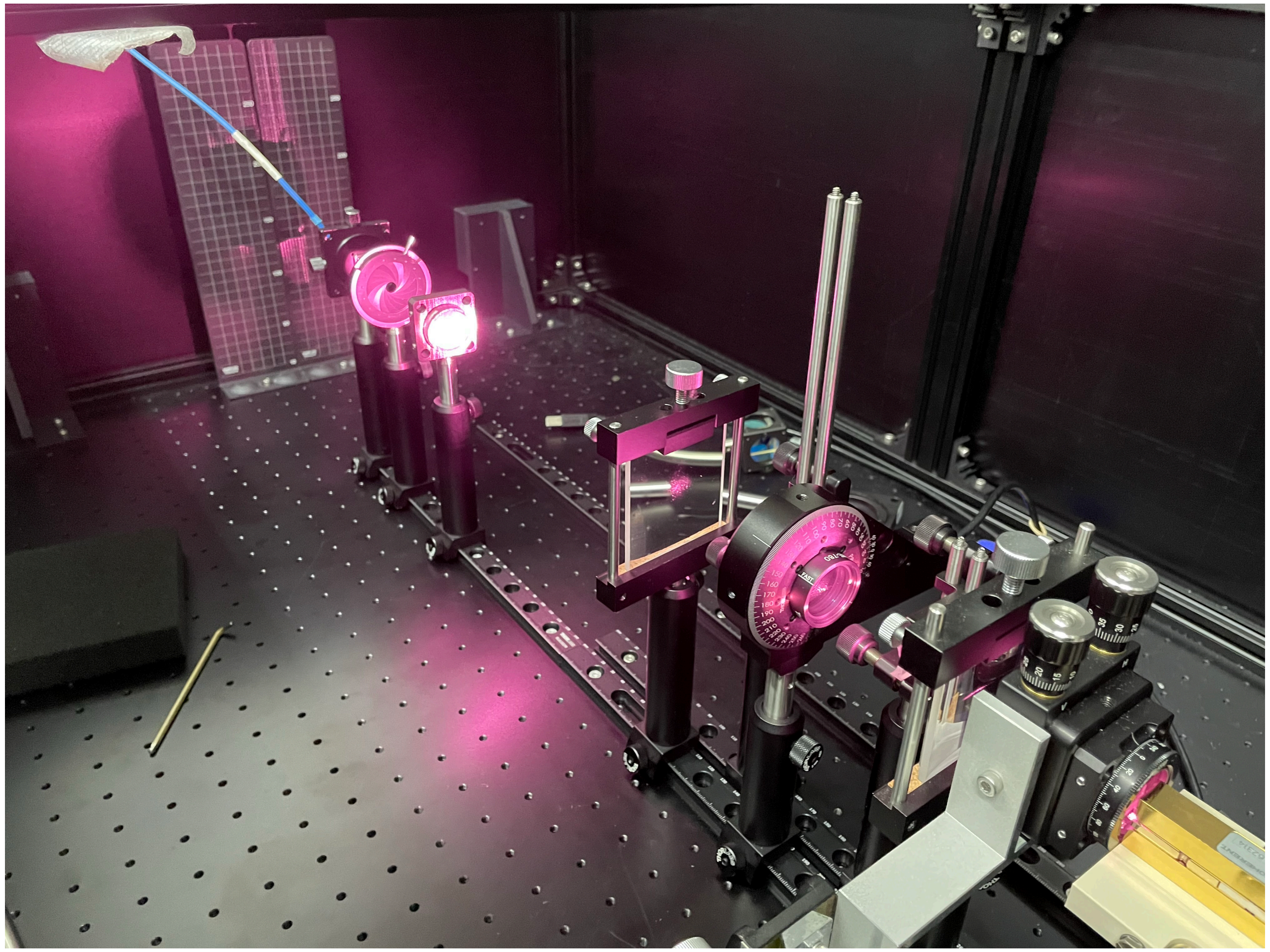
Present status of spectroscopy of the hyperfine structure and repolarization of muonic helium atoms at J-PARC



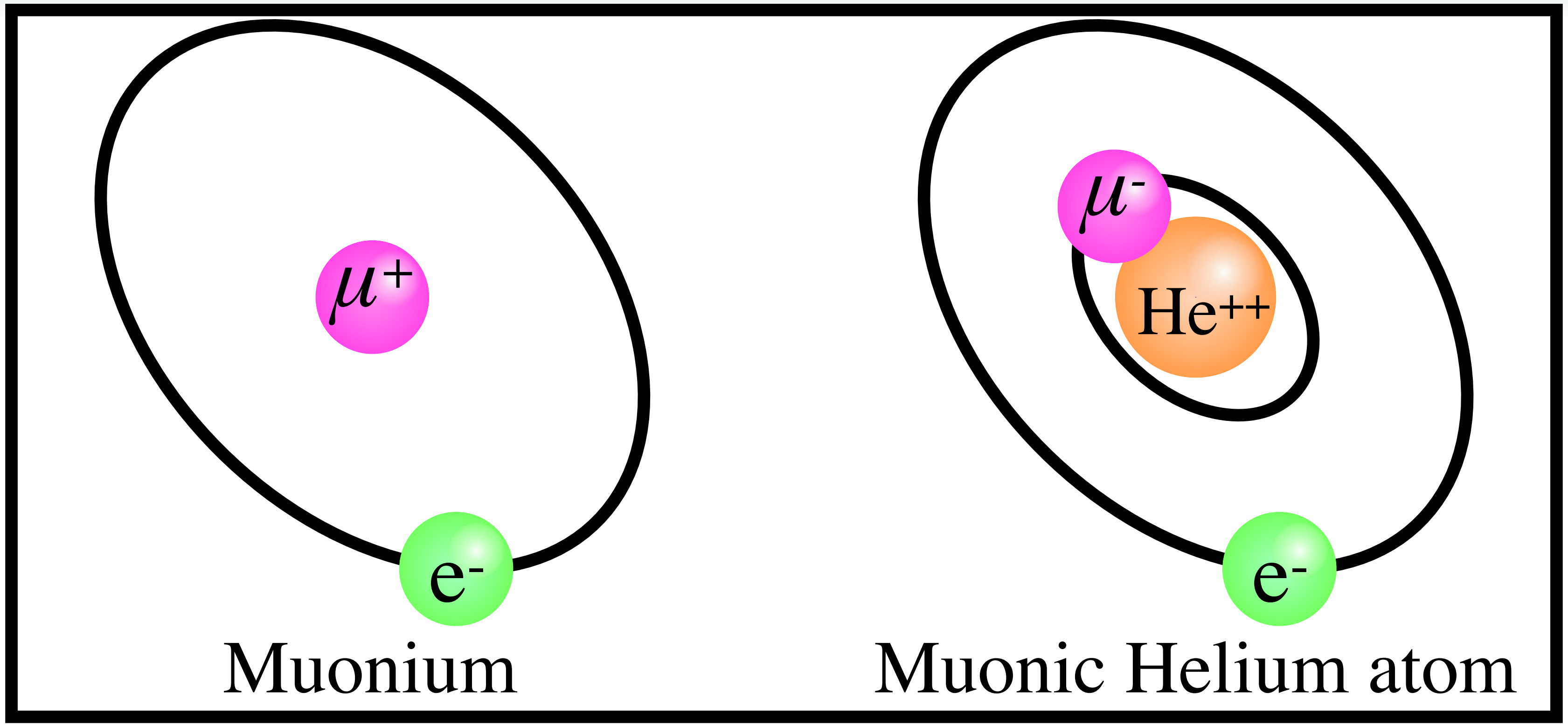
Seiso FUKUMURA (Nagoya University)

P. Strasser, T. Ino, S. Kanda, K. Shimomura, S. Nishimura (KEK IMSS),
T. Oku (JAEA, Ibaraki University),T. Okudaira (Nagoya University, JAEA),
M. Kitaguchi, H. M. Shimizu, H. Tada (Nagoya University) and H. A. Torii (The University of Tokyo)

Laboratory for Particle Properties

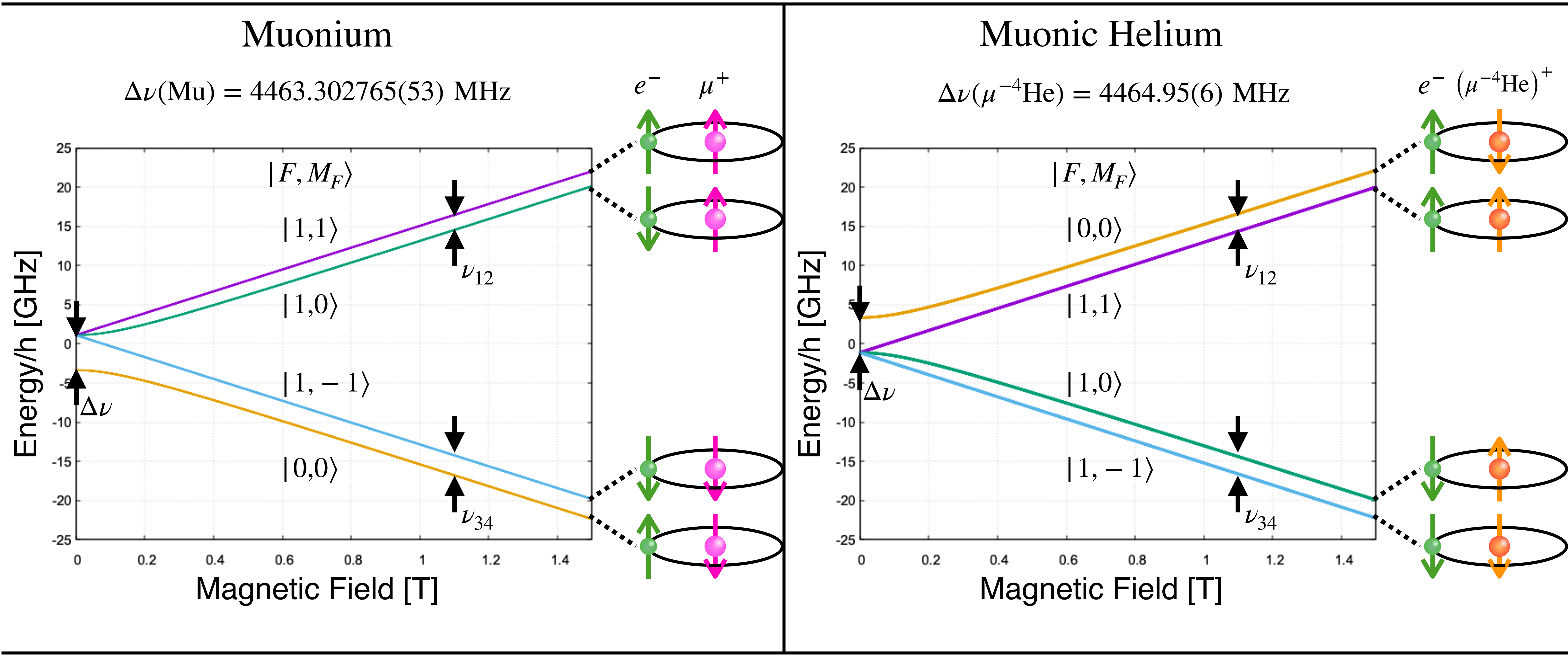
SEUM

Muonic helium atom



- Exotic helium atom where one of the two electrons is replaced by a μ^-
- Interaction of the electron and the negative muon magnetic moment produces the ground state hyperfine structure (HFS)
- Powerful tool to test
  - Theories of quantum three-body systems
  - CPT symmetry with 2nd generation lepton

Hyperfine structure (HFS)



- The magnetic field is measured from $h\nu_p = 2B\mu_p$ (ν_p: NMR frequency of free proton)
- The HFS frequency $\Delta\nu$ is always the sum of two transition frequencies ν_{12} and ν_{34}

Motivation of HFS measurement

- Precise determination of μ_{μ^-}/μ_p

  →Allowing to precisely determine a_{μ^-} and g-factor

- Precise determination of m_{μ^-}

  ... The negative muon mass was determined by muonic X-ray spectroscopy (3.1 ppm)

  ...I. Beltrami, et al., Nucl. Phys. A **451**, 679 (1986)

  →HFS measurement can improve precision of m_{μ^-} up to same level as m_{μ^+} (120 ppb)

  ...W. Liu, et al., Phys. Rev. Lett. **81**, 711 (1999)

  →Allowing CPT test with muon mass

muonic helium HFS

Test theories of quantum three-body systems

μ_{μ^-}/μ_p determination

Parameter of muon g-2 experiment
→New physics?

m_{μ^-} determination

- Parameter of SM
- CPT test
- Same method of m_{μ^+} determination

In high magnetic field

$$m_{\mu^-} = m_e \frac{g_{\mu^-}}{g_e} \frac{\mu_p}{\mu_{\mu^-}} \frac{\mu_e}{\mu_p}$$

Previous works

Target	Magnetic Field (G)	Gas Pressure (atm)	Result
^{4}He	very low (< 20 mG)	19.4 atm	4464.94(6) MHz (13 ppm)
	11.5 kG or 13.6 kG	5 atm or 15 atm	4465.004(29) MHz (6.5 ppm)
^{3}He	very low (< 20 mG)	20 atm	4166.41(5) MHz (12 ppm)

… ^{4}He,Low Field : H.Orth, et al., Phys. Rev. Lett. 45, 1483 (1980)
^{4}He,High Field : C.J.Gardner, et al., Phys. Rev. Lett. 48, 1168 (1980)
^{3}He,Low Field : V.W. Hughes, G.z. Putliz, in: T. Kinoshita (Ed.), Quantum Electrodynamics, World Scientific Publishing Co. Pte. Ltd. (1990)

- Previous experimental results were statistically limited

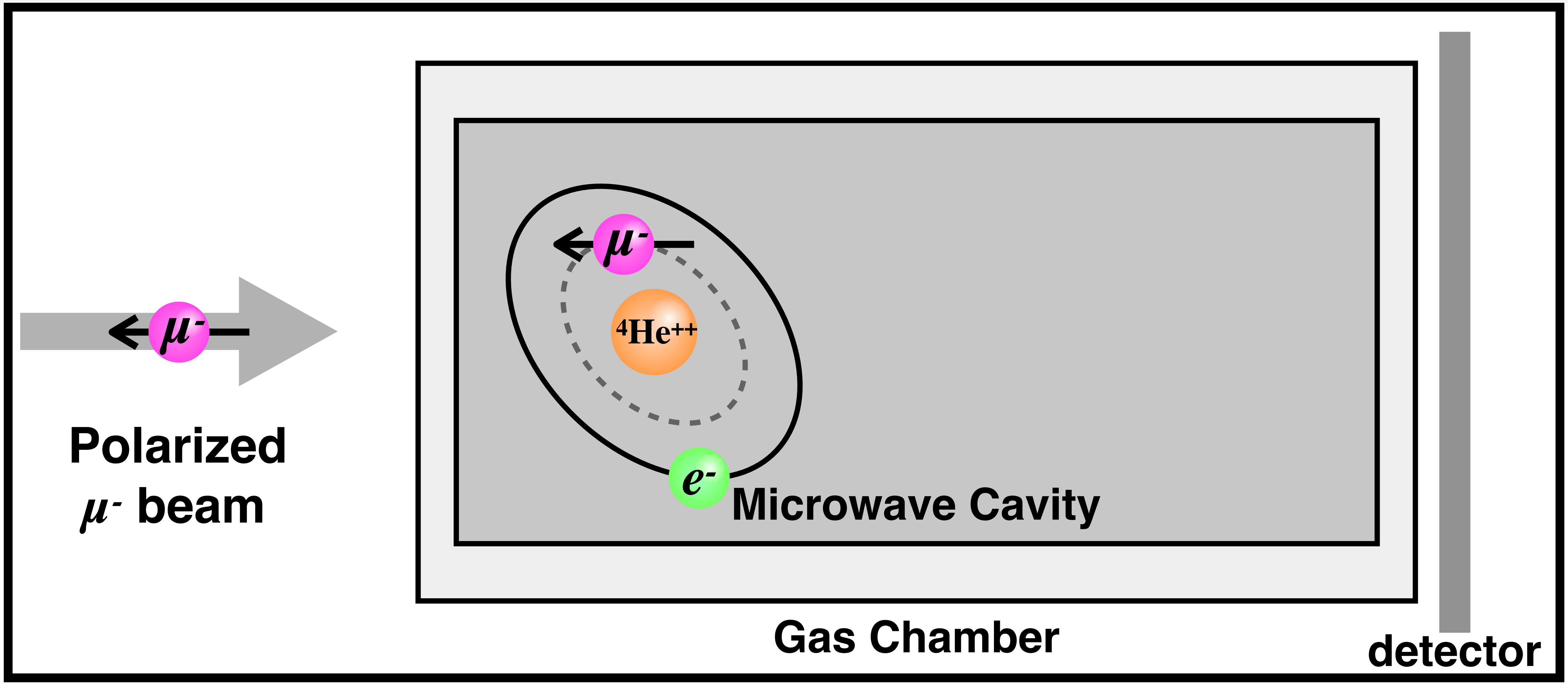
  ... 1. Limited negative muon beam intensity

  2. Depolarization of muons by Auger transition and Stark mixing (~6%)

  cf). 50% for muonium case

- Our goal is $O(10)$ ppb

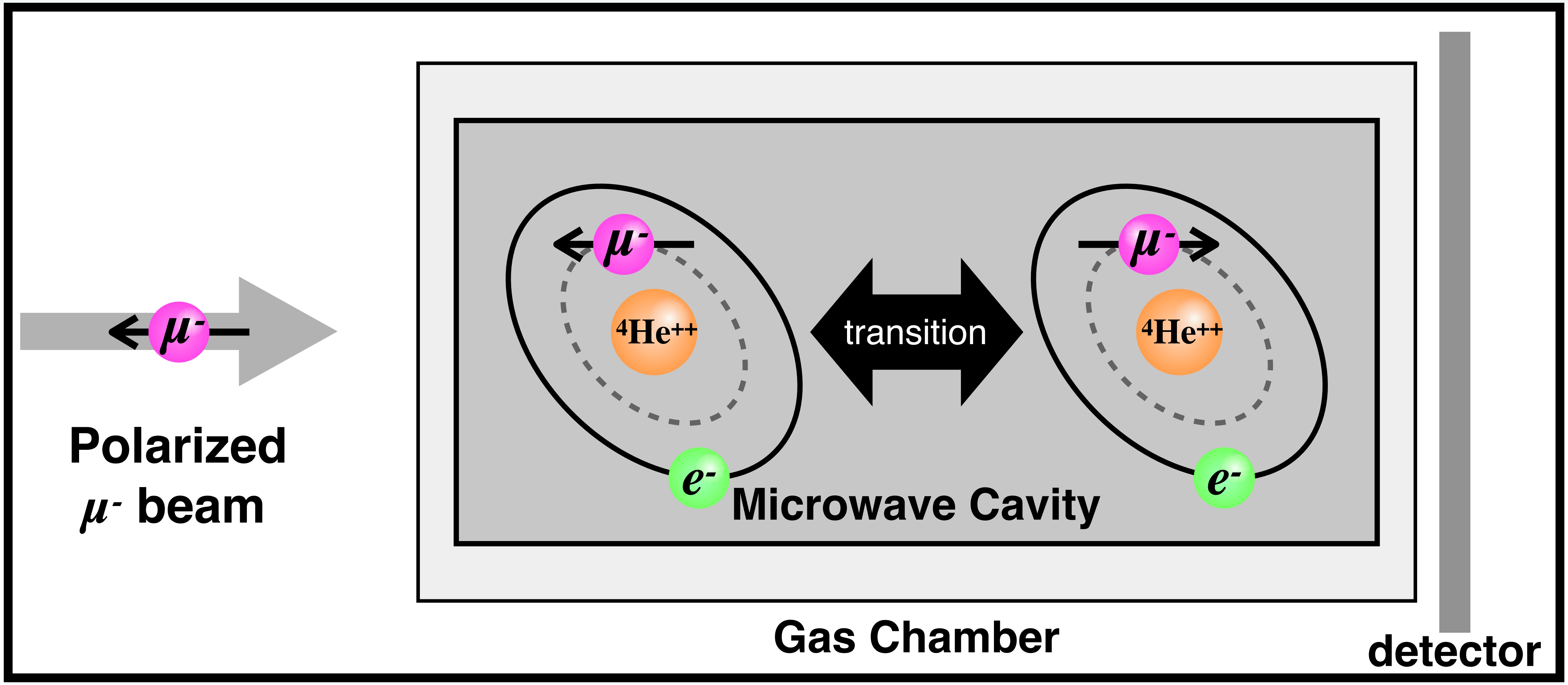
Measurement principle



A polarized negative muon beam is stopped in helium gas inside microwave cavity

The gas chamber is filled with ^{4}He gas and a small amount (~2%) of CH_4 as an electron donor

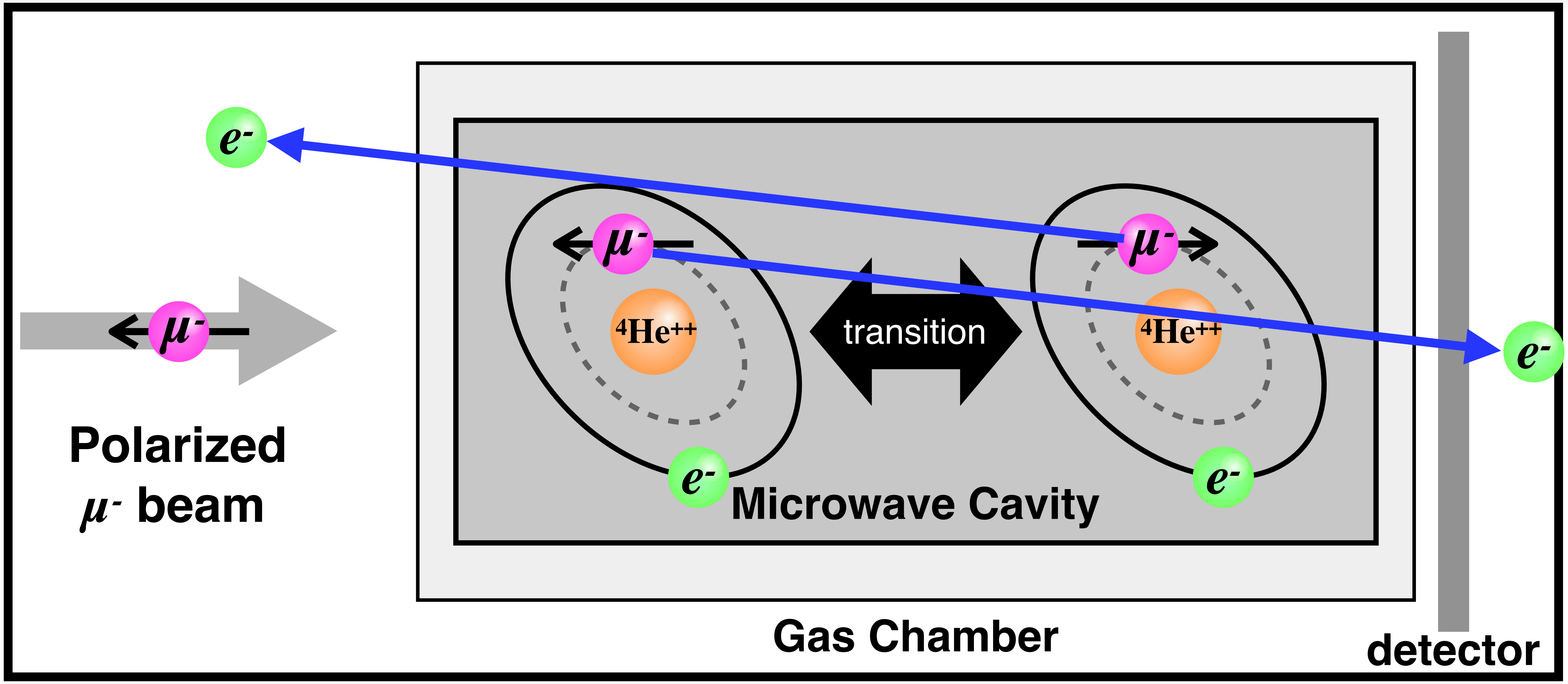
Measurement principle



Applying a microwave field

→The spin of the negative muon in muonic helium is flipped at the resonance frequency

Measurement principle



μ^- decays in 2.2 μs and emits electron along opposite direction of the spin

→Determine the HFS by counting the number of decay electrons with varying the microwave frequency

- HFS value shifts by surrounded gas pressure

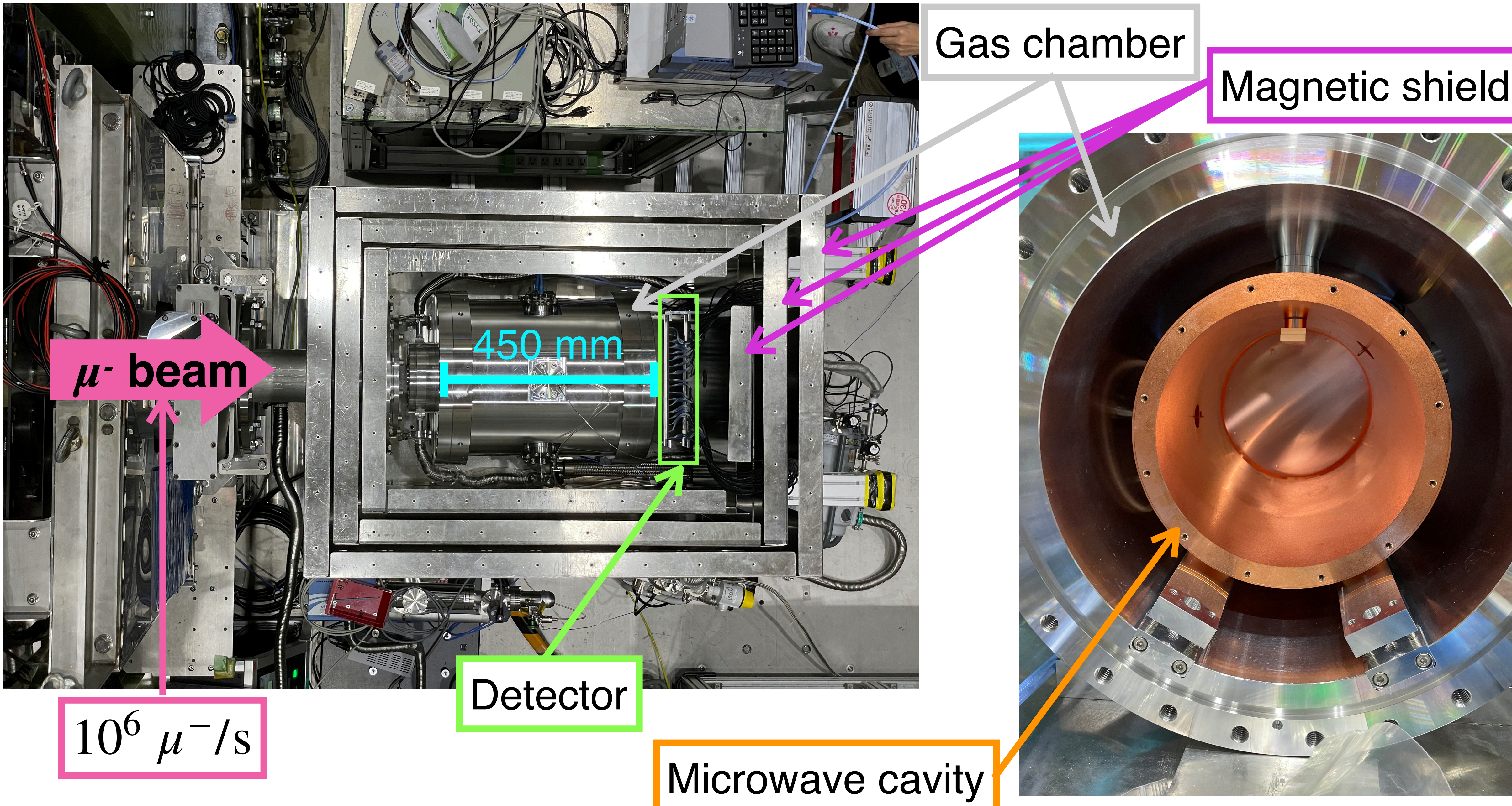
  →Need to measure in some pressure and extrapolate to vacuum

Recent experiment

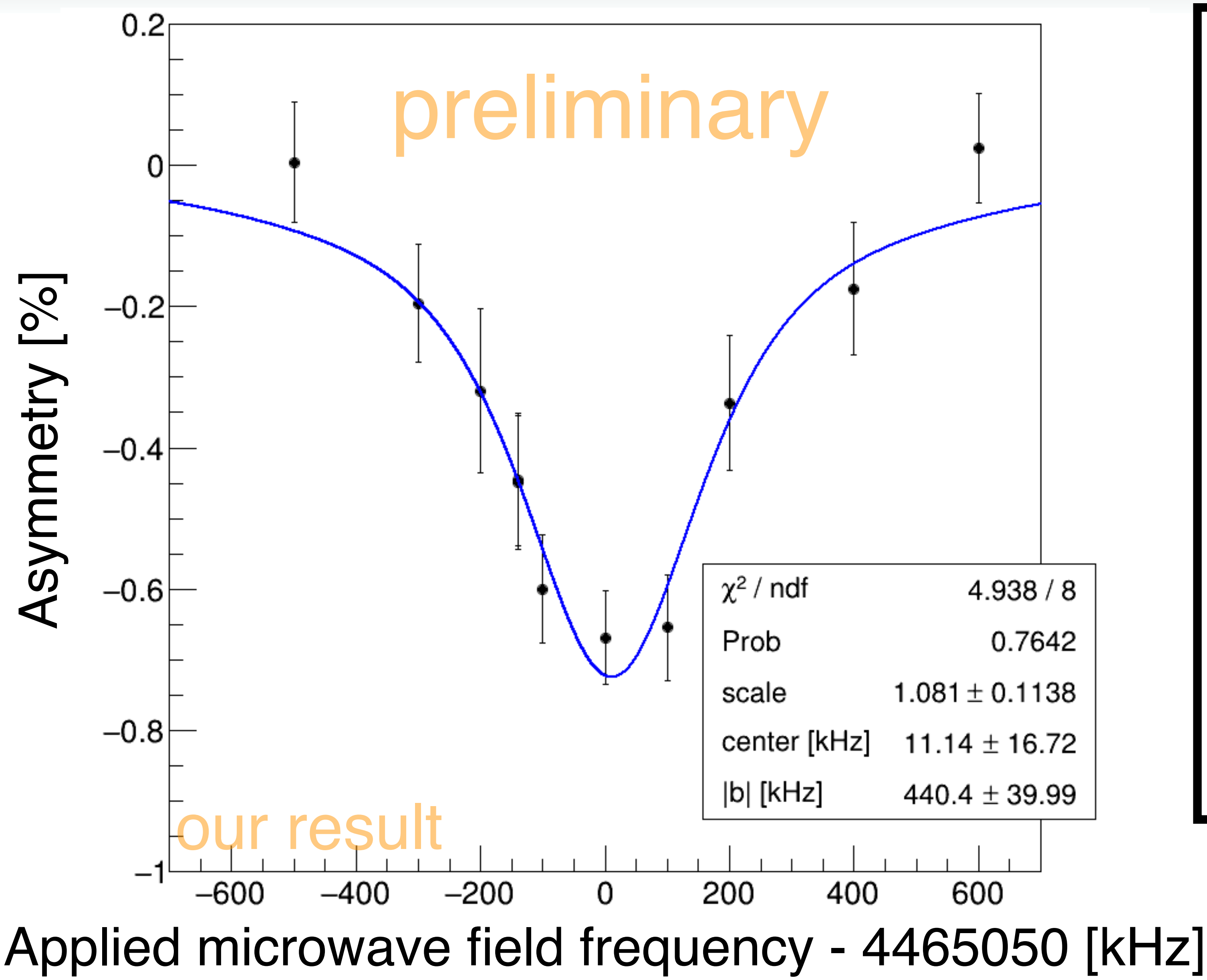
Two experimental campaigns were performed at J-PARC MUSE D2

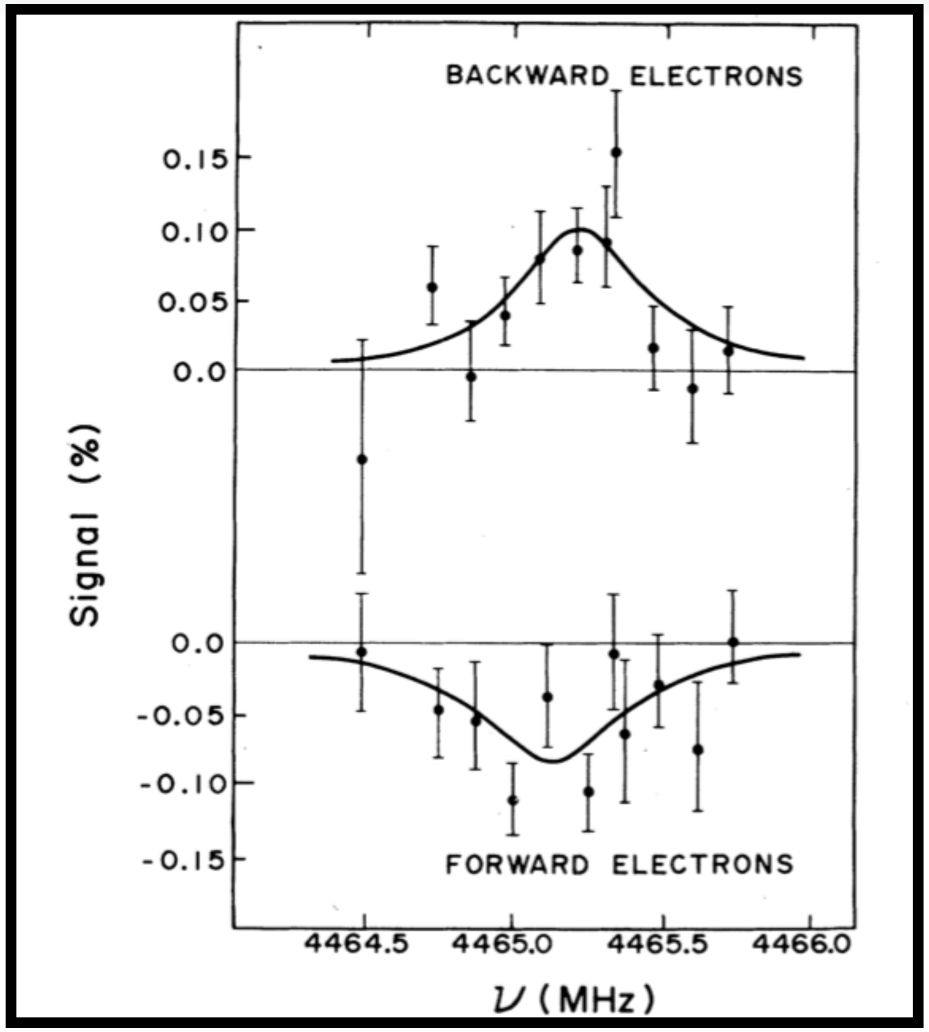
…Measured at zero magnetic field. Total pressures of gas target are

4 atm(@2021), 10.5 atm, 3 atm(@2022)



Result (@4 atm, March 2021)





↑Result of previous work in zero field

...H.Orth, et al., Phys. Rev. Lett. 45, 1483 (1980)

- Result :

  $$\Delta\nu(4\ \text{atm}) = 4465.011\,(16)\ \text{MHz}\ (4\ \text{ppm})$$

- Asymmetry is about 8 times higher than in previous work (0.1%)

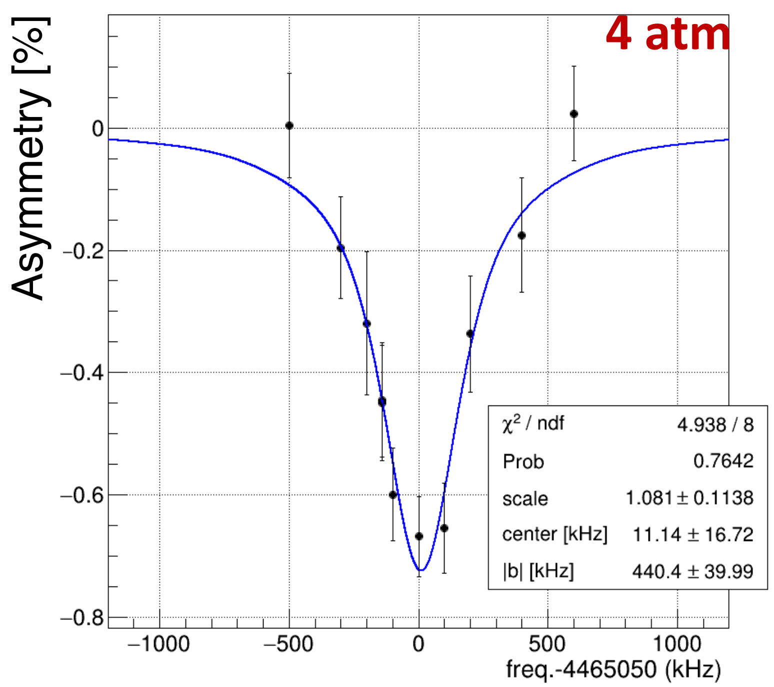
$$\text{Asymmetry} = \frac{N_{\text{off}}}{N_{\text{on}}} - 1$$

N_{on} : Number of detected e^- with microwave

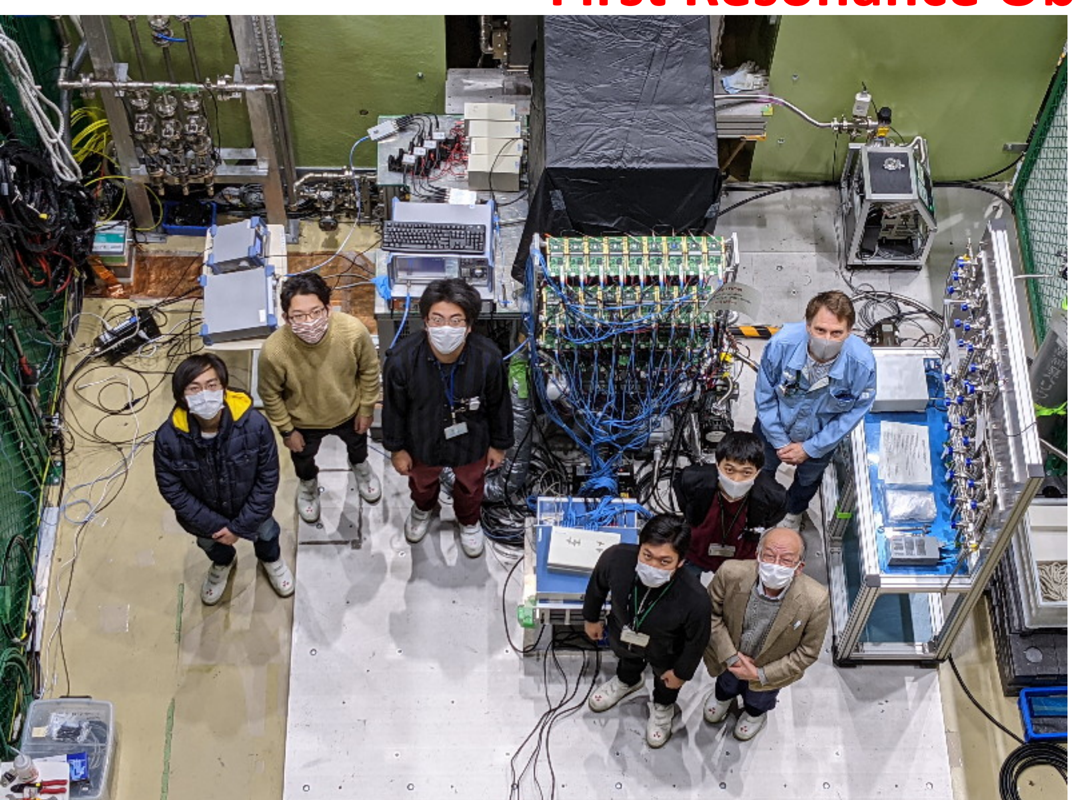
N_{off} : Number of detected e^- without microwave

μ⁻⁴He HFS Resonance Curve

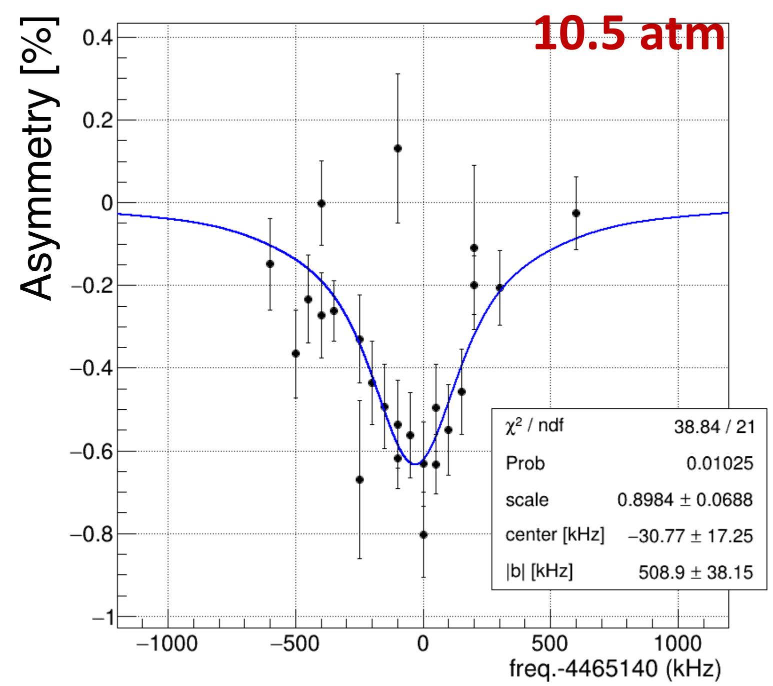
March 2021 Beamtime [2020B0333]



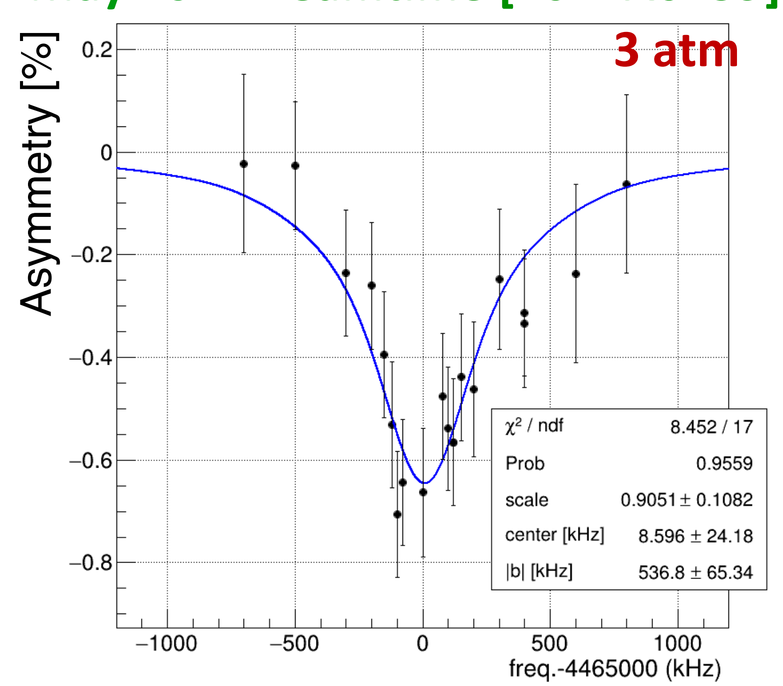
First Resonance Observed



February 2022 Beamtime [2021B0169]



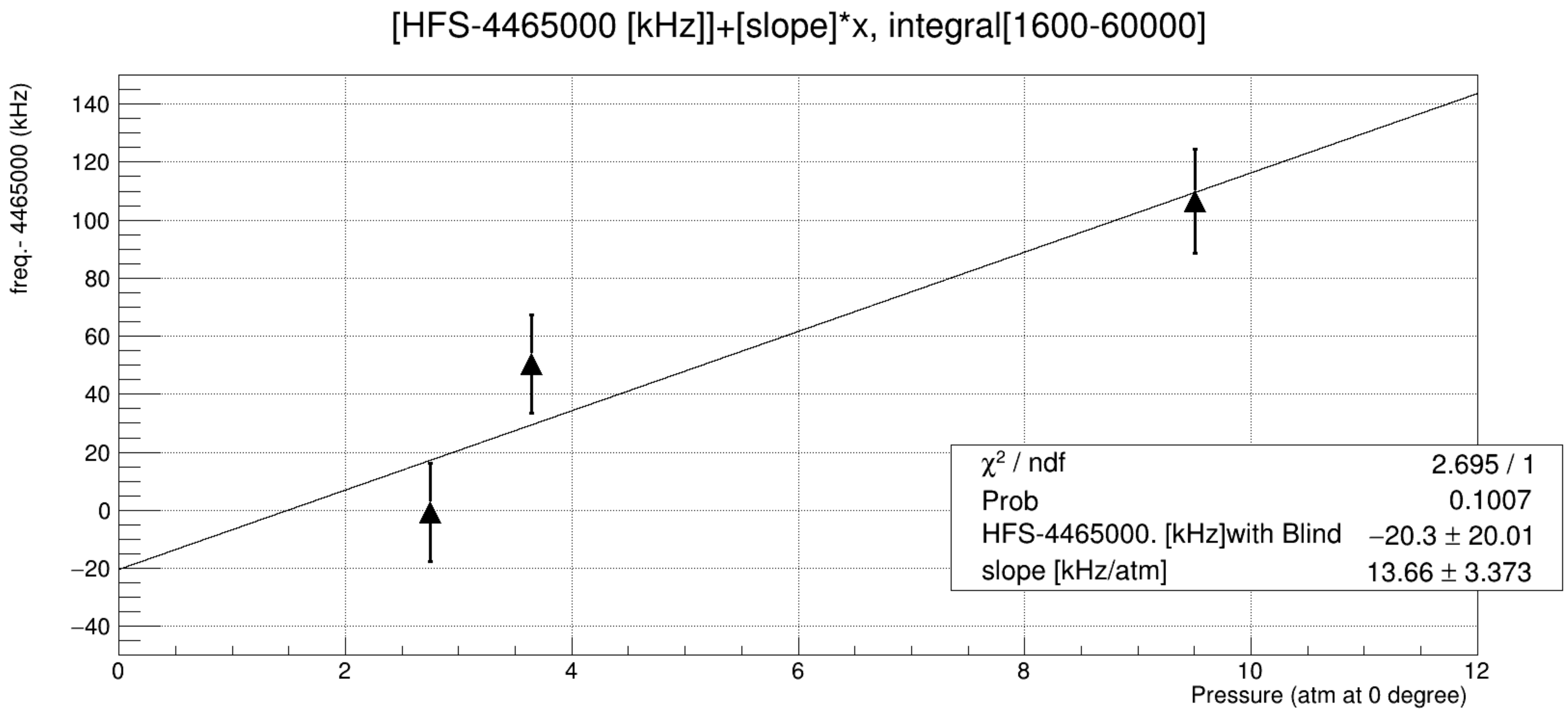
May 2022 Beamtime [2022A0159]



Time cut: electron data from 2 μs after second μ⁻ pulse !

Extrapolation

- The result of vacuum extrapolation is...



$$\Delta\nu(0\ \mathrm{atm}) = 4464.980\,(20)\ \ \mathrm{MHz}\,\left(4.5\ \mathrm{ppm}\right)$$

Blind Analysis for MuSEUM

Hidden answer method

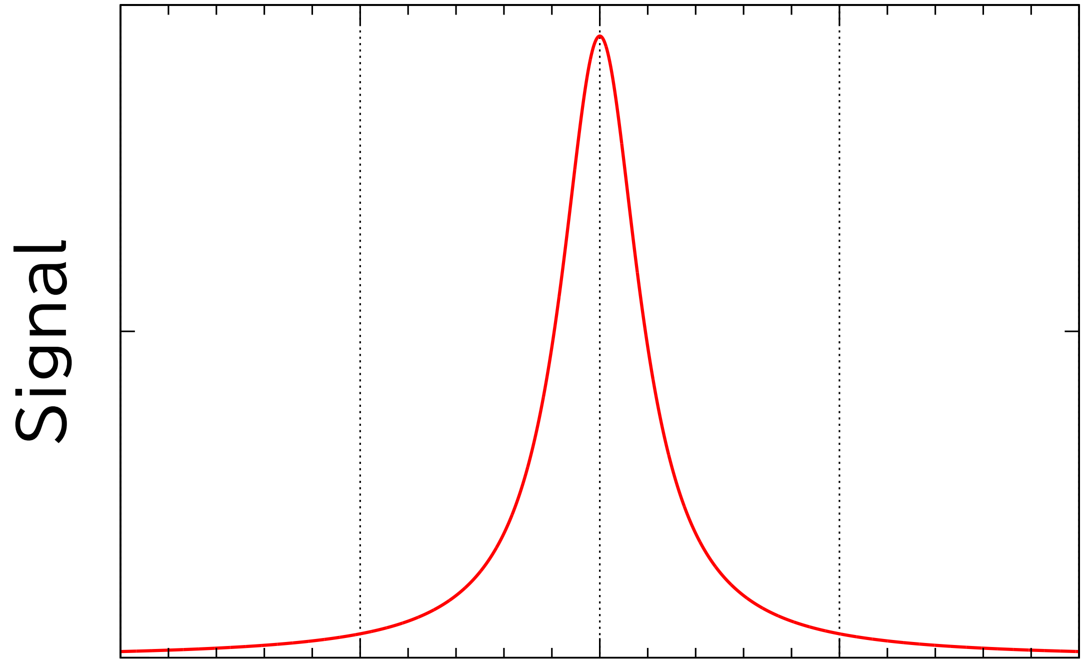
Value to be blinded | Injecting microwave frequency

- Microwave frequency input by user | ν_{set}
- Blinded offset | δ
- True microwave frequency | ν_{mw}

$$\nu_{mw} = \nu_{set} + \delta$$

- δ must be constant for all ν_{set} in order to draw a resonance curve
- If $|\delta| < 8$ kHz,
  - the blind value is sufficient for the target precision
  - the rate of change in stored microwave energy < 0.07%

Before opening the blind



ν_{mw} −4,463,302 kHz − δ

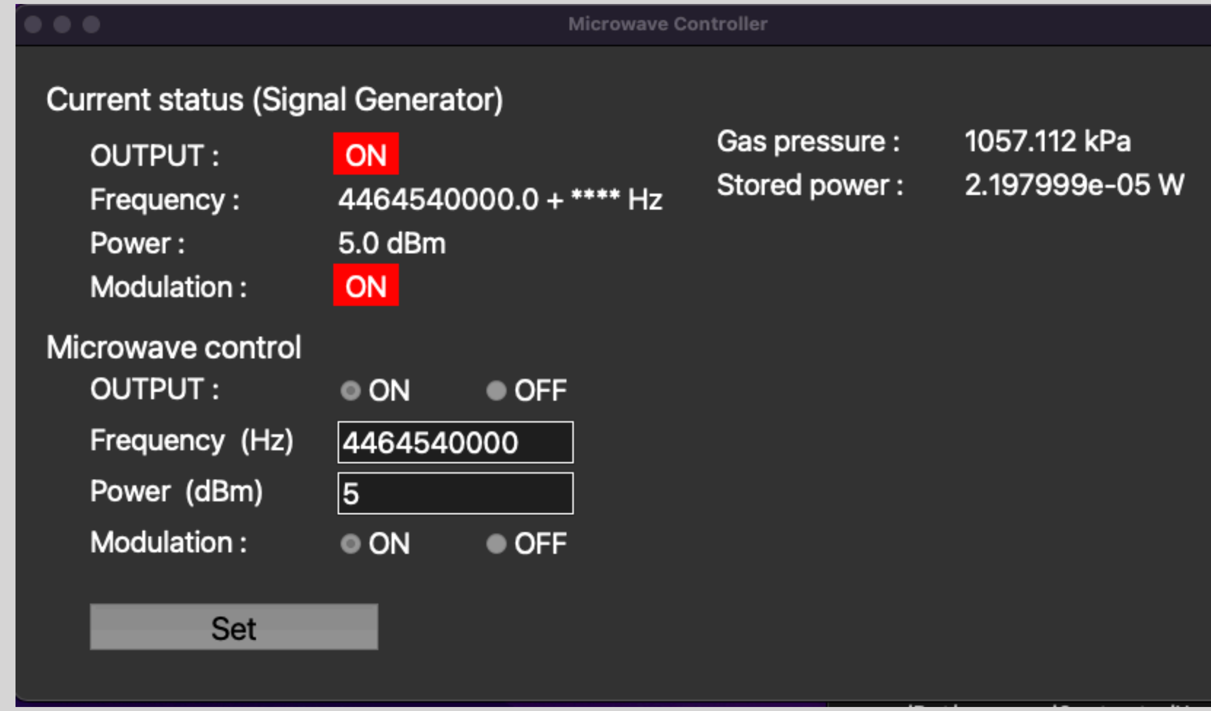
$= \nu_{set}$ −4,463,302 kHz

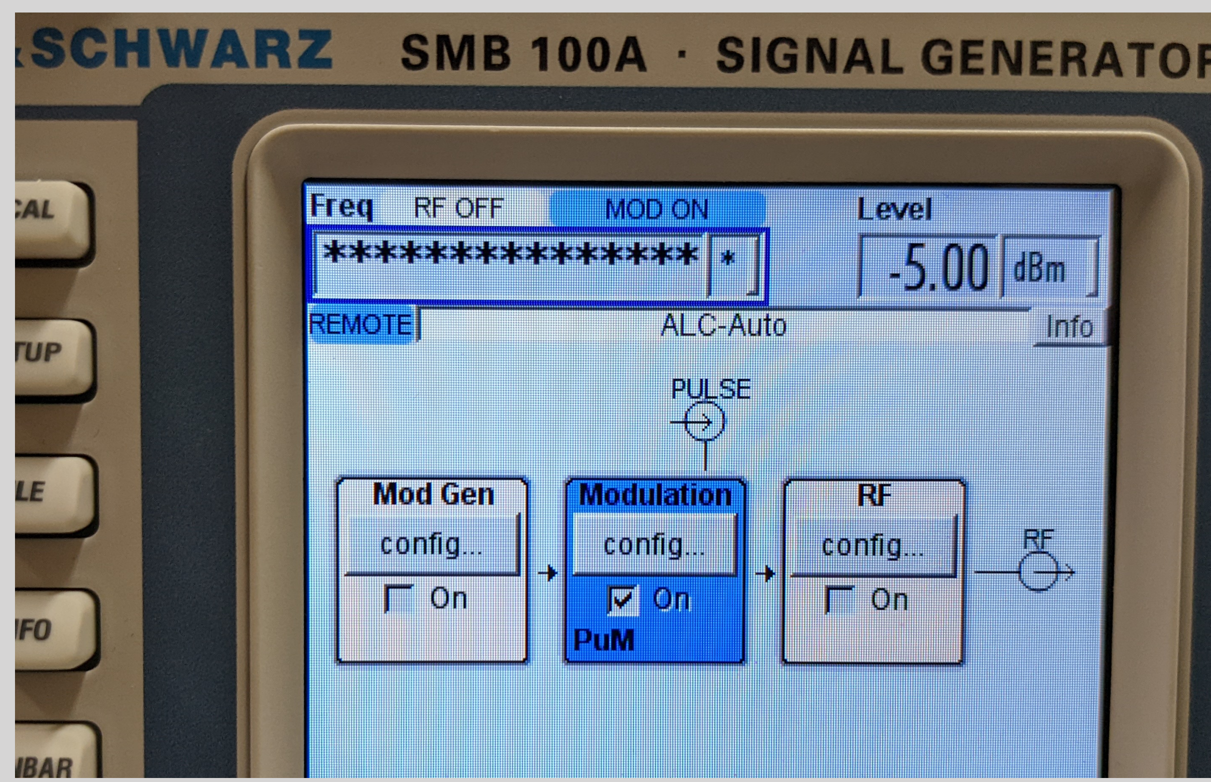
S.G. Controller & Slow Monitor

Implemented in Python3

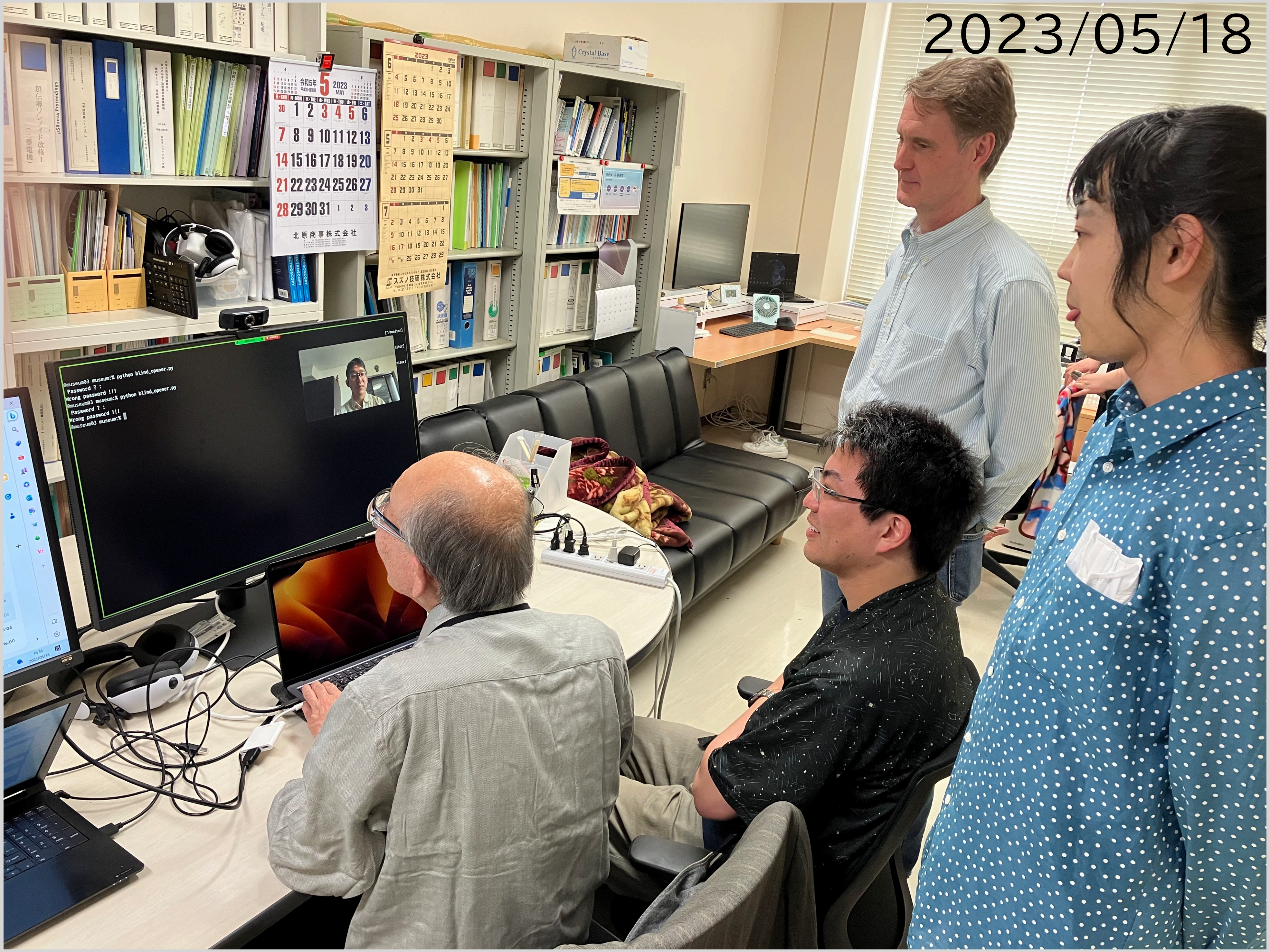
Function

- Password is required to execute
- Displayed value on the signal generator is blinded
- There are some safety/ protection features to prevent mis-operation
- Microwave power and gas pressure are also monitored and recorded





Blind Test (for μHe)

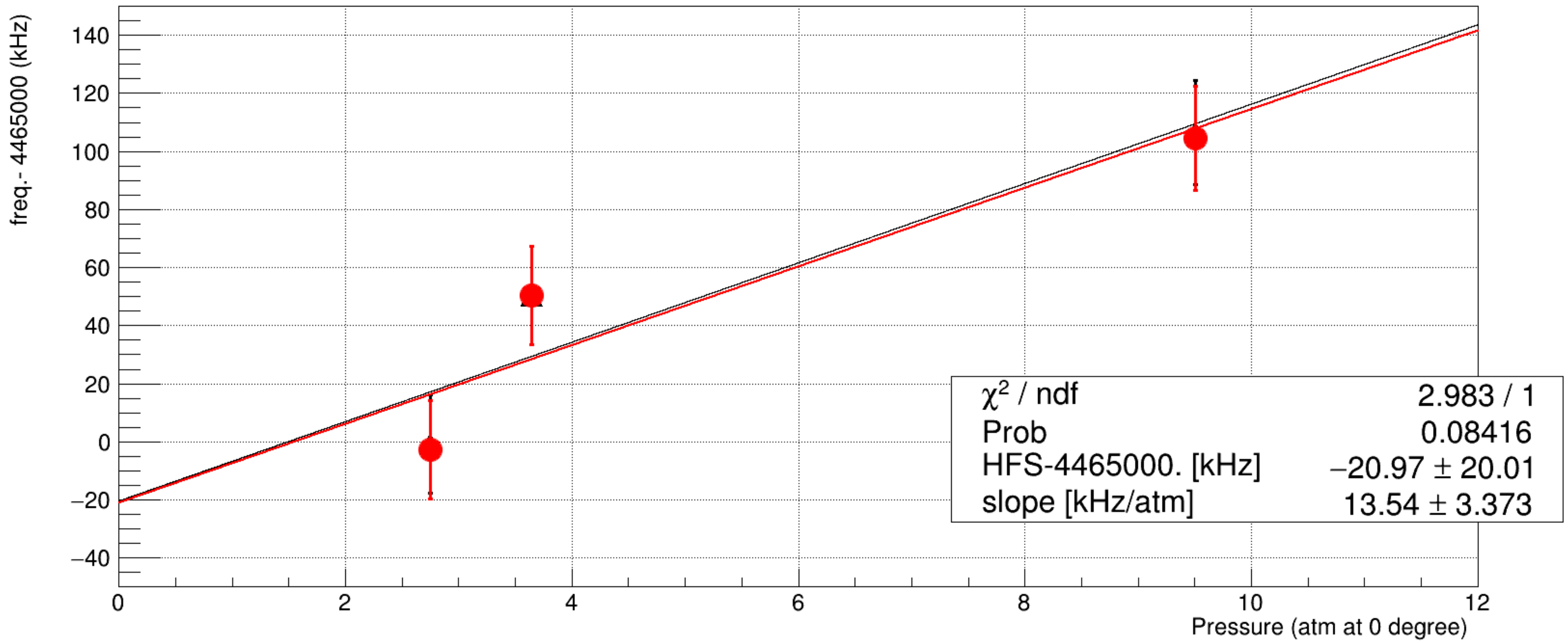


Blind analysis

- The blinded offset value is -1.926 kHz

  →The result of vacuum extrapolation after unblind is...

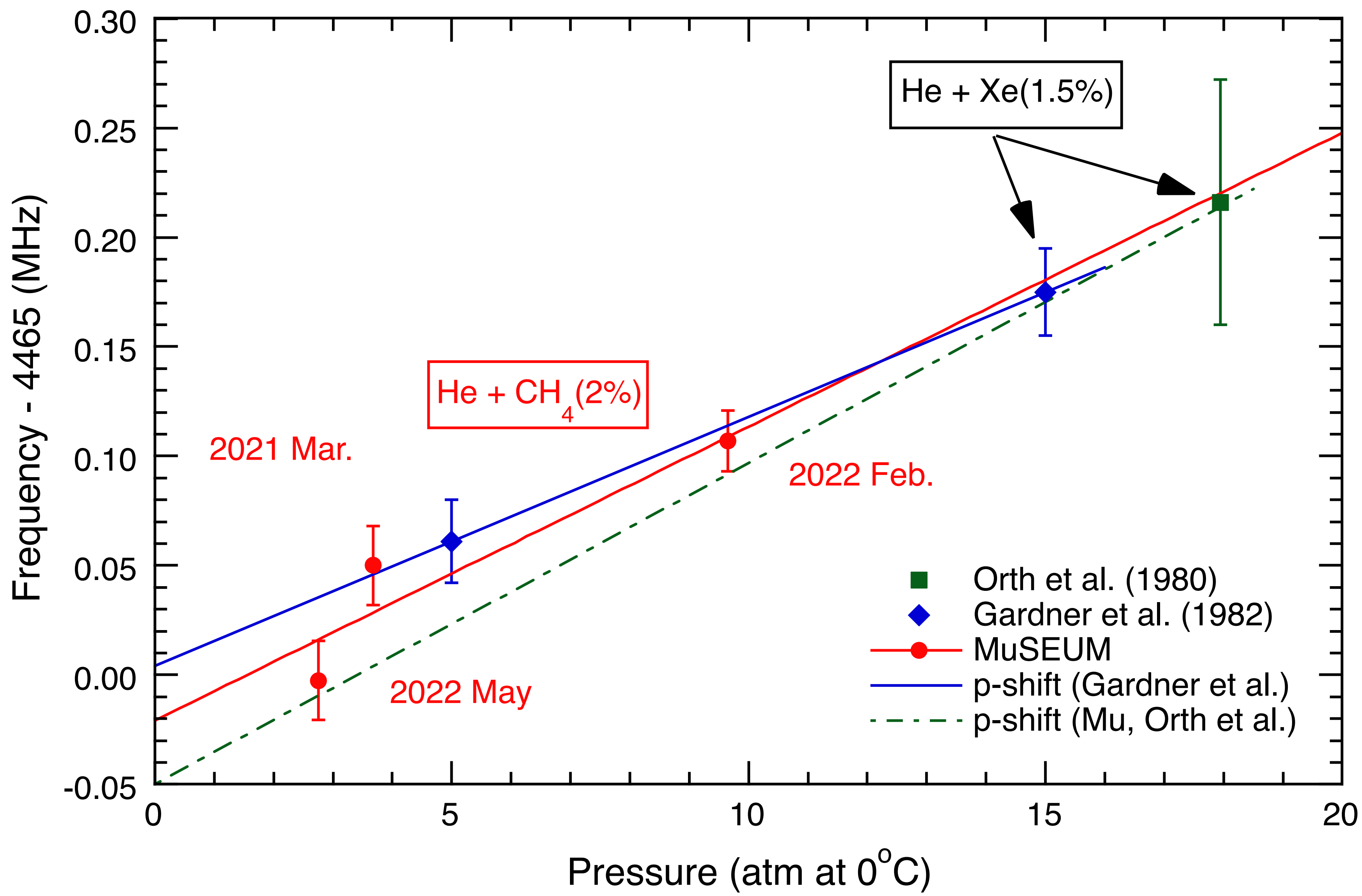
[HFS-4465000 [kHz]]+[slope]*x, integral[1600-60000]



$$\Delta\nu(0\ \text{atm}) = 4464.980\,(20)\ \ \text{MHz}\ (4.5\ \text{ppm})$$

$$\rightarrow \Delta\nu(0\ \text{atm}) = 4464.979\,(20)\ \ \text{MHz}\ (4.5\ \text{ppm})$$

Extrapolation to Zero Pressure



$\Delta\nu$ = 4464.95(6) MHz (Orth et al.) [13 ppm] zero field (ZF)

$\Delta\nu$ = 4465.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)

$\Delta\nu$ = 4464.979(20) MHz (MuSEUM) [4.5 ppm] zero field

consistent within 1σ

➢ **World Record!**

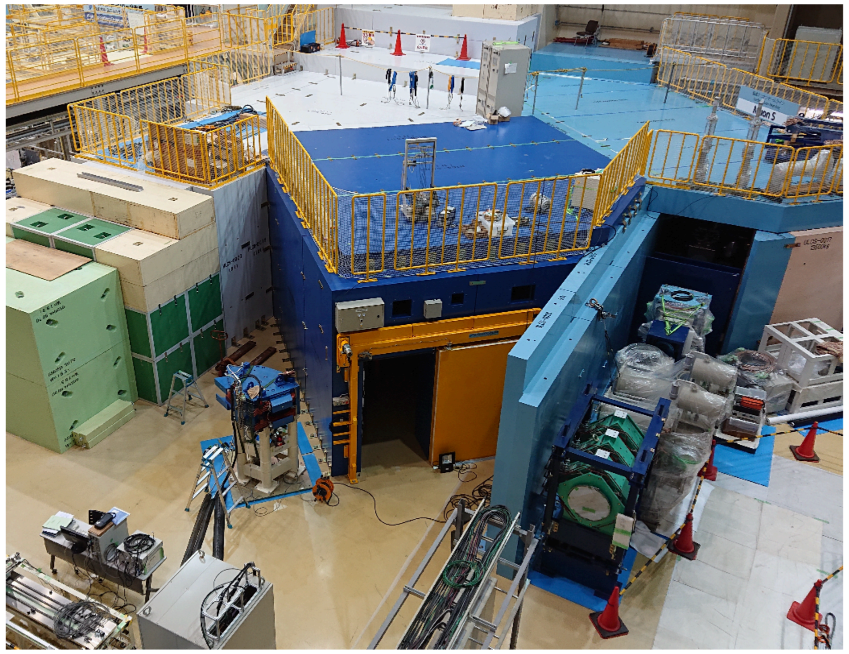
ZF : H. Orth et al., PRL 45 (1980) 1483
HF : C. J. Gardner et al., PRL48 (1982) 1168

Toward higher precision

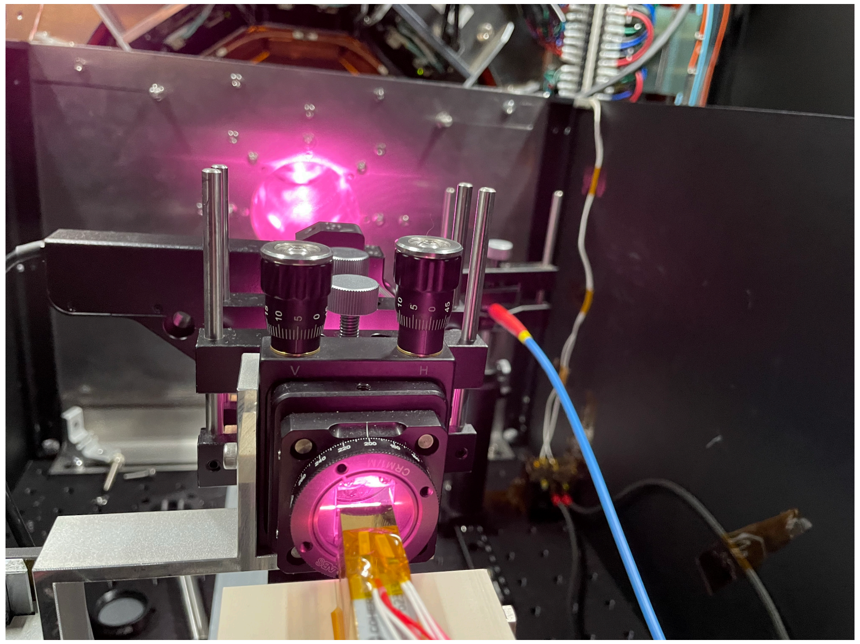
- We determined the Muonic Helium HFS with a precision of 4.5 ppm at zero field ... World record

- Precision will be further improved by using a new high intensity beamline "H-Line" at J-PARC (10 times higher rate)

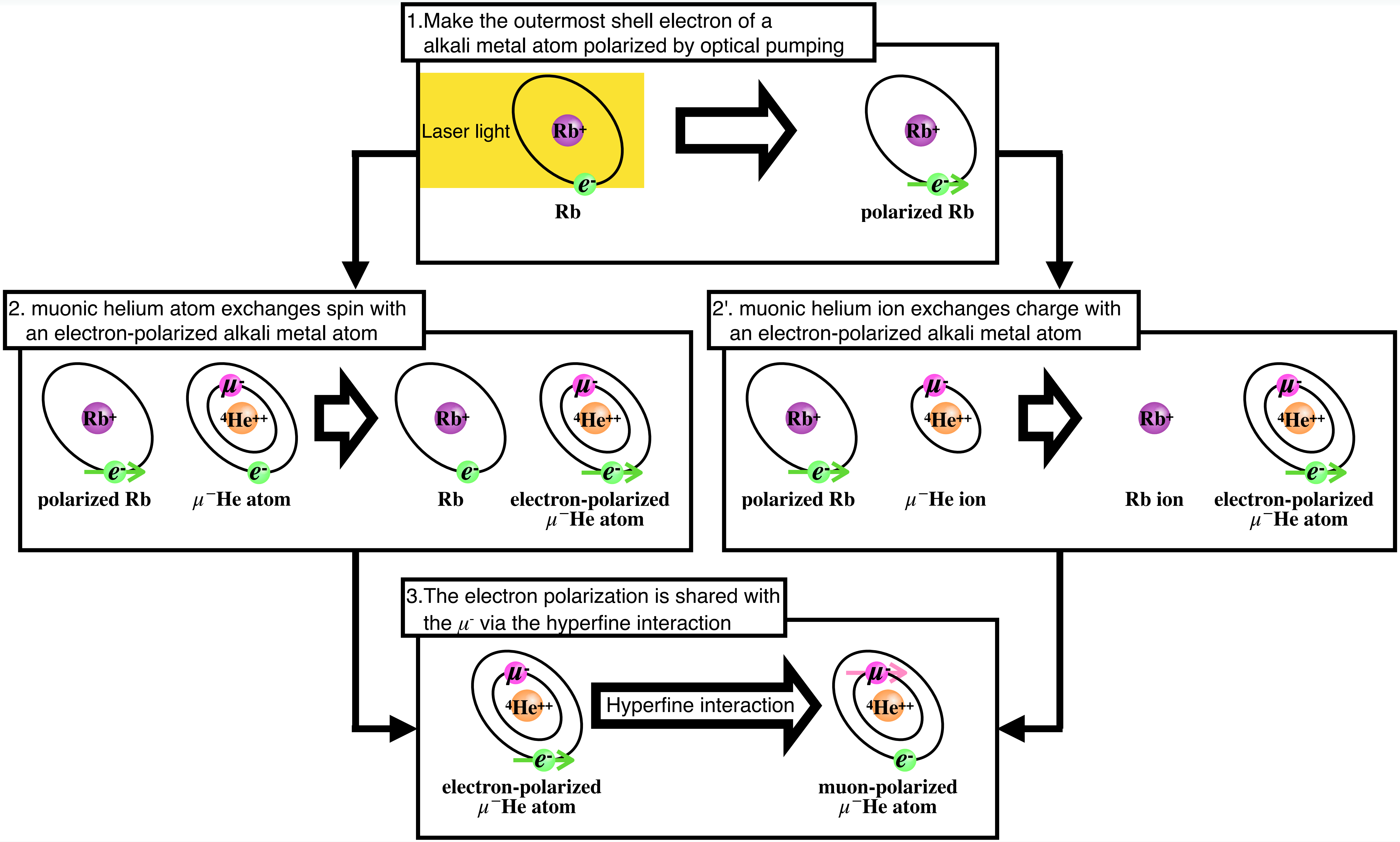
...T. Yamazaki, et al., EPJ Web Conf. **282** 01016 (2023)
N. Kawamura, et al., Prog. Theor. Exp. Phys. 2018, 113G01 (2018)



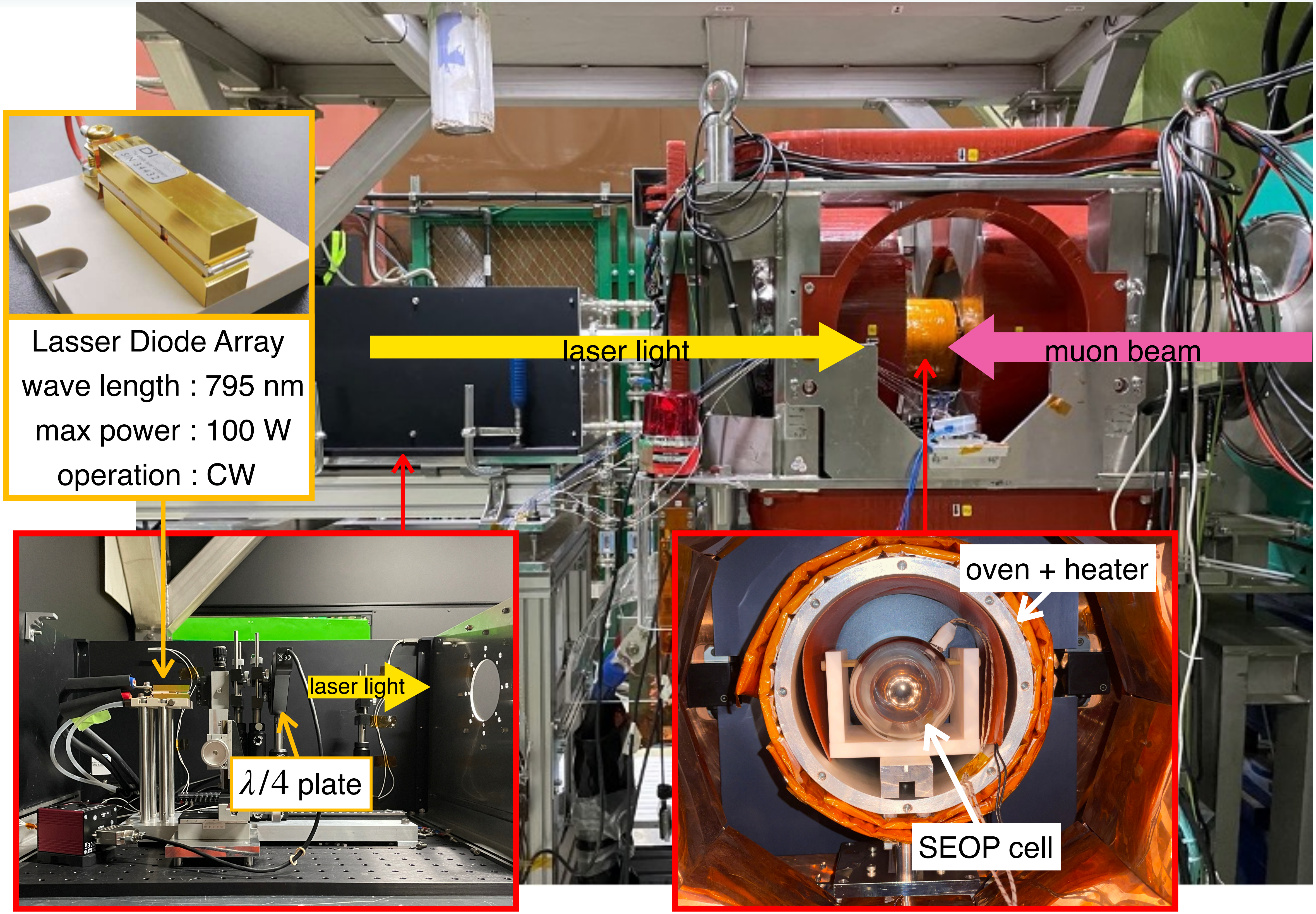
- The polarization of μ^- still significantly limits the measurement precision
  →Develop Spin Exchange Optical Pumping (SEOP) to repolarize the μ^-



SEOP for Muonic Helium

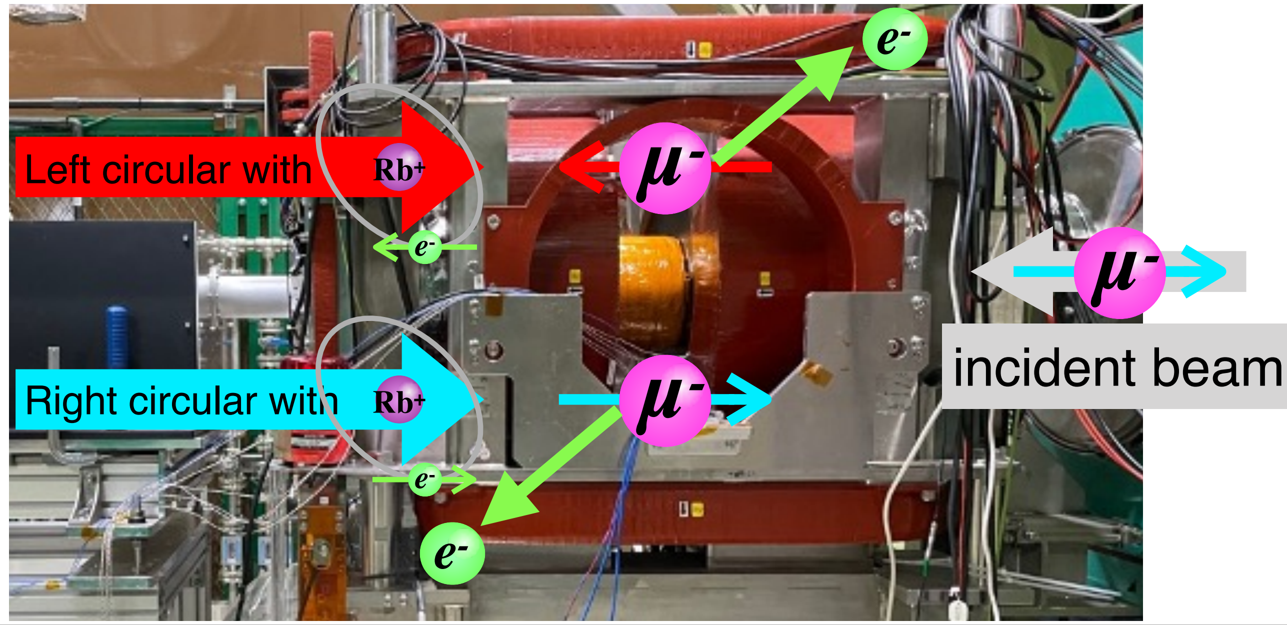


Setup of muonic helium SEOP @2023 Feb



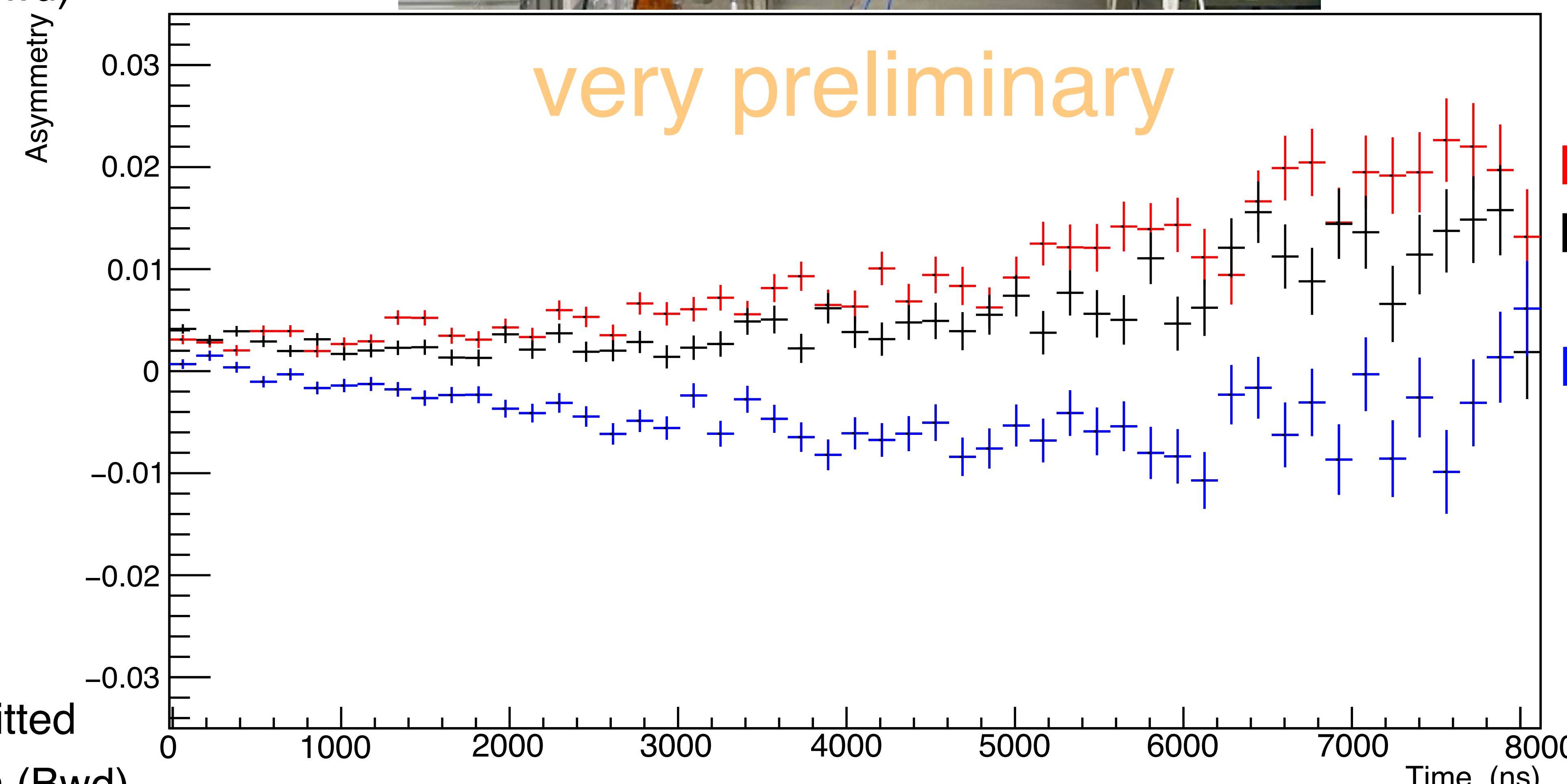
Result

- Hybrid cell, 200°C



electron emitted upstream (Fwd)

electron emitted downstream (Bwd)



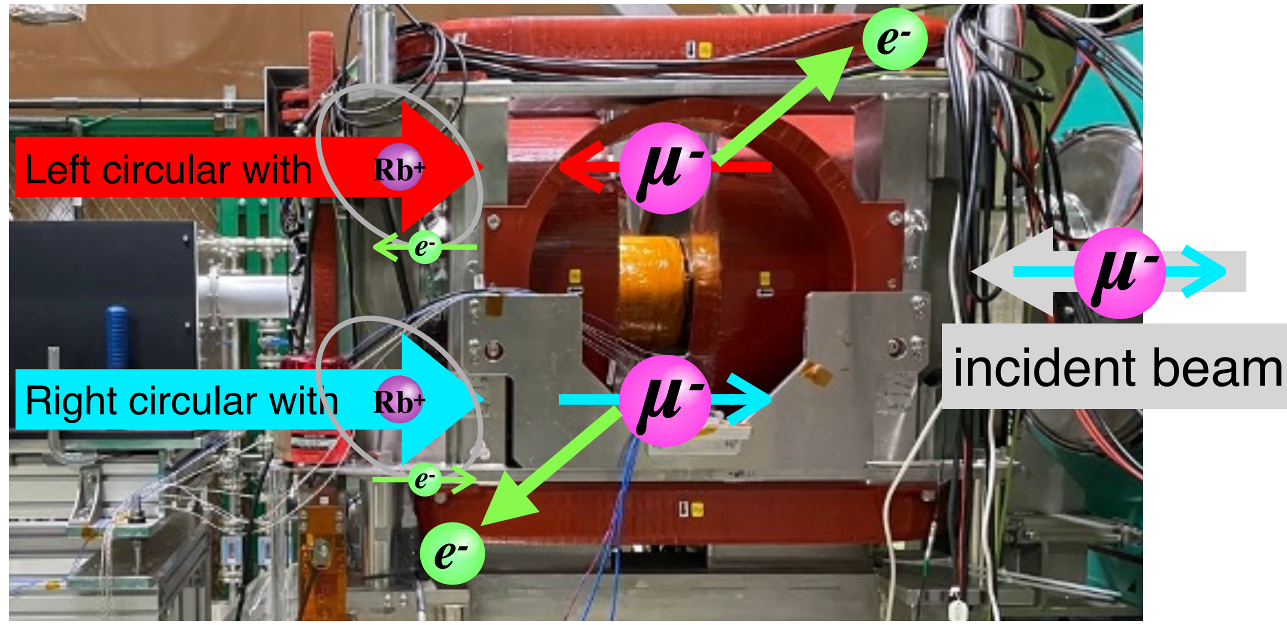
Left circular

Linear

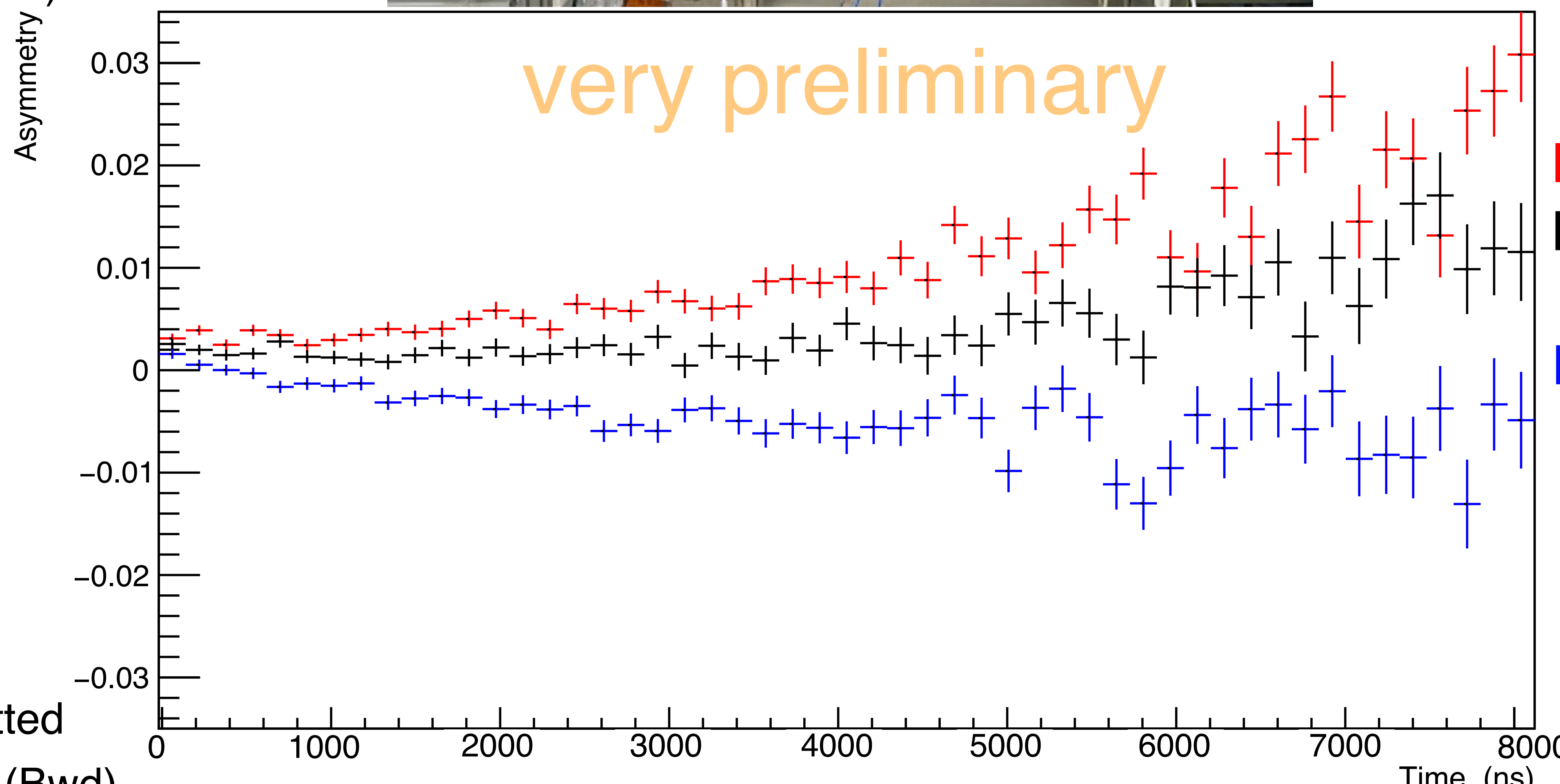
Right circular

Result

- Hybrid cell, 220°C



electron emitted upstream (Fwd)

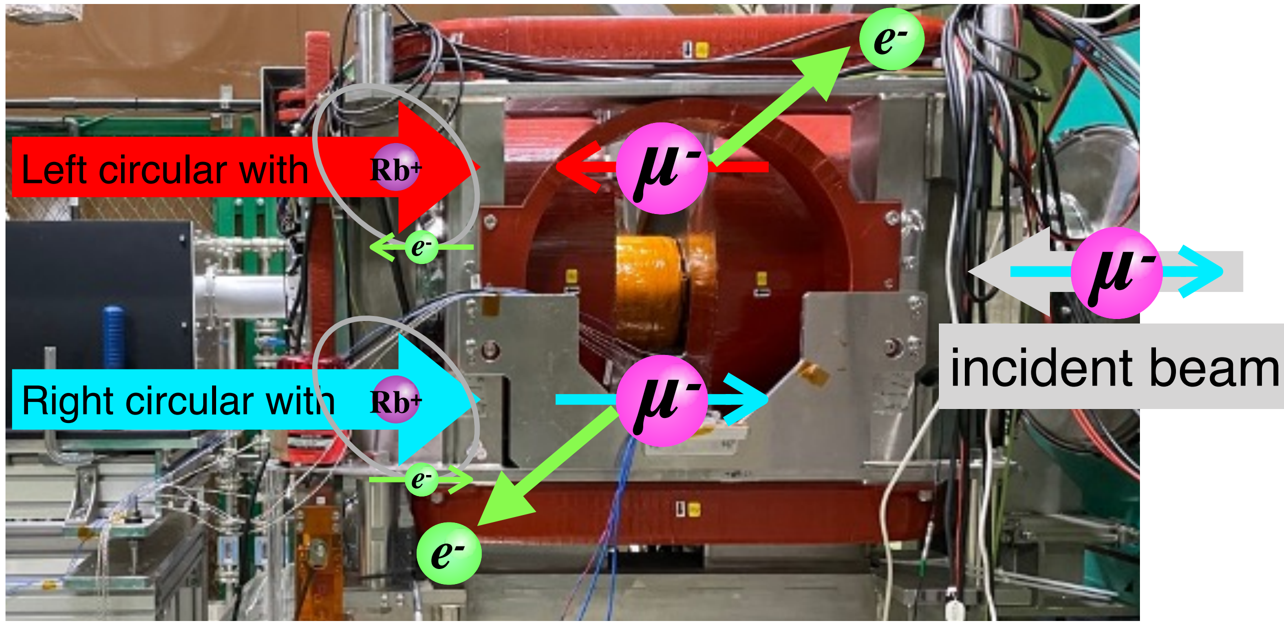


electron emitted downstream (Bwd)

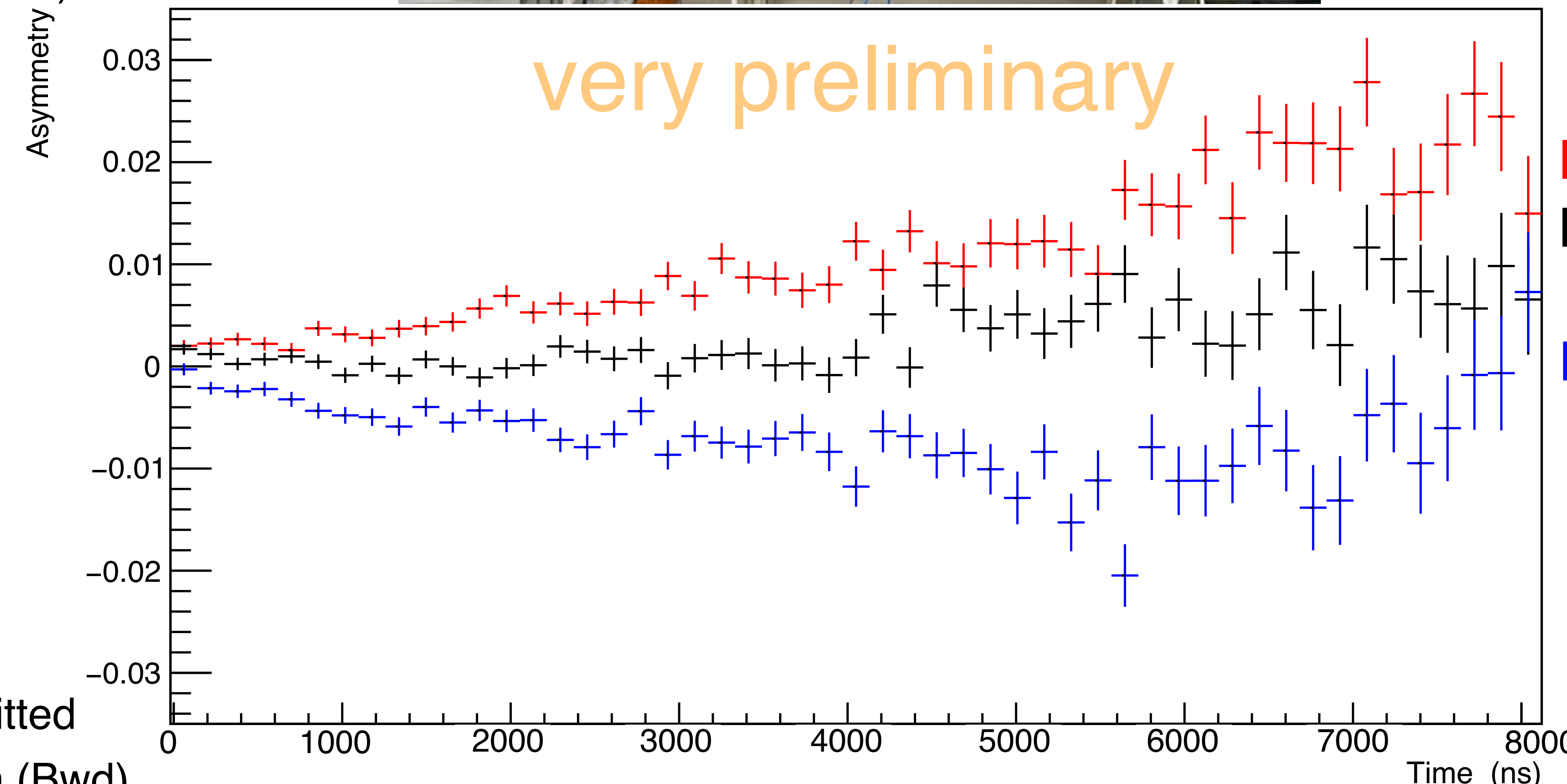
Left circular
Linear
Right circular

Result

- Hybrid cell, 240°C



electron emitted upstream (Fwd)



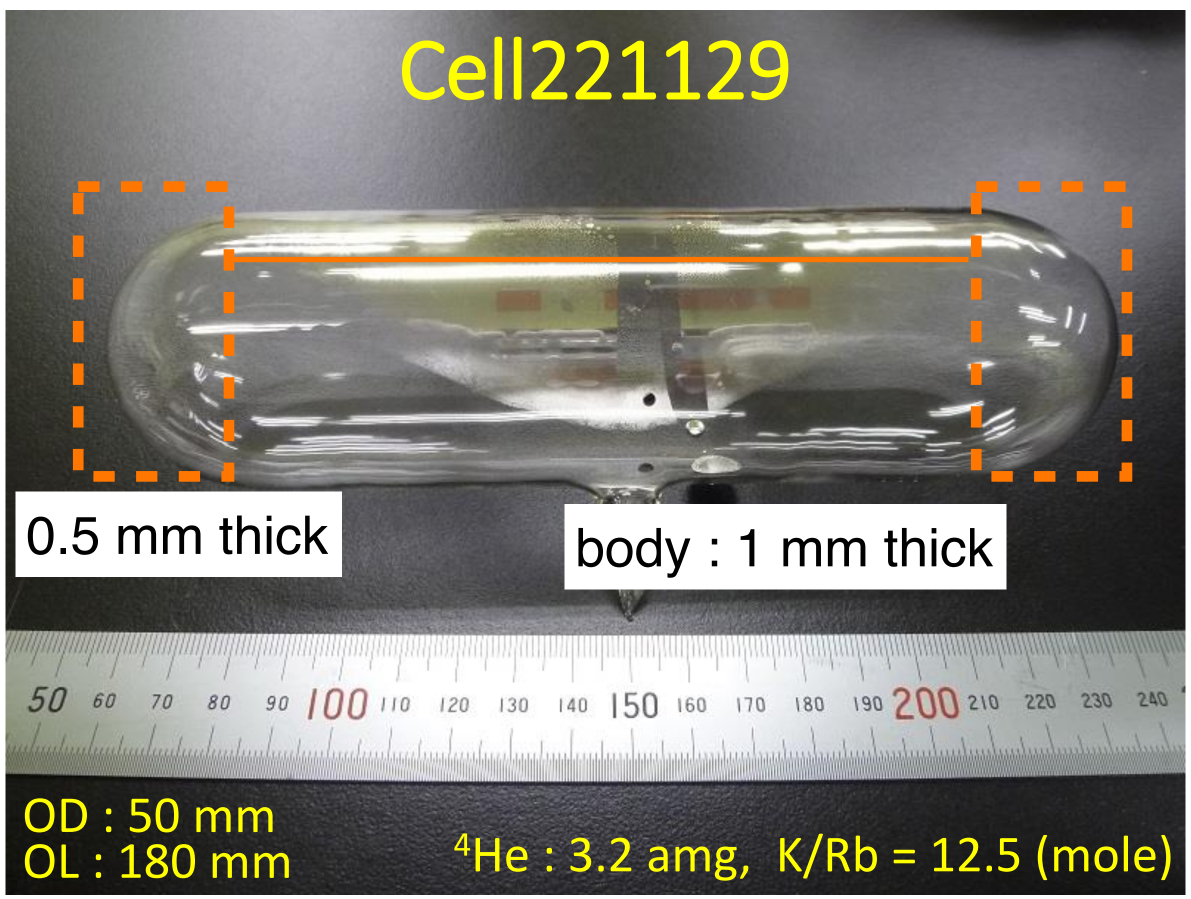
Left circular

Linear

Right circular

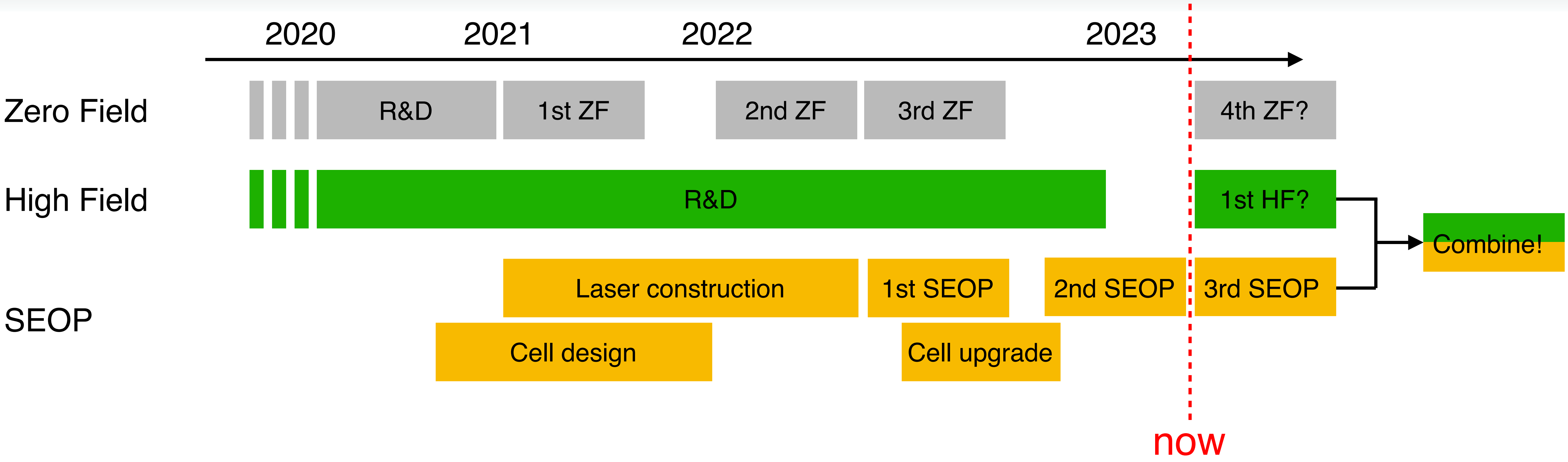
electron emitted downstream (Bwd)

Cells for muonic helium SEOP



- Made from GE180, which is a kind of glass with alkali metal resistance
- Produced by Tohoku University Glass Factory
- The laser was shaped to about Φ40 mm
  So next, we will use a cell with an outer diameter of 50 mm to improve achieved polarization
- Our next beamtime will assigned next month

Status and summary



- Muonic helium : Powerful tool to test theories of quantum three-body systems

  In high magnetic field, we can determine μ_{μ^-} and m_{μ^-} with HFS
- Zero Field : World Record!
- High Field : Toward higher precision with very high intensity muon beam and superconducting magnet
- SEOP : Toward higher precision with repolarized μ^-

  Next beamtime, we will use slim cell and aim to product more highly polarized muonic helium atoms.
- In future, the SEOP system and high field experiment will be combined!

Theory of HFS

- Hamiltonian of muonic helium in static magnetic field $\vec{B}$

$$\mathcal{H} = \underbrace{-h\Delta\nu \vec{I}\cdot\vec{J}}_{\text{Hyperfine interaction}} + \underbrace{g_J \mu_B \vec{J}\cdot\vec{B} + g'_\mu \mu_B^\mu \vec{I}\cdot\vec{B}}_{\text{Zeeman effect}}$$

$g_J,\ g'_\mu$: The g-factors of the electron and muon bound in muonic helium

μ_B : $e\hbar/2m_e c$ (Bohr magneton)

μ_B^μ : $e\hbar/2m_\mu c$

→Energy levels given by Breit-Rabi formula

$$\lambda = \frac{h\Delta\nu}{4} + g'_\mu \mu_B^\mu M_F B_z \mp \frac{1}{2}\sqrt{h^2\Delta\nu^2\left(I+\frac{1}{2}\right)^2 - 2h\Delta\nu\left(g_J\mu_B - g'_\mu\mu_B^\mu\right)M_F B_z + \left(g_J\mu_B - g'_\mu\mu_B^\mu\right)^2 B_z^2}$$

$$\rightarrow h\nu_{12} = -g'_\mu \mu_B^\mu B_z + \frac{h\Delta\nu}{2}\left(1 - x + \sqrt{1+x^2}\right)$$

$$h\nu_{34} = g'_\mu \mu_B^\mu B_z + \frac{h\Delta\nu}{2}\left(1 + x - \sqrt{1+x^2}\right)$$

$$\rightarrow \nu_{12} + \nu_{34} \equiv \Delta\nu$$

$$x = \left(g_J\mu_B - g'_\mu\mu_B^\mu\right)B_z/h\Delta\nu$$

Theory of HFS

- The difference of ν_{12} and ν_{34} is directly related to the ratio of the negative muon and proton magnetic moments

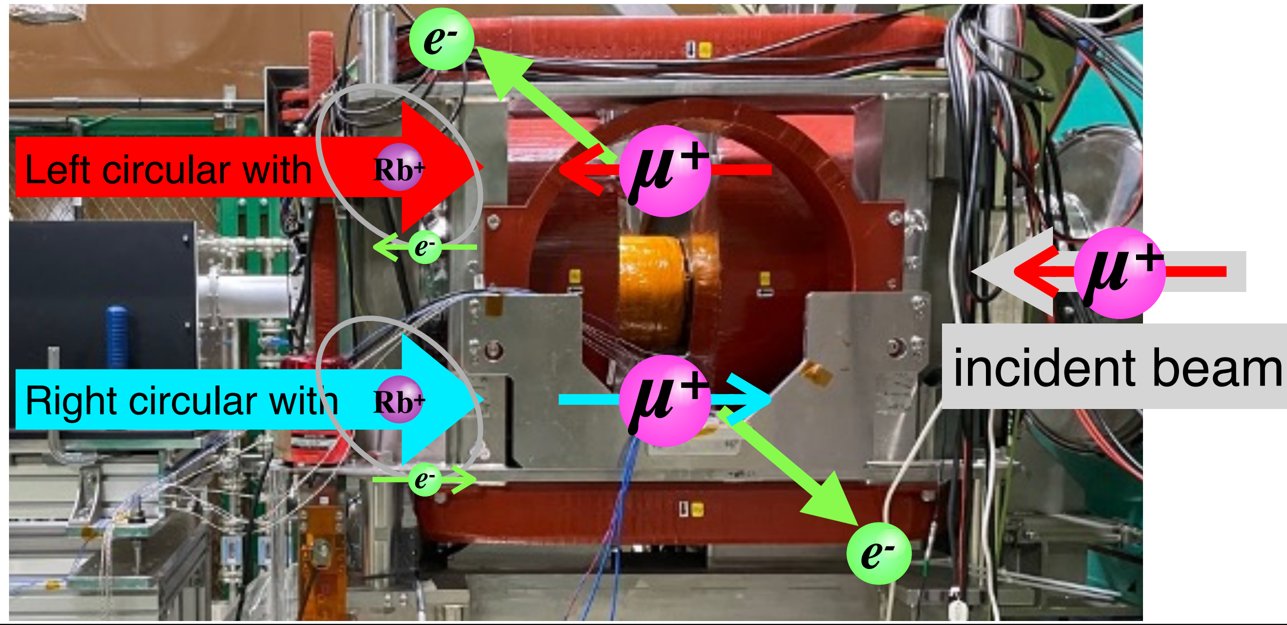
$$\nu_{34} - \nu_{12} = 2g'_\mu \mu_B^\mu \frac{B_z}{h} + \Delta\nu \left(x - \sqrt{1 + x^2}\right)$$
$$= g'_\mu \mu_B^\mu \frac{\nu_p}{\mu_p} + \Delta\nu \left(x - \sqrt{1 + x^2}\right)$$

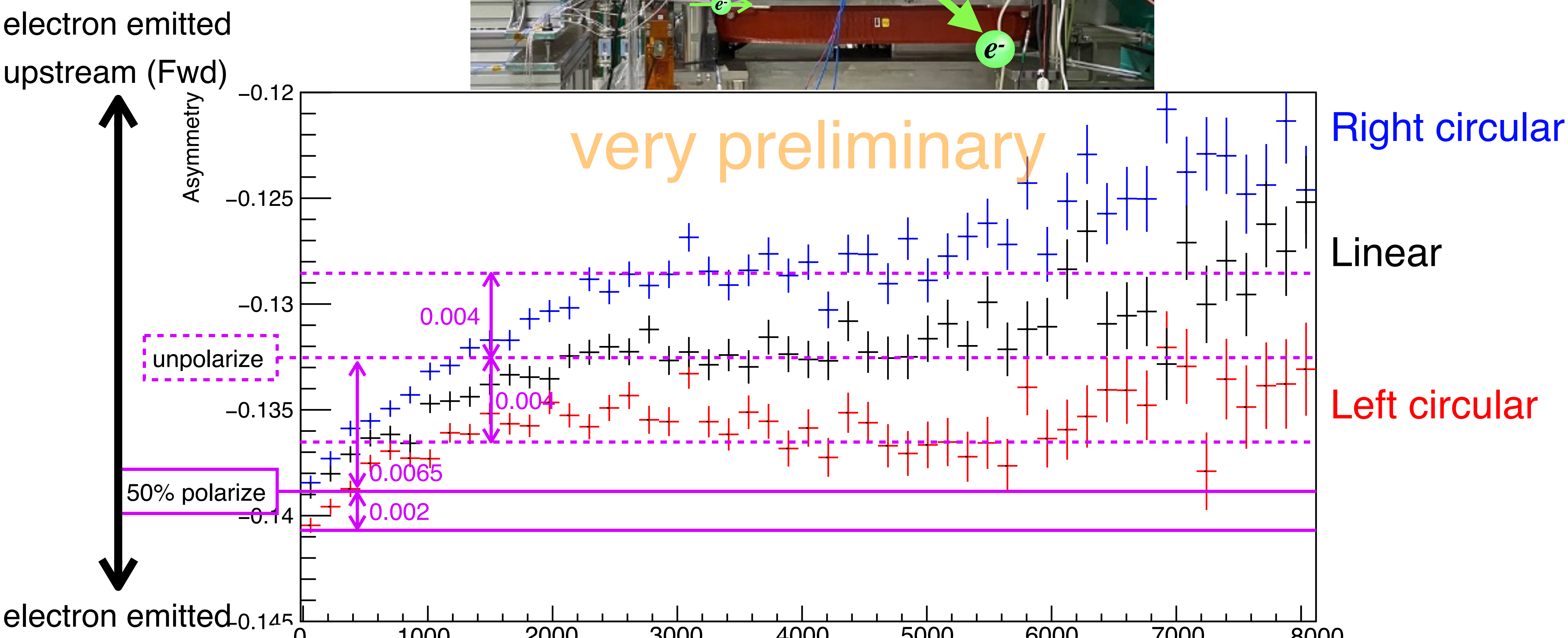
by using $r'_e = \mu_e/\mu_p = g_J \mu_B/2\mu_p$ and $r'_\mu = \mu_\mu/\mu_p = g'_\mu \mu_B^\mu/2\mu_p$,
then $x = \left(r'_e - r'_\mu\right) \nu_p/\Delta\nu$ and

$$\frac{\mu_{\mu^-}}{\mu_p} = r'_\mu \frac{g_\mu}{g'_\mu}$$
$$= \frac{2\nu_{12}\nu_{34} + r'_e v_p(\nu_{34} - \nu_{12})}{v_p\left[2r'_e v_p - (\nu_{34} - \nu_{12})\right]} \frac{g_\mu}{g'_\mu}$$

Result

- Rb cell, 200°C
  Inject μ^+ into the cell
  →forming muonium





Roughly estimated polarization of Rb (= achieved polarization of μ) from asymmetry is 30%.