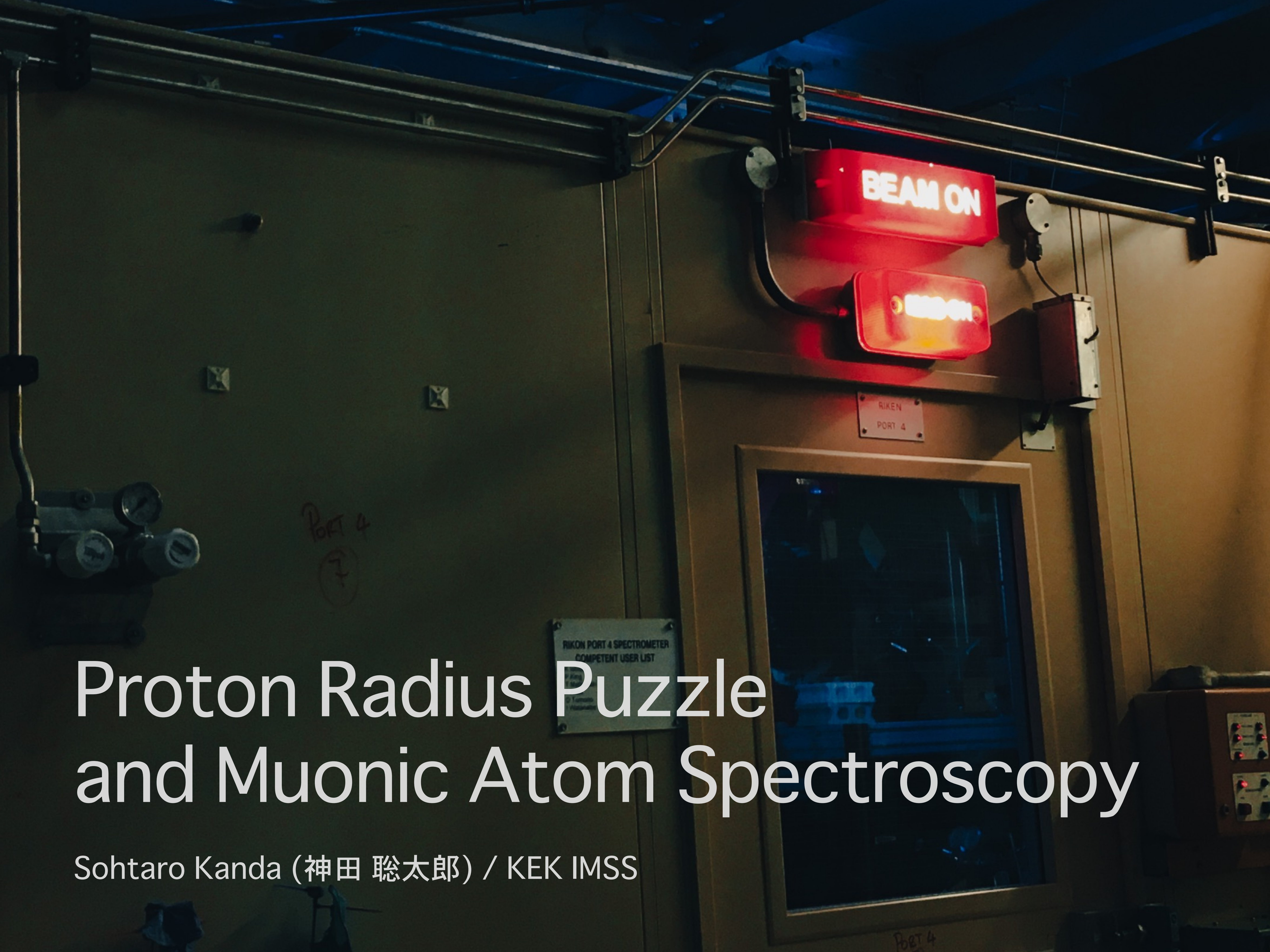
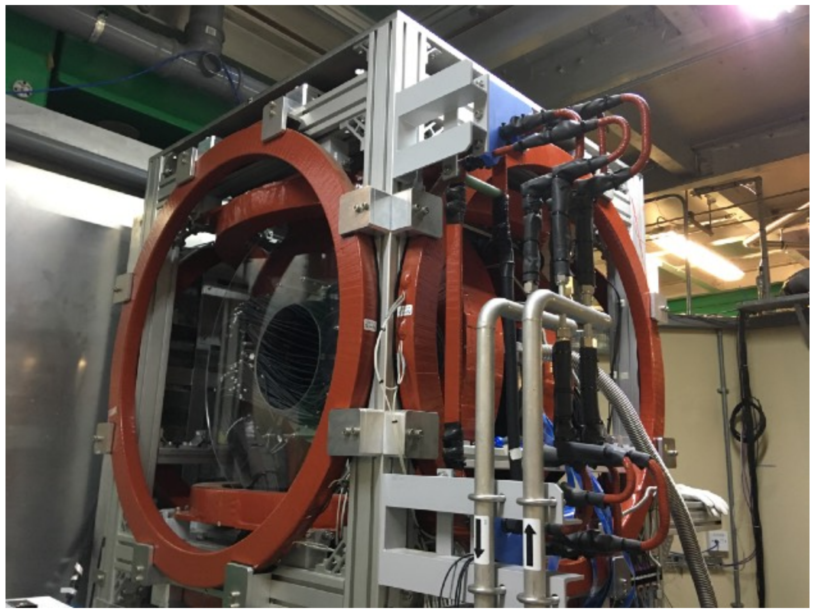


Proton Radius Puzzle and Muonic Atom Spectroscopy

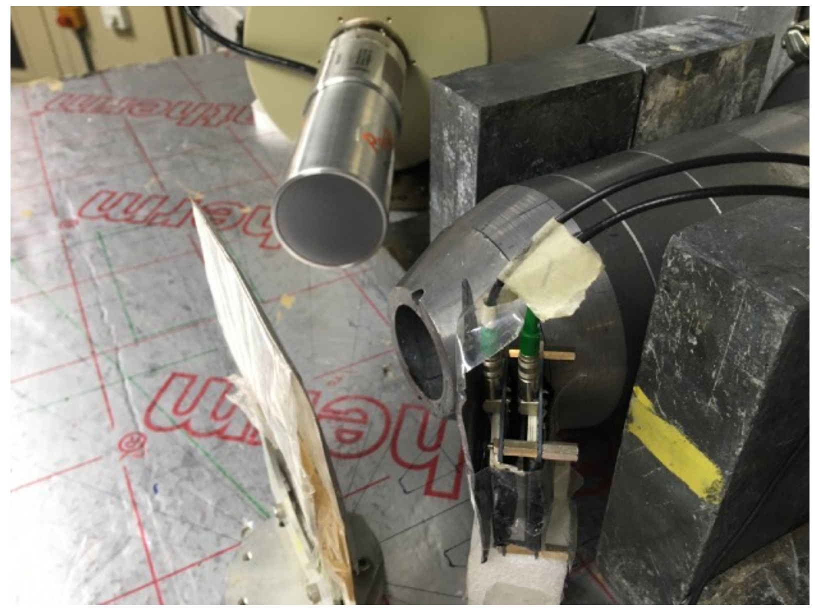
Sohtaro Kanda (神田 聡太郎) / KEK IMSS

My Research Life in IWASK Lab.

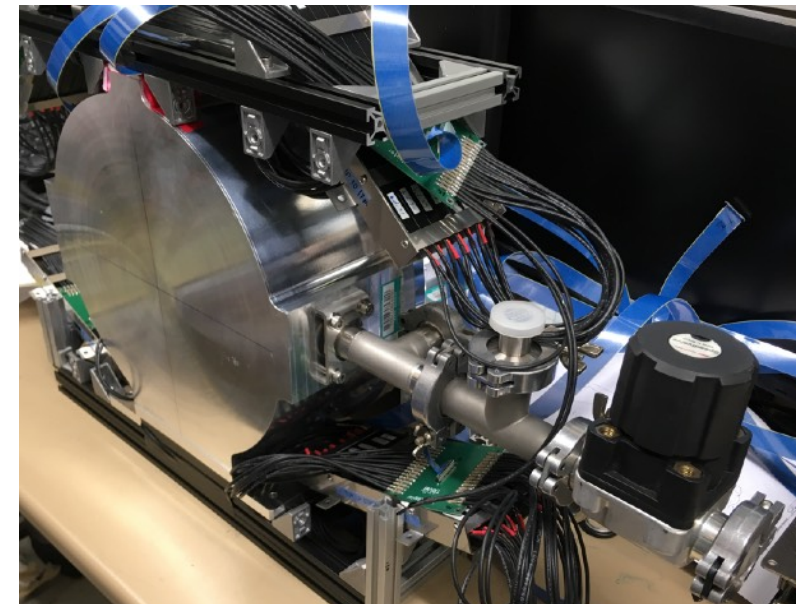
Good Memories from 2017 to 2019



CHRONUS at RIKEN-RAL Port4



Detector beam test



Target gas chamber

A snowy day at RAL

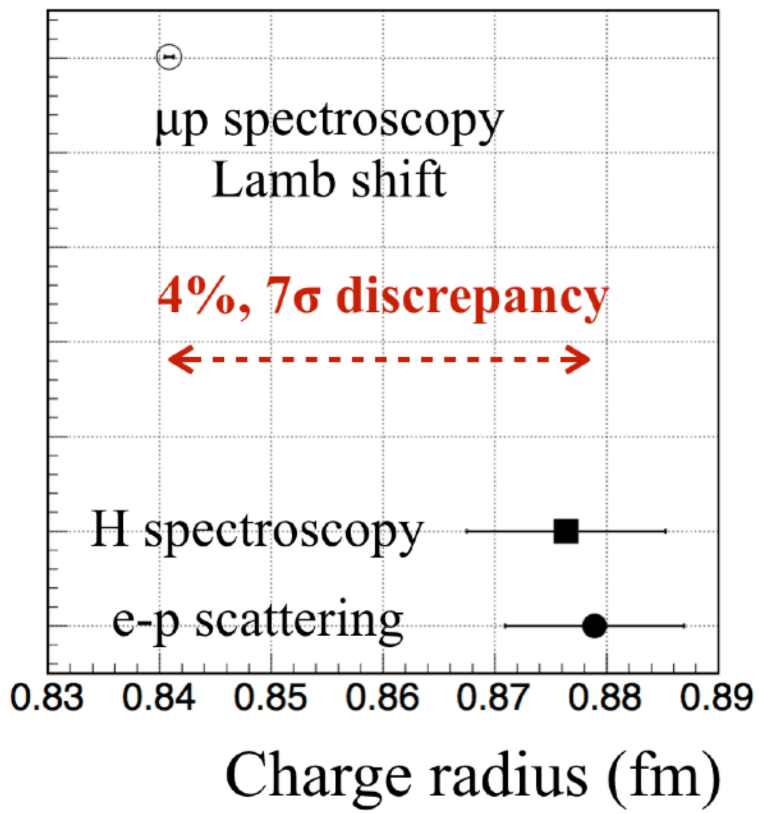
The cafeteria before Christmas

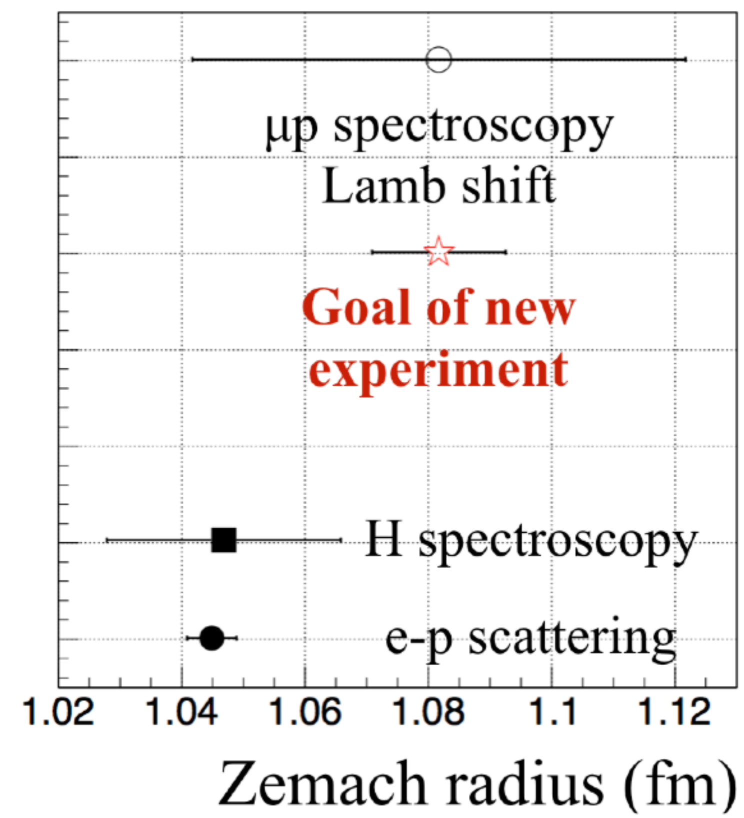
Fish and chips on Friday

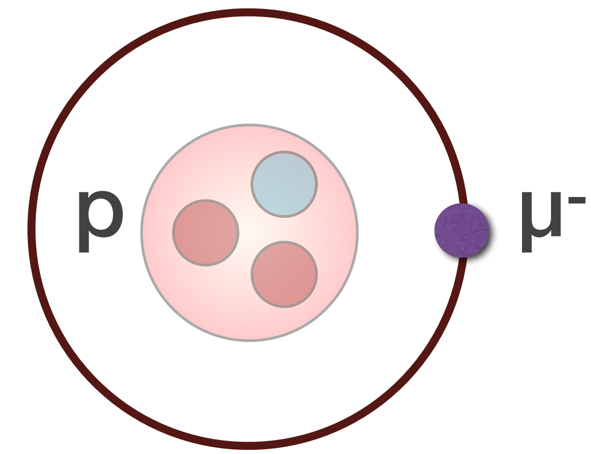
Mars bar for overnight exp.

Proton Radius Puzzle

Unsolved Problem in Subatomic Physics





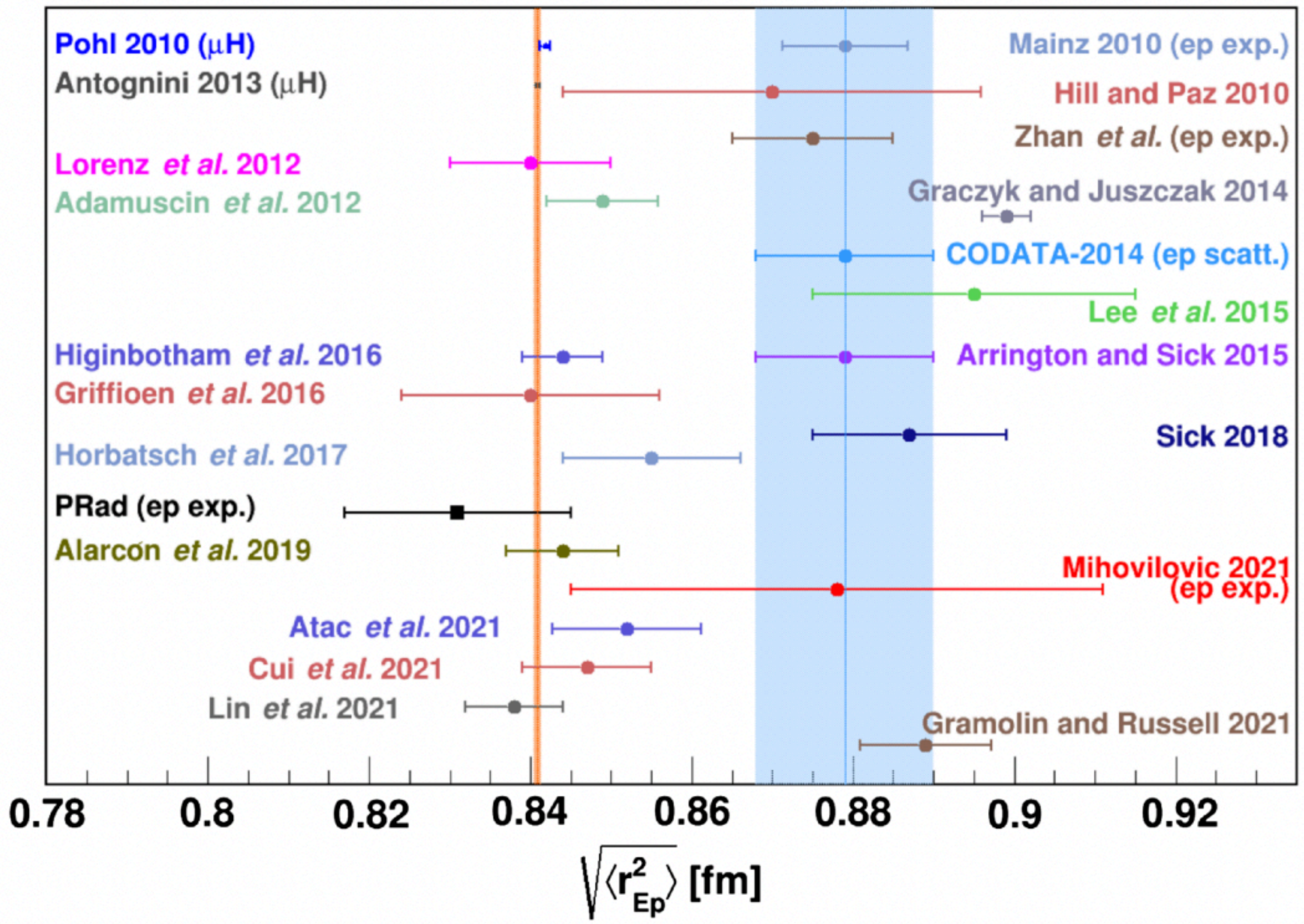


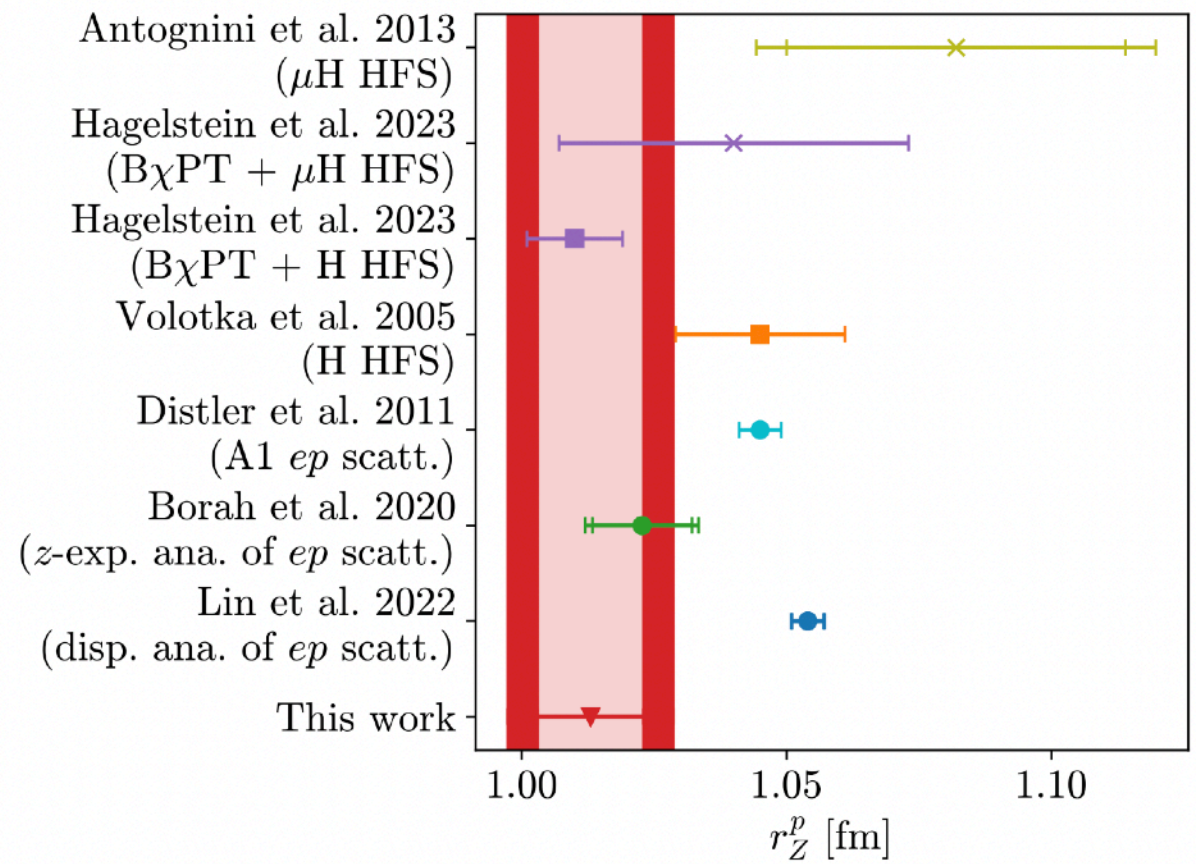
Muonic hydrogen atom consists of a proton and a negative muon. Muons are the 2nd generation leptons, which can be regarded as electrons 200 times heavier.

- The proton is fundamental building block of the universe. However, it is a composite particle with a complex structure.
- A large discrepancy in results of the proton's charge radius from electronic and muonic systems has been known since 2010.
- As an alternative approach to this problem, we proposed a measurement of the Zemach radius taking into account the magnetic moment distribution.

Proton Radius Puzzle

More recent situation





The results on charge radius have become more abundant, but there has not been much increase in information about what is happening with the Zemach radius.

Left: H. Gao and M. Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022).
Right: D. Djukanovic et al., arXiv:2309.17232 [hep-lat].

Proton Zemach Radius

Spatial distribution of charge and spin

- Defined by a convolution of the charge distribution with a magnetic moment distribution.

$$R_Z = \int d^3r \int d^3r' \rho_E(r') \rho_M(r - r')$$

A. C. Zemach, Phys. Rev. 104, 1771 (1956).

- Can be obtained by measuring the hyperfine splitting.

$$E_{\mathrm{HFS}} = E_{\mathrm{F}}(1 + \delta_{\mathrm{QED}} + \delta_{\mathrm{Proton}})$$

(E_F=182.443 meV)

$$\delta_{\mathrm{Proton}} = \delta_{\mathrm{Rec}} \quad 1.06 \text{ meV}$$
$$+ \delta_{\mathrm{Pol}} \quad 0.084 \text{ meV}$$
$$+ \delta_{\mathrm{HVP}} \quad 0.004 \text{ meV}$$
$$+ \delta_{\mathrm{Zemach}} \quad -1.36 \text{ meV}$$

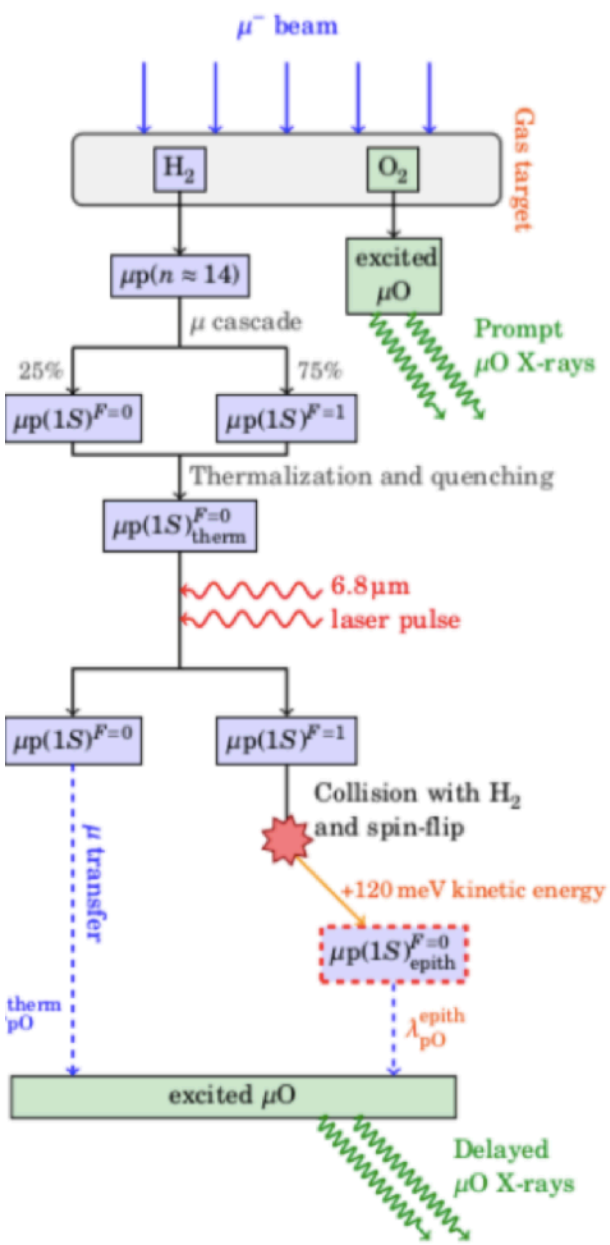
$\longleftarrow \delta_{\mathrm{Zemach}} = -2\alpha m_{\mu p} R_Z$

R. N. Faustov and A. P. Martynenko, J. Exp. Theor. Phys. 98, 39 (2004).

Three μp-HFS Projects

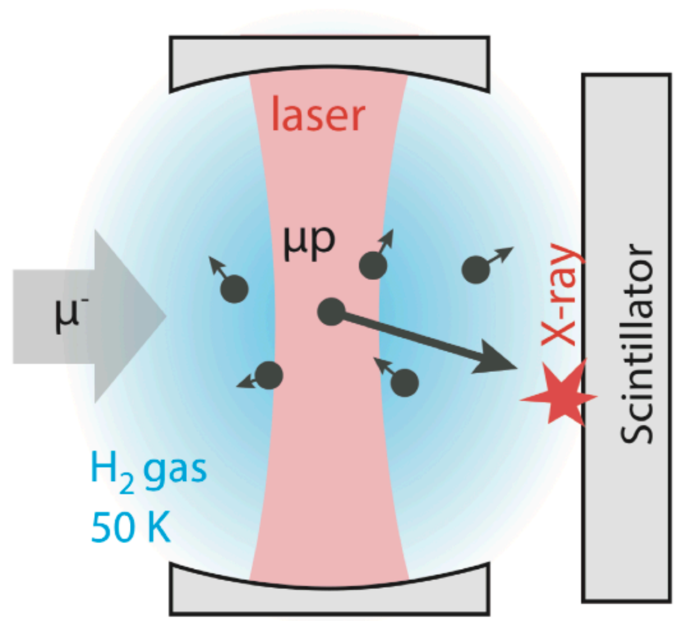
Independent approaches at RAL, PSI, and RIKEN

FAMU



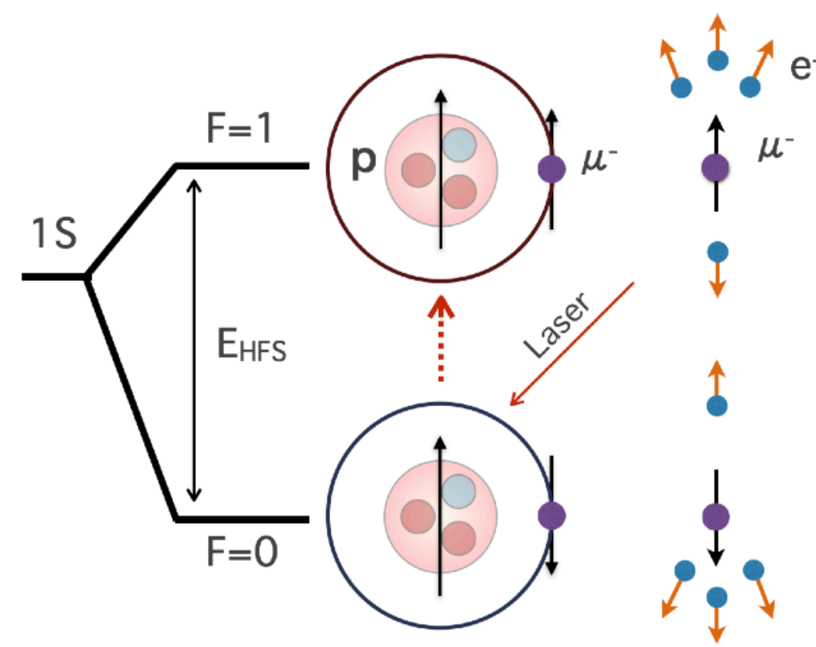
E. Mocchiutti, in PREN2022 workshop

Hyper-Mu



A. Antognini, in PREN2022 workshop

RIKEN/J-PARC

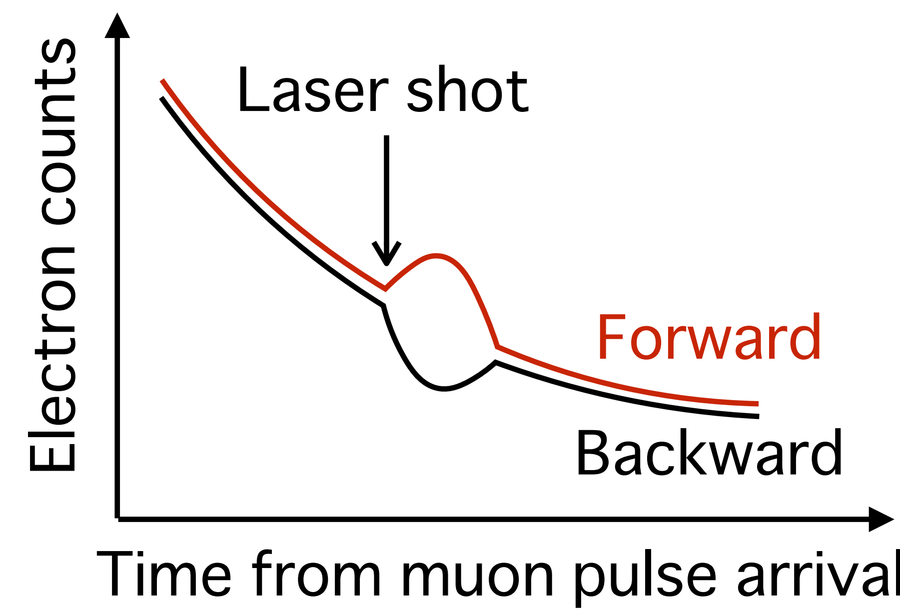


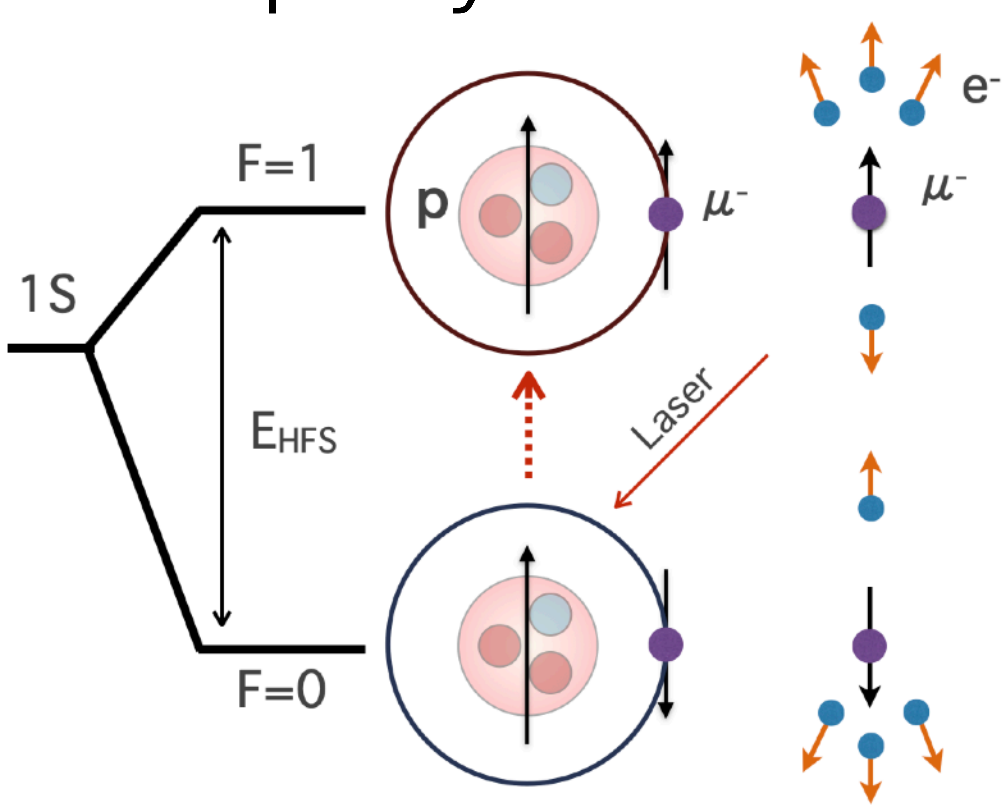
	FAMU	PSI	RIKEN
Method	Transfer	Diffusion	Asymmetry
Detection	X-Rays	X-Rays	Electrons
Beam	Pulsed	Contiuous	Pulsed

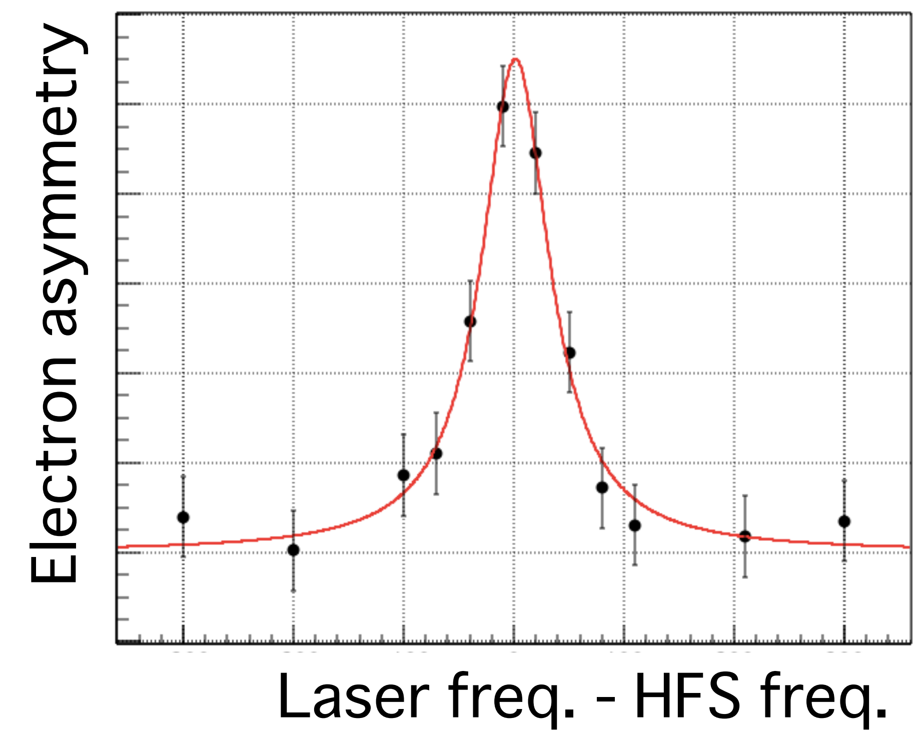
Laser Spectroscopy of μp-HFS

Method of our experiment

- Laser induced hyperfine transition and muon spin flip
- Parity violating muon decay
- Decay electron angular asymmetry
- Laser frequency scan







Project Timeline

Since the experimental proposal

2013	2014	2015	2016	2017	2018	2019

Target R&D

RAL Test1

RAL Test2

RAL Test3

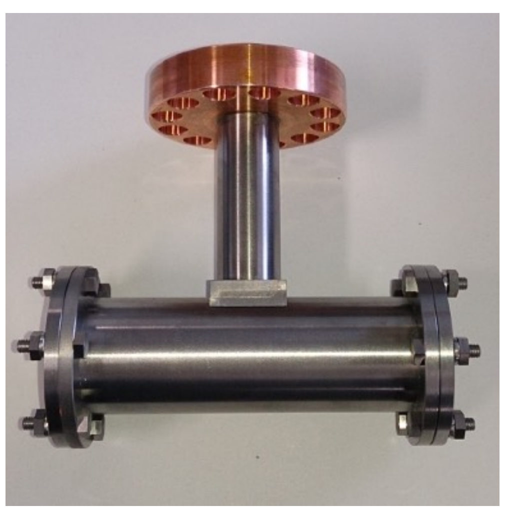
The Puzzle

Proposal Submitted

Detector R&D

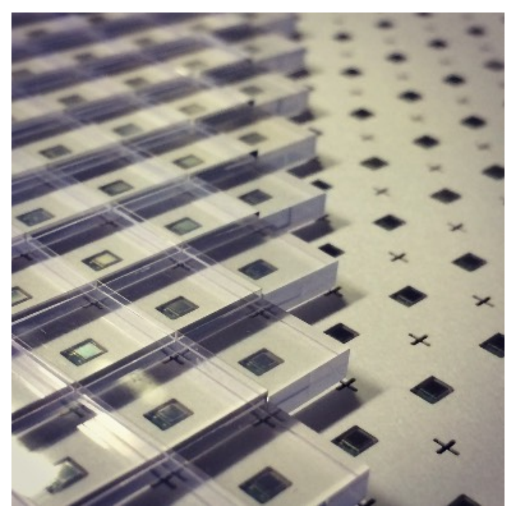
J-PARC Test

Laser R&D

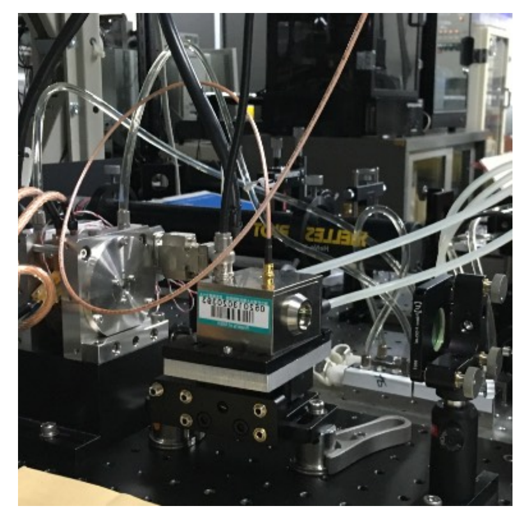


Target Cell

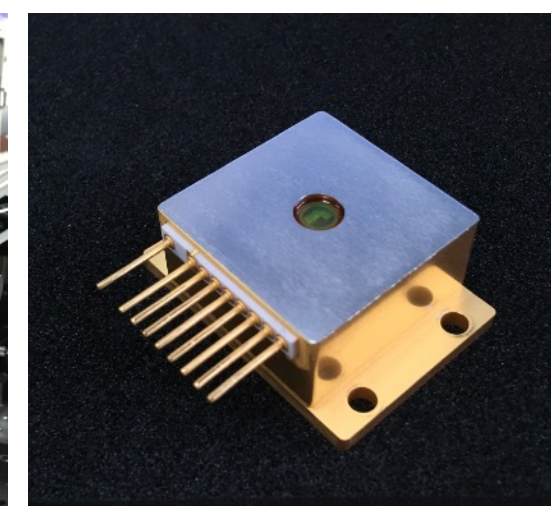
Cryostat



Detector



Pump Laser



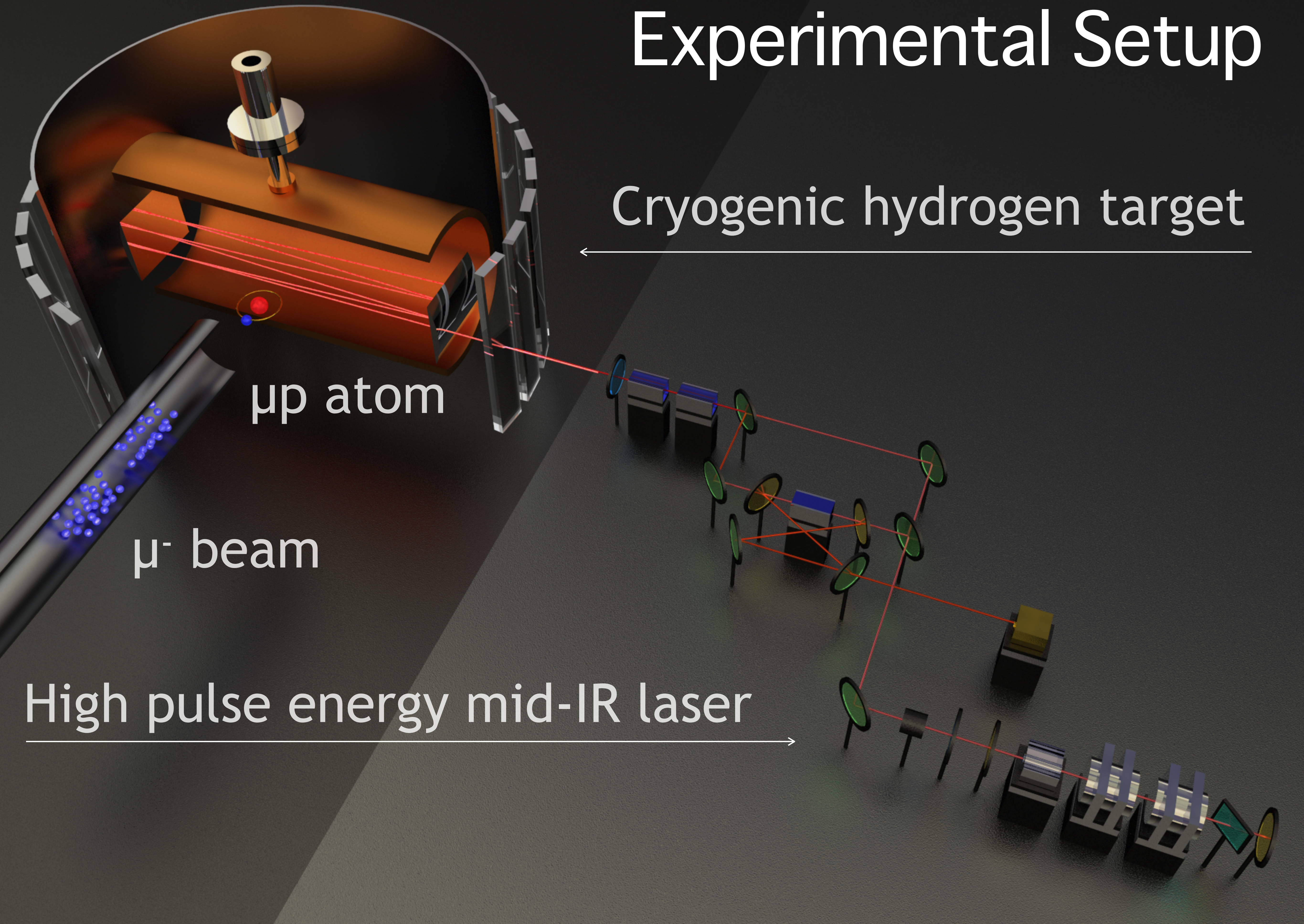
Seed Laser

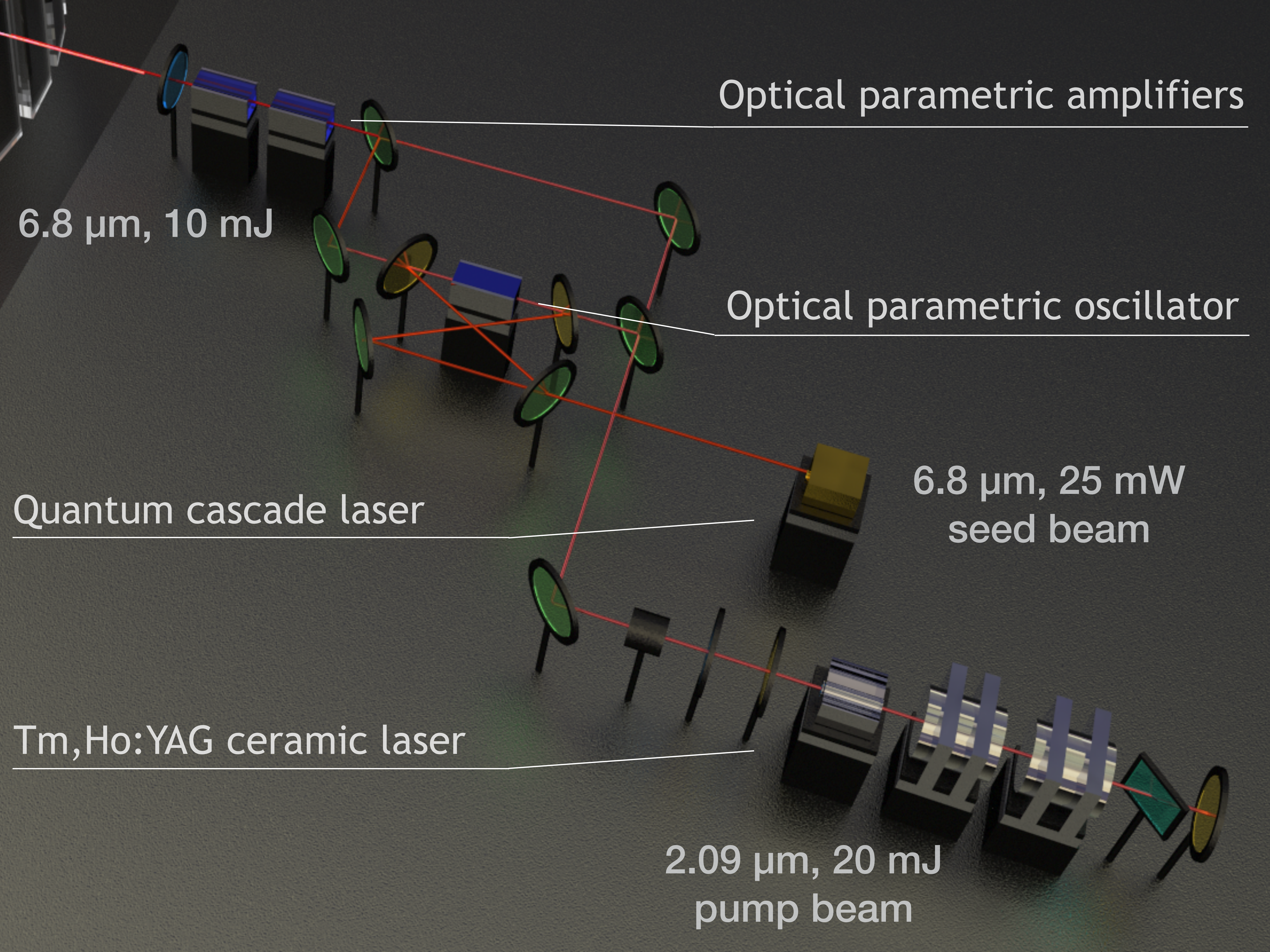
M. Sato, K. Ishida

S. Okada, Y. Ma

S. Aikawa, M. Yumoto, N. Saito, Y. Oishi

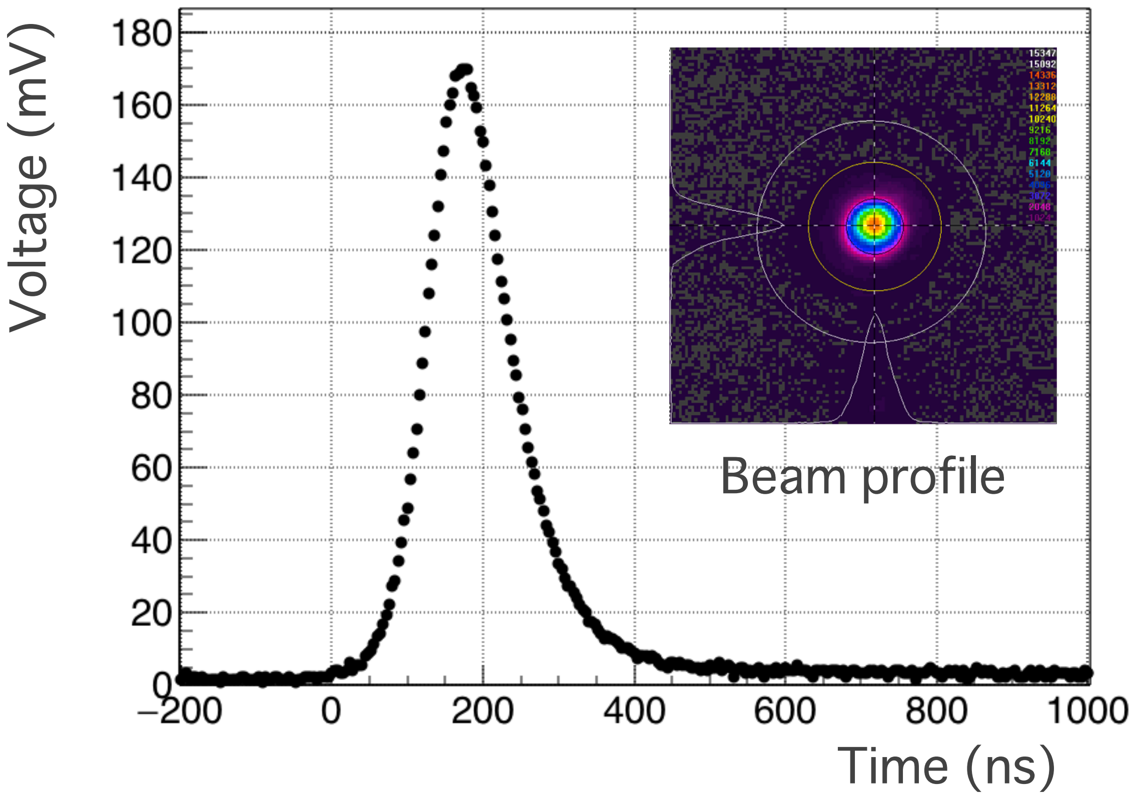
Experimental Setup

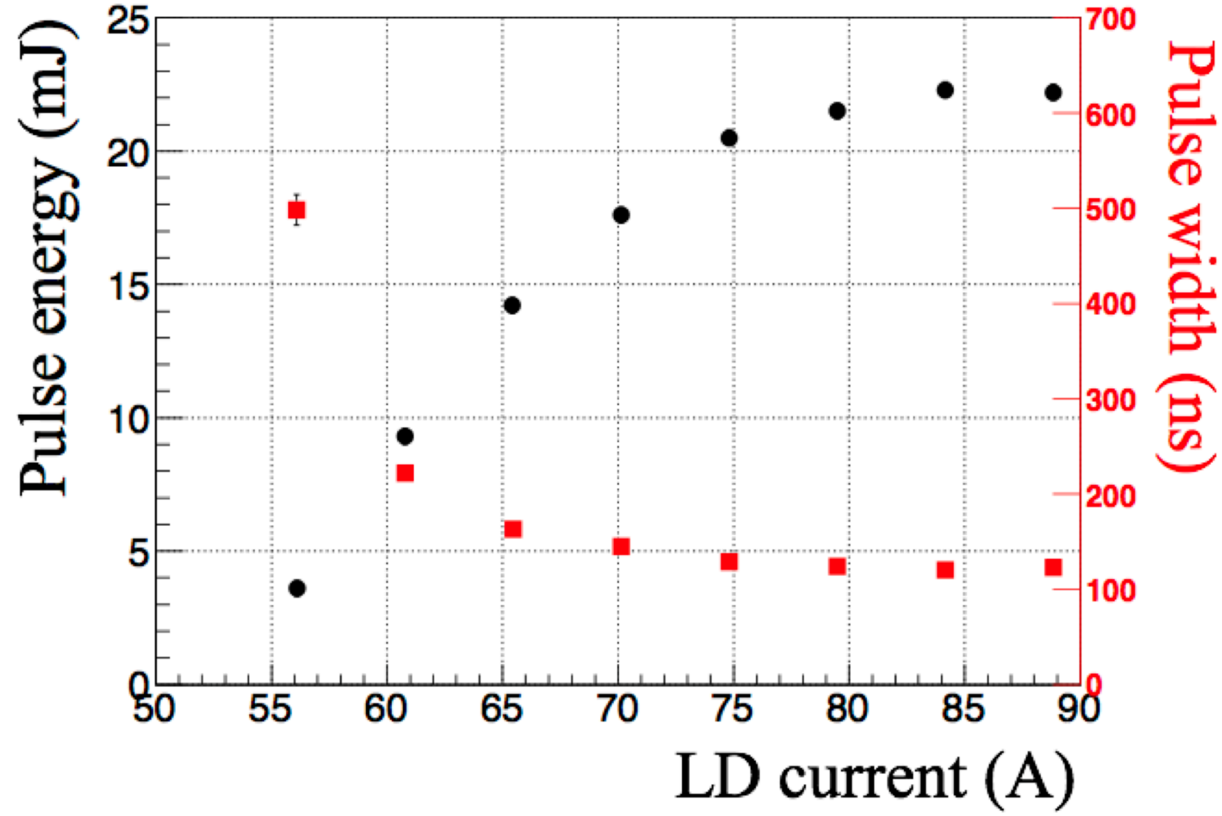



Optical parametric amplifiers
6.8 µm, 10 mJ
Optical parametric oscillator
Quantum cascade laser
6.8 µm, 25 mW
seed beam
Tm,Ho:YAG ceramic laser
2.09 µm, 20 mJ
pump beam

Tm,Ho: YAG Ceramic Laser

for a pump beam



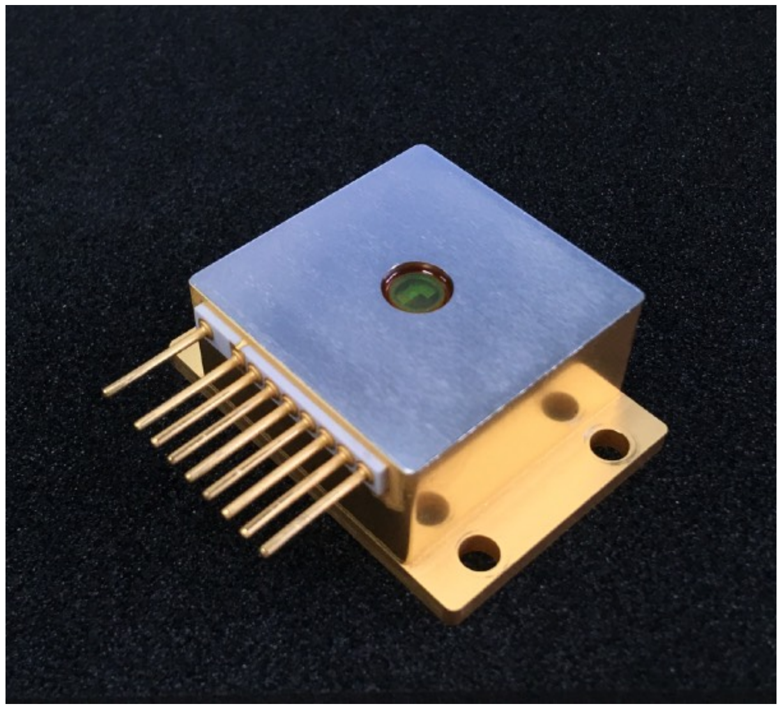


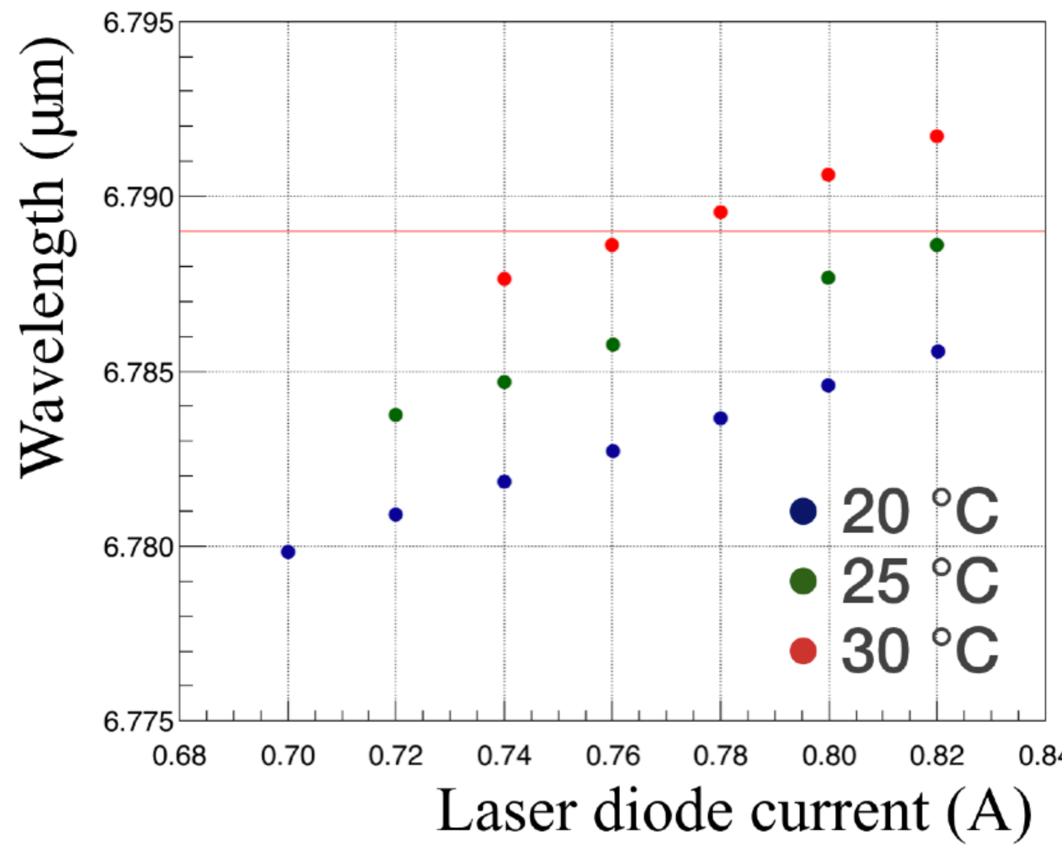
- 2.09 μm light is necessary for 6.8 μm light generation via an OPO.
- LD pumped, Q-switching, Tm^{3+},Ho^{3+} co-doped YAG ceramic laser was developed.
- Sufficient performance as a pumping beam for the ZGP-OPO was achieved (E>20 mJ, Width<150 ns).

S. Kanda et al., RIKEN Accelerator Progress Report 51, 214 (2018).

Quantum Cascade Laser

for a seed beam

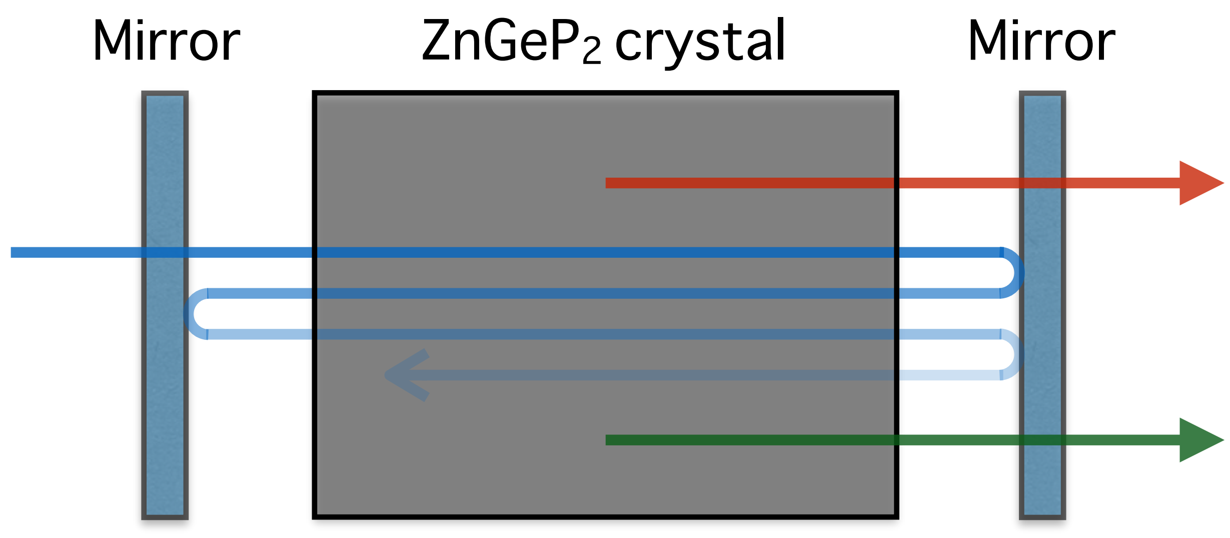




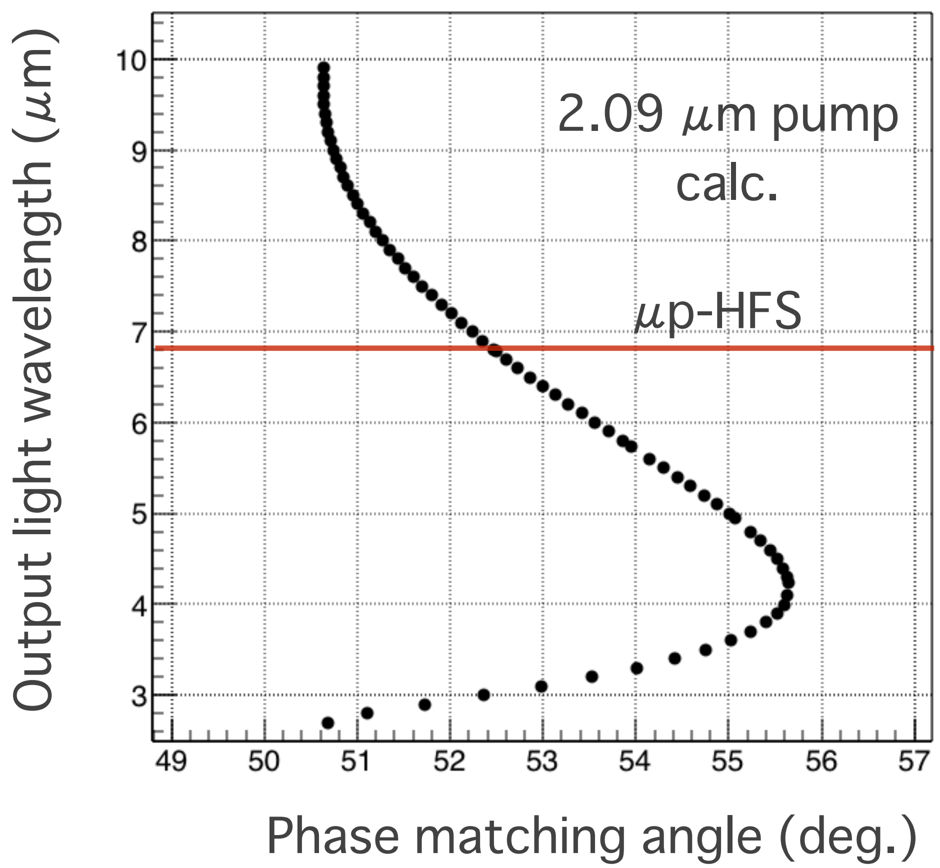
- Quantum cascade laser (QCL) for a seeder was developed.
- Oscillation at 1473.03 cm-1 = 6.778 μm was confirmed.
- Radiant output power was 25 mW at 6.778 μm (high enough).

Optical Parametric Oscillator

for frequency conversion



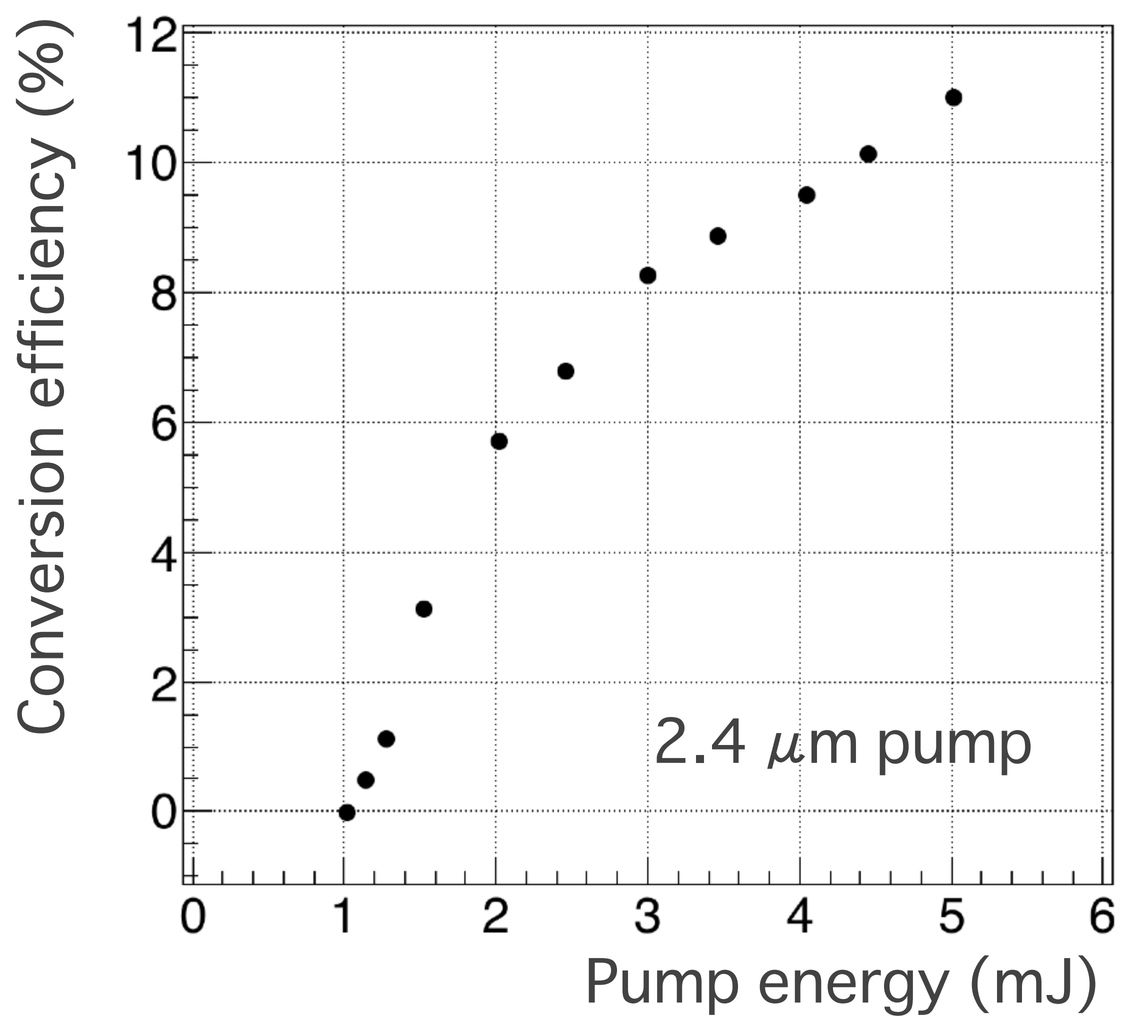
$$\frac{1}{\lambda_p} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

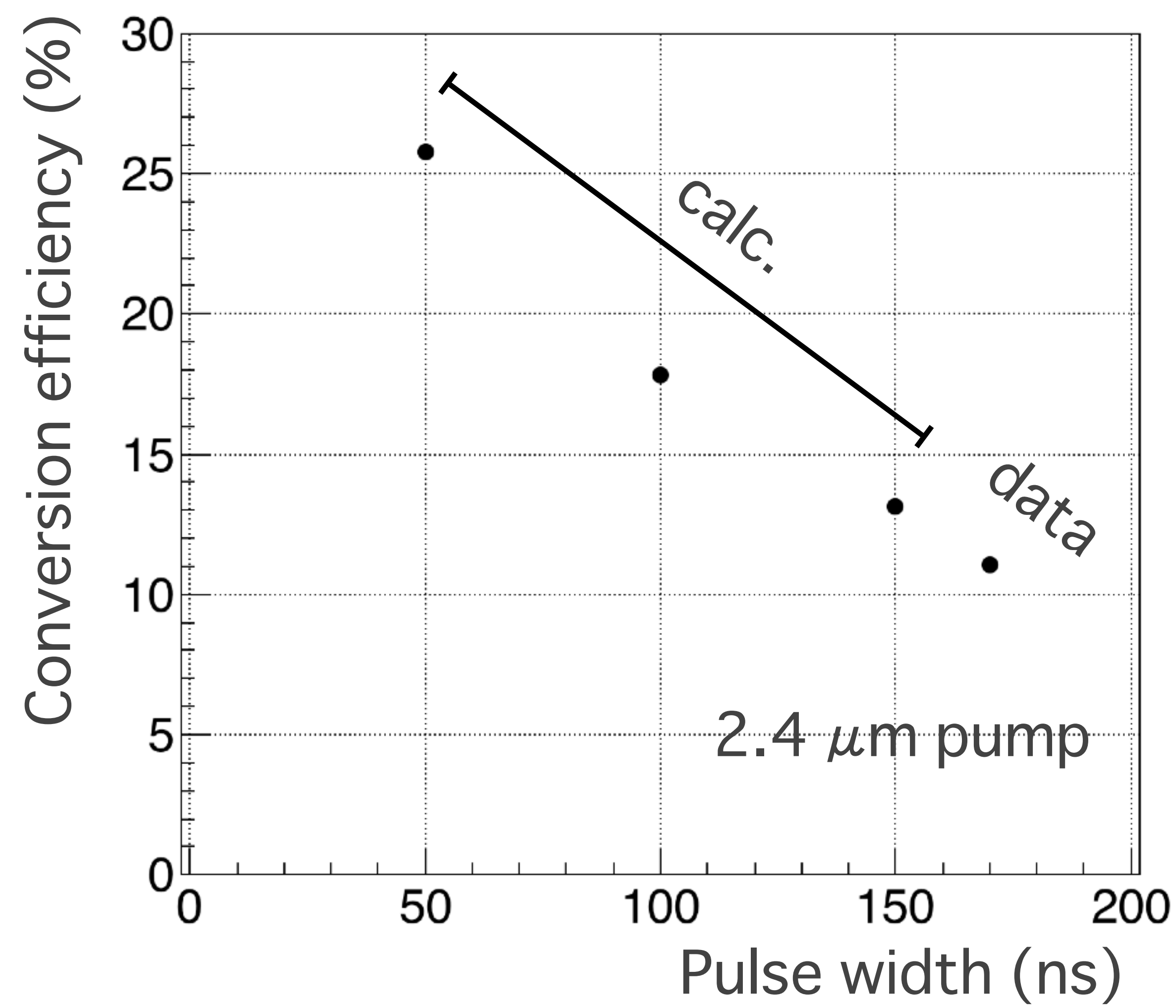


- Optical parametric oscillator provides two lower frequency lights from a pumping light via non-linear optical effect.
- ZGP is an optimum from viewpoints of the damage threshold and non-linear optical coefficient.

Optical Parametric Oscillator

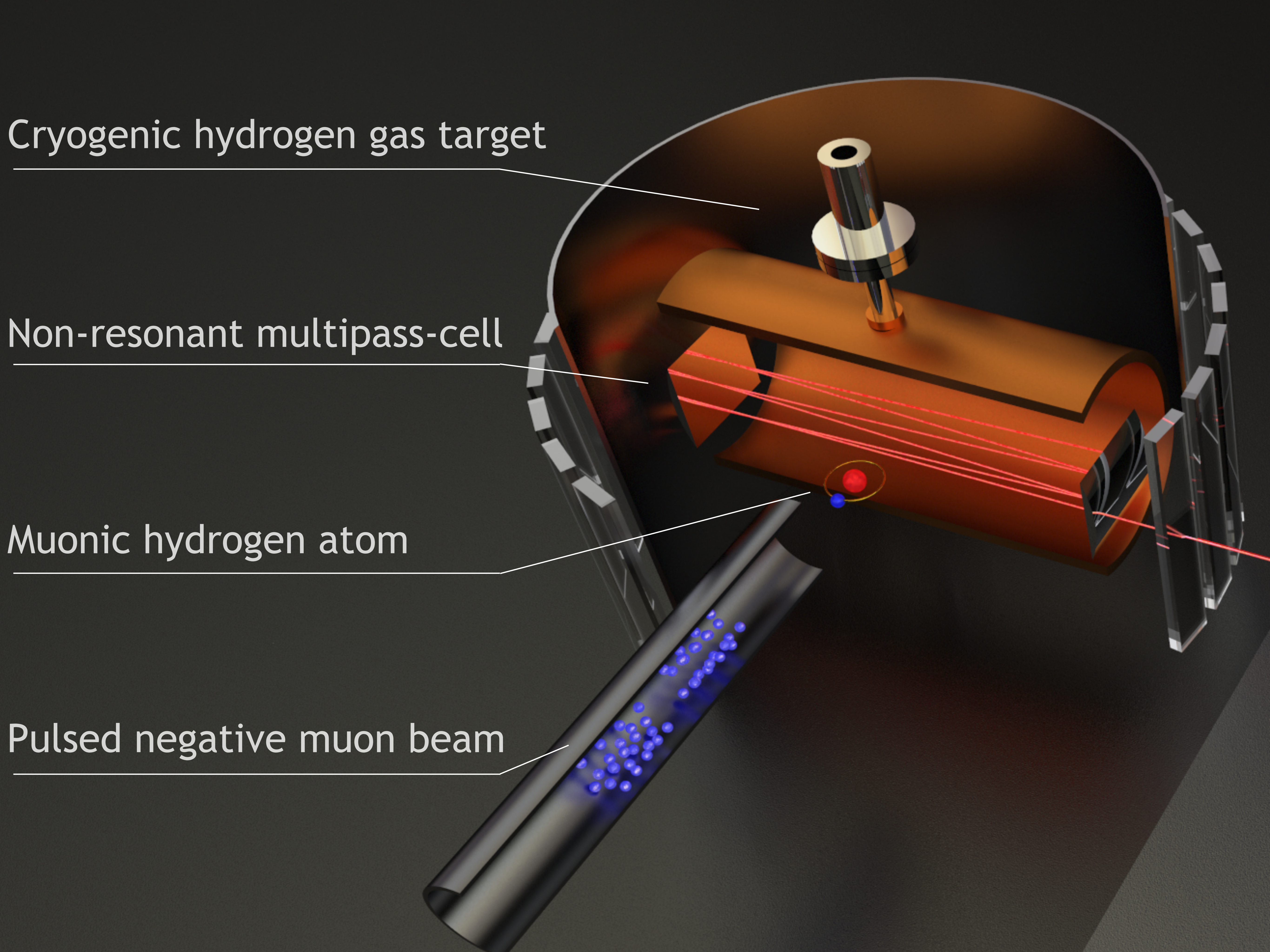
for frequency conversion





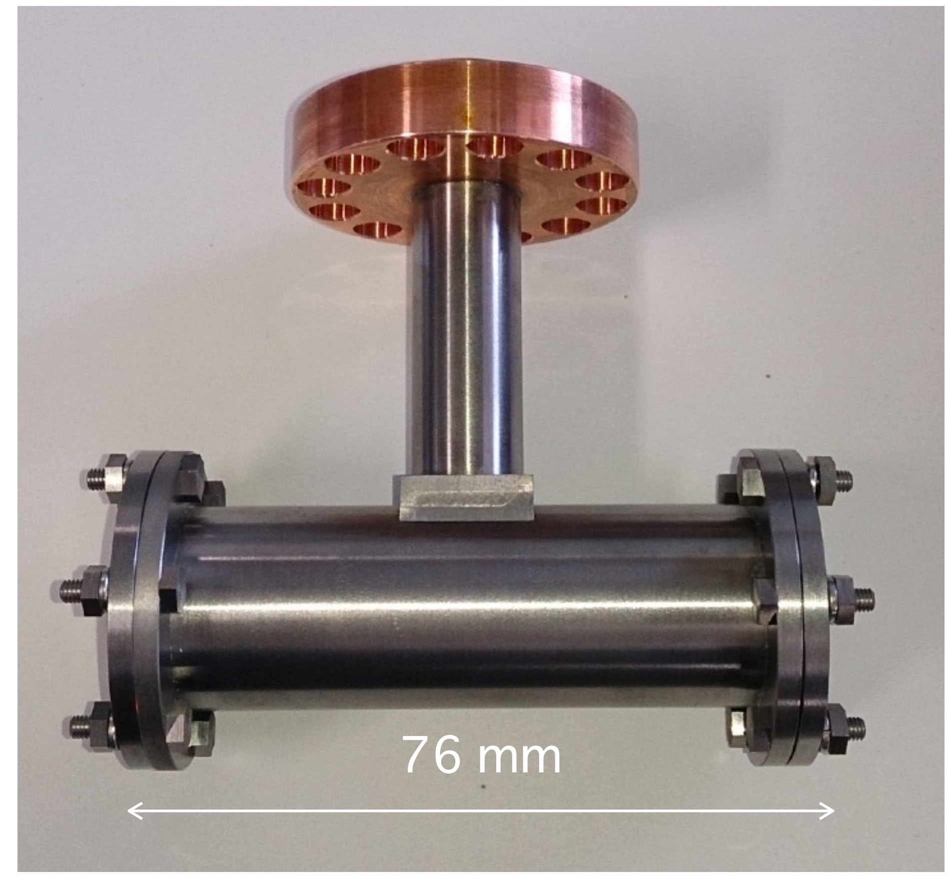
- The ZGP-OPO was demonstrated with Cr:ZnSe laser (2.4 μm).
- Similar performance is expected with 2.09 μm pump.
- The conversion efficiency of 13% or above is achievable.

S. Aikawa, Master Thesis, Tokyo Institute of Technology (2016).


Cryogenic hydrogen gas target
Non-resonant multipass-cell
Muonic hydrogen atom
Pulsed negative muon beam

Hydrogen Gas Target

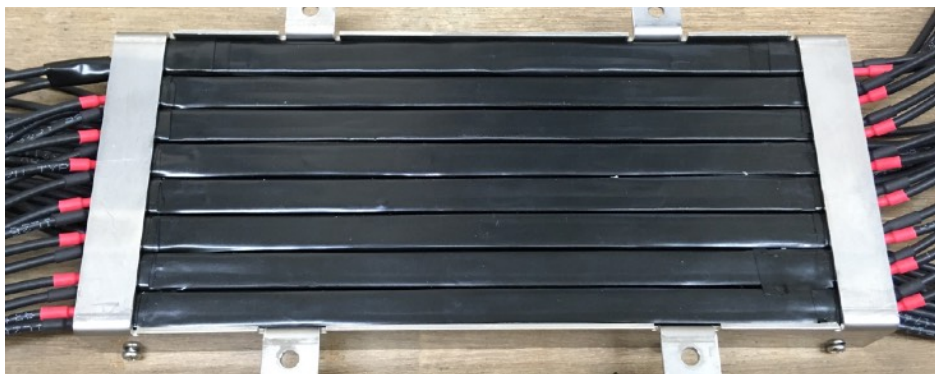
at cryogenic temperatures

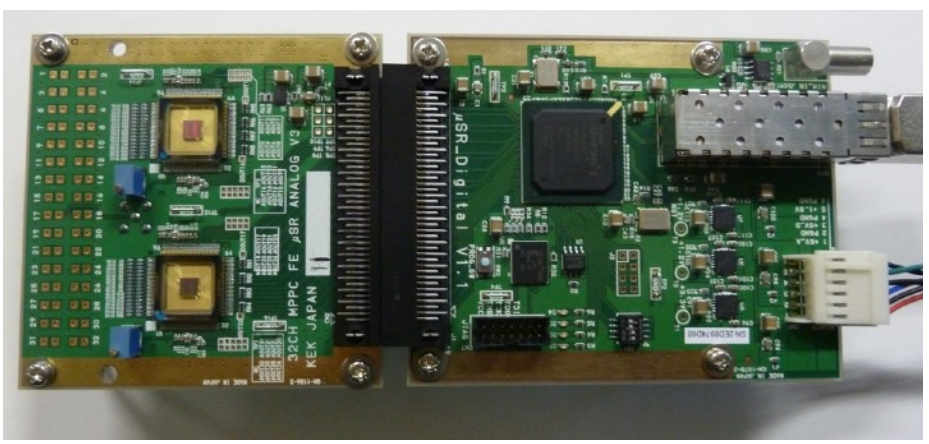


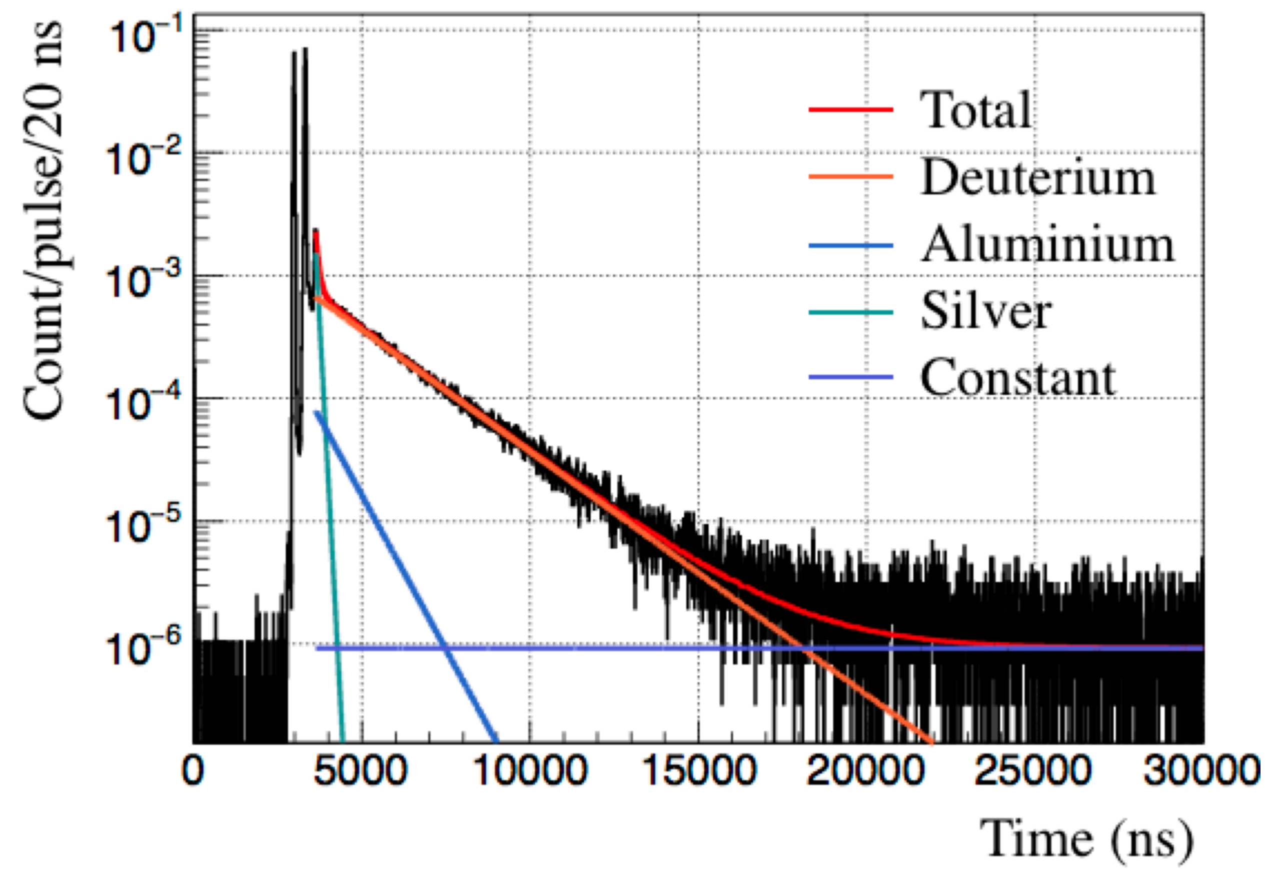
- Target is cooled down to 20 K by using a pulse-tube cryostat.
- Gas density is monitored by a Baratron pressure gauge.
- Target cell is made of tungsten for background suppression.

Electron Detector

for a muon spin measurement





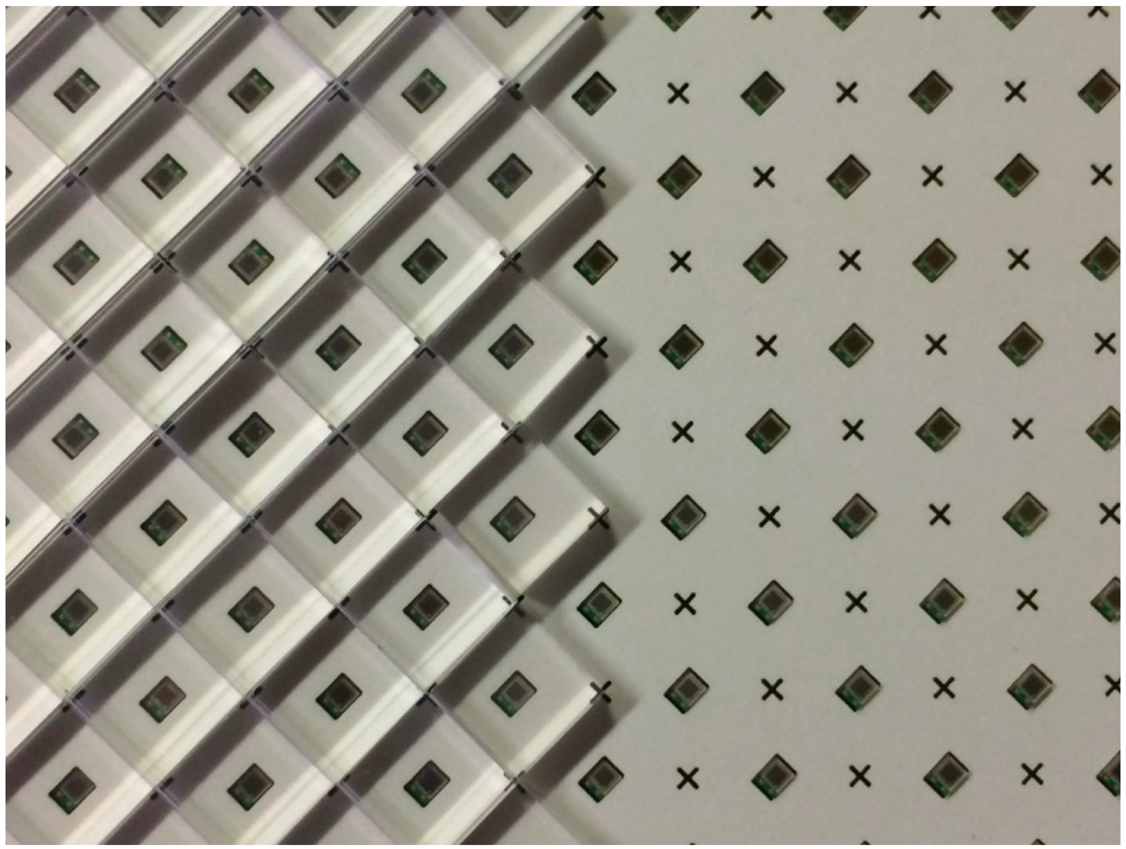


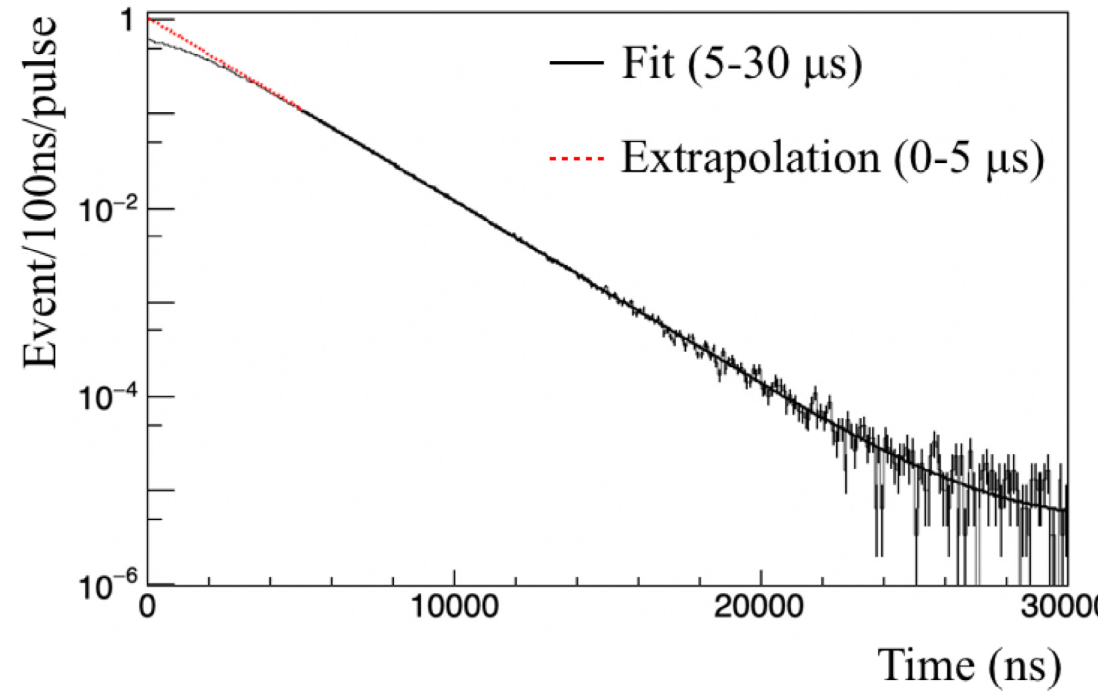
- A segmented scintillation counter consisting of scintillator bars and silicon photomultipliers (SiPMs). A fast frond-end electronics for SiPM readout is used.
- Coincidence analysis for signal-to-noise ratio improvement.
- Tested at RIKEN-RAL muon facility and sufficient performance was confirmed.

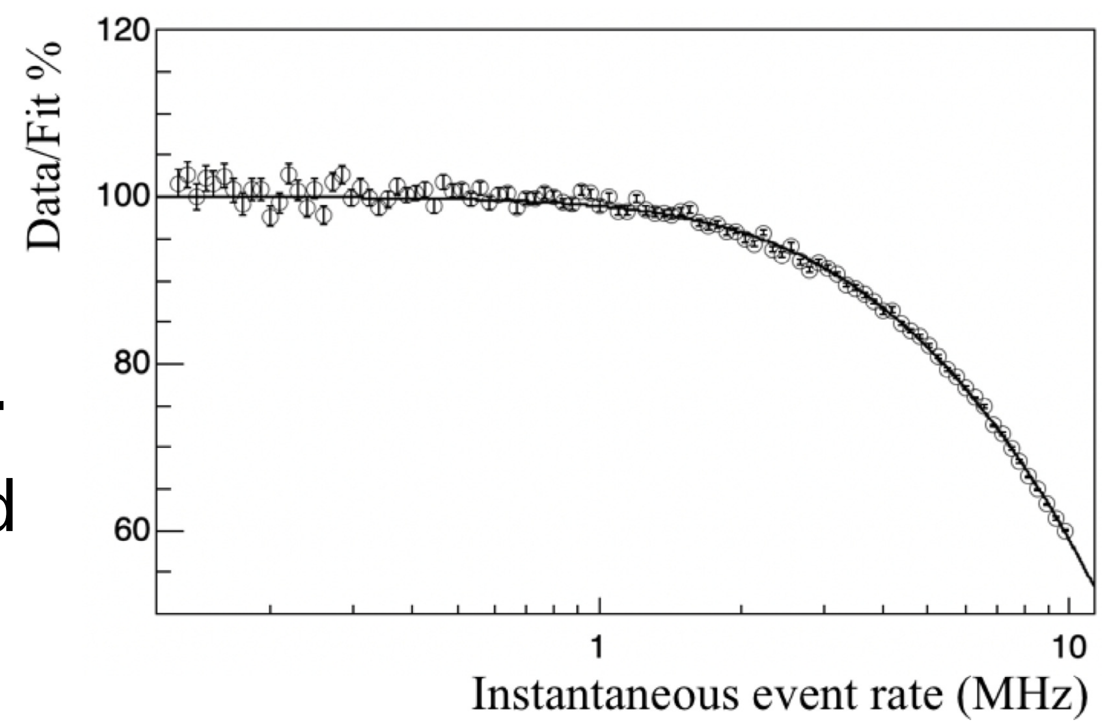
S. Kanda et al., RIKEN Accelerator Progress Report 52, 180 (2019).

Electron Detector Upgrade

for a muon spin measurement





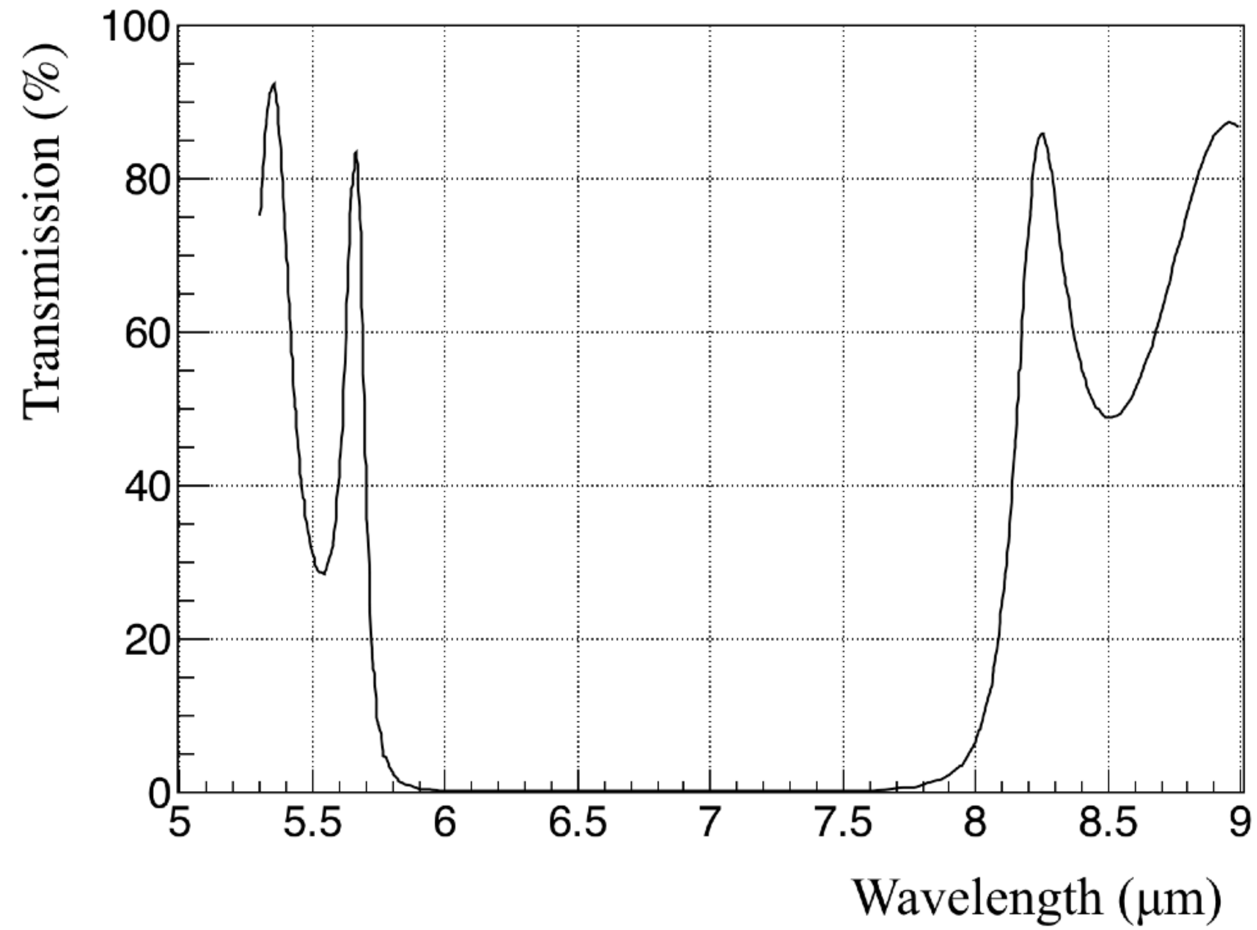


- Segmented scintillation counter consisting of 1152 tiles and SiPMs. Developed for muonium spectroscopy.
- Working well with high-intensity pulsed muon beams.

S. Kanda et al., Phys. Lett. B 815, 136154 (2021).

Multipass-Cell

for laser-light reflections

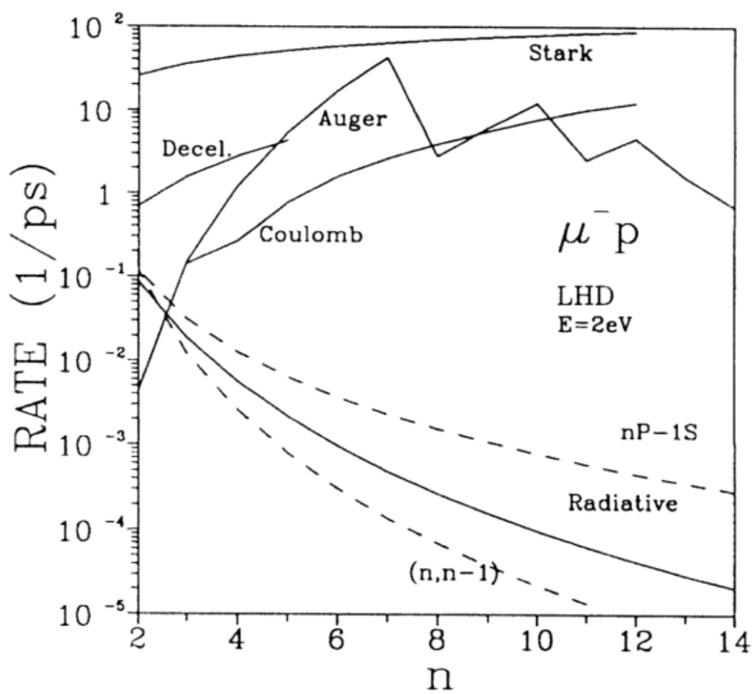


- The reflective index of 99.95% is desirable.
- A pair of prototype mirrors were fabricated and tested.
- A precise measurement of the reflective index is in progress.

Cascade De-excitation

of muonic atoms in a low-density gas

Mechanism	Process (Hydrogen case)
Radiative transition	$(\mu p)_i \rightarrow (\mu p)_f + \gamma$
External Auger effect	$(\mu p)_I + H_2 \rightarrow (\mu p)_f + e^- + H_2^+$
Stark mixing	$(\mu p)_{nl} + H \rightarrow (\mu p)_{nl'} + H$
Elastic scattering	$(\mu p)_n + H \rightarrow (\mu p)_n + H$
Coulomb de-excitation	$(\mu p)_i + p \rightarrow (\mu p)_f + p$



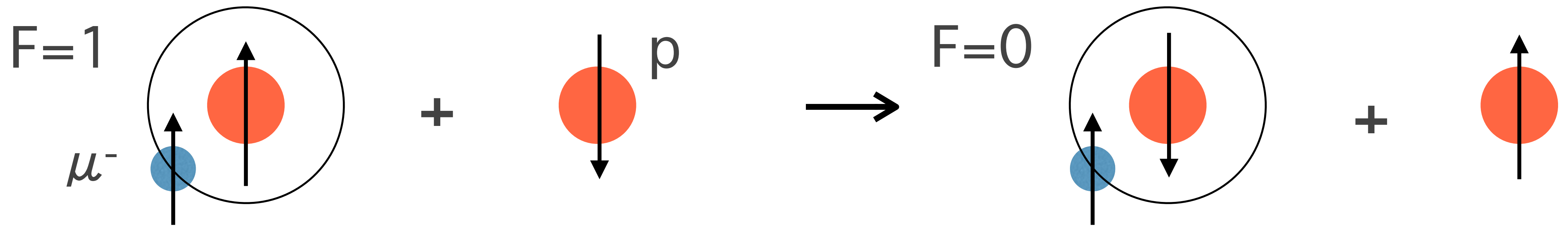
V. A. Markushin, Phys. Rev. A 50, 1137 (1994).

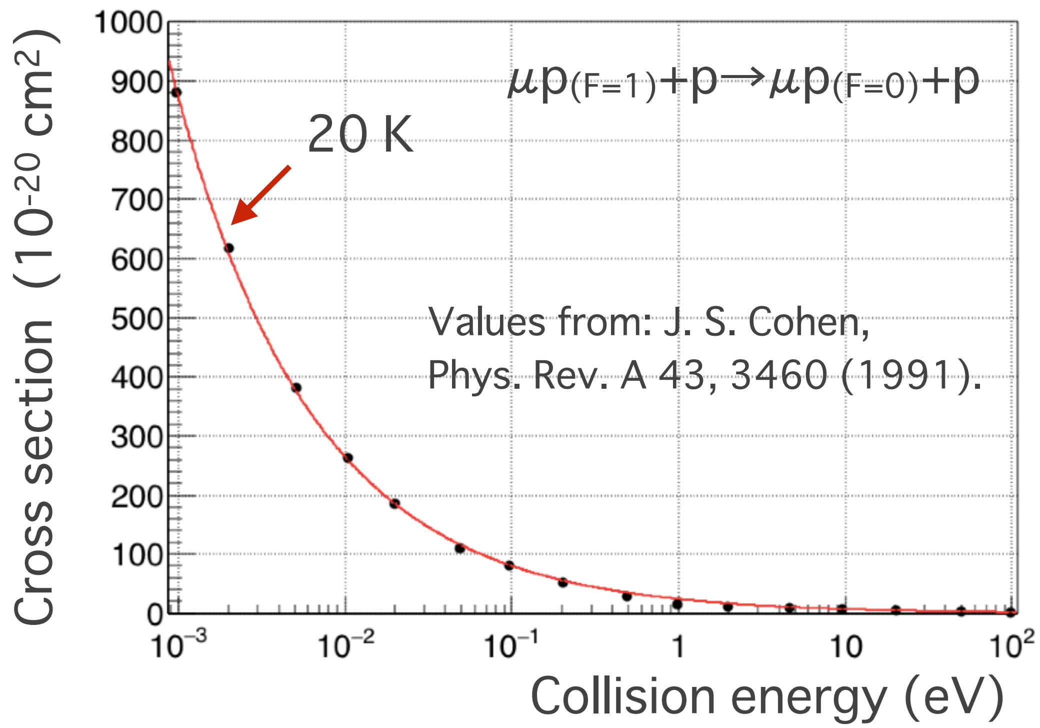
- When a nuclear Coulomb potential captures a negative muon, the muon forms an exotic bound state called muonic atom.
- Initial state is highly excited with the principle quantum number $n \sim 14$ ($\sim\sqrt{m_\mu/m_e}$).
- Muon spin depolarization due to Auger electrons.
- Acceleration by Coulomb de-excitations.
- Coulomb explosion of a molecule.
- Electron refilling from surrounding atoms.
- Too fast to track one-by-one.

Atomic Collisional Quenching

De-excitation of the hyperfine triplet

- Collisional quenching of the HFS triplet state
- Inelastic scattering μp(F=1)+p -> μp(F=0)+p
- Only theoretical predictions are known and no measurement had been performed.

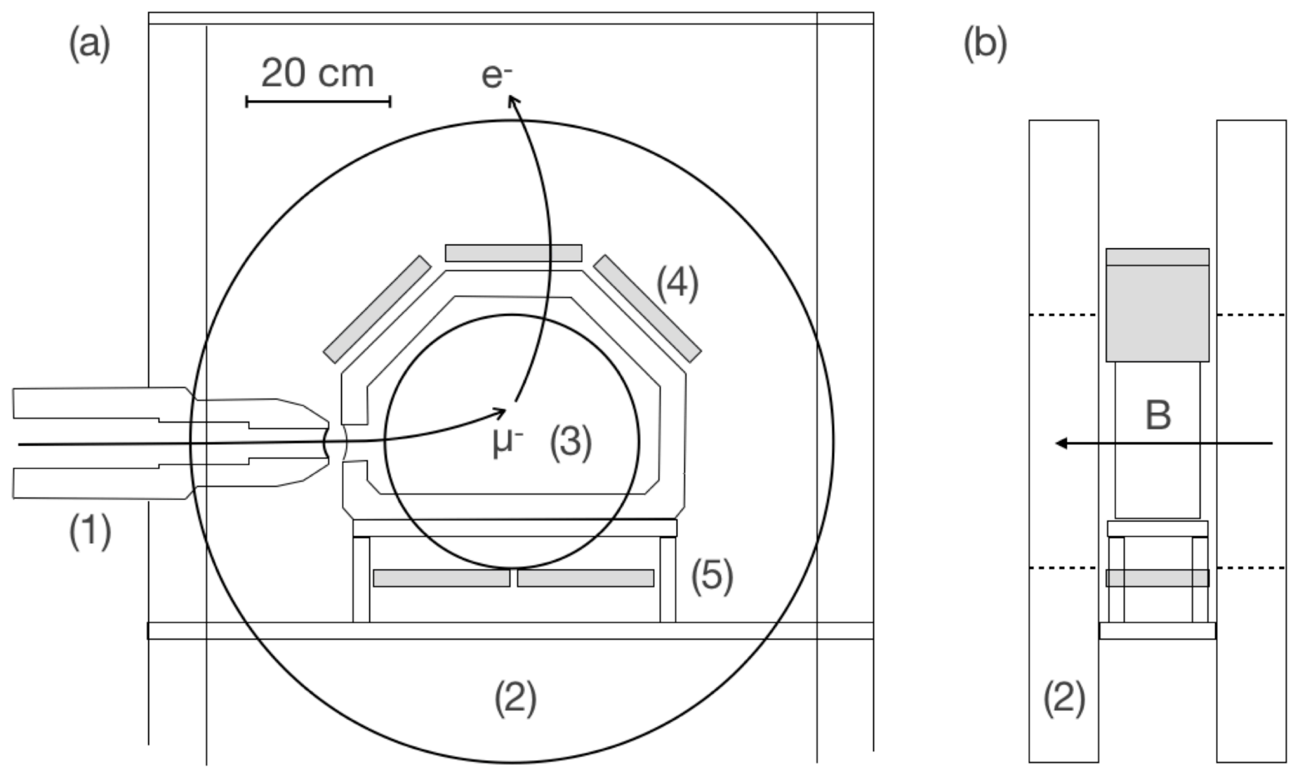




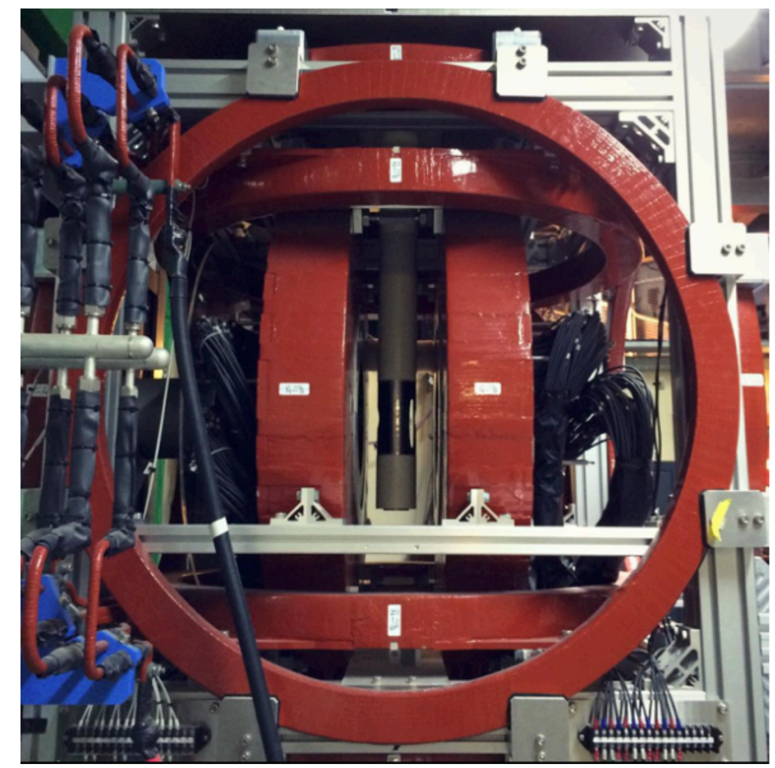
- Quenching rate depends on collision energy and gas pressure.
- Expected lifetime at 20 K, 0.06 atm is approximately 50 ns.
- A new experiment for direct measurement of the quenching rate was proposed.

Collisional Quenching Measurement

at RIKEN-RAL Muon Facility



Experimental setup



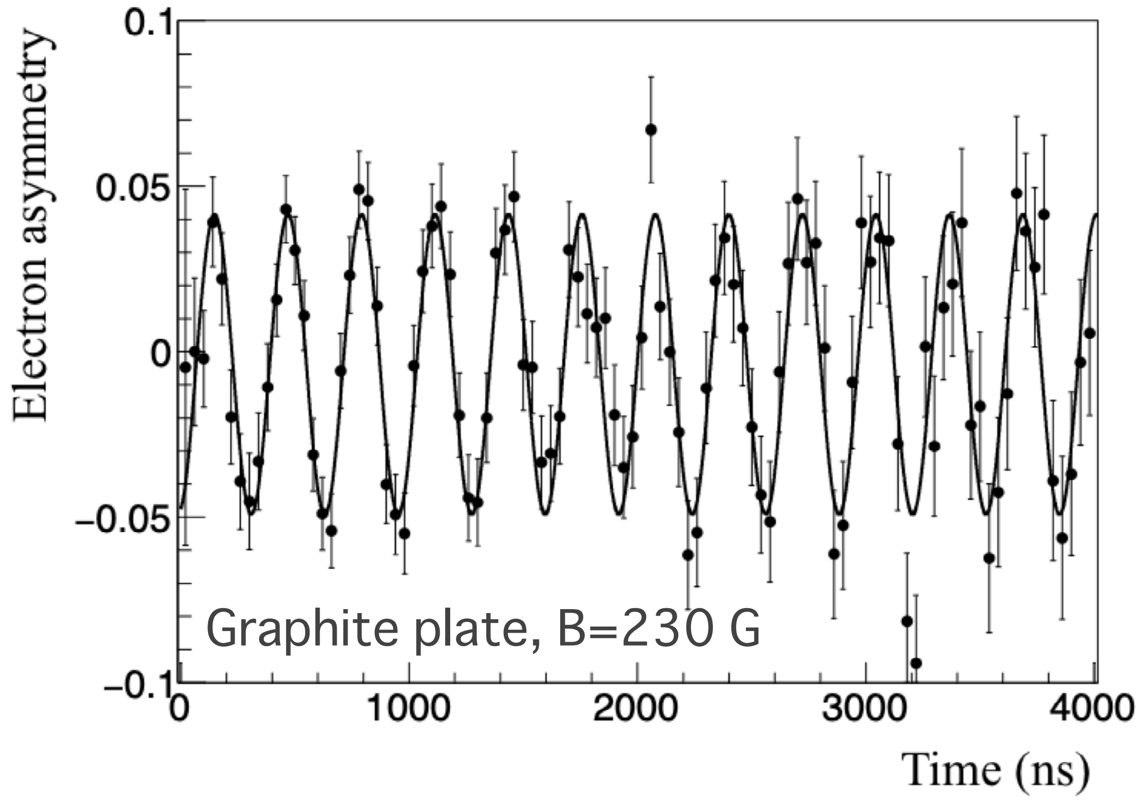
CHRONUS spectrometer

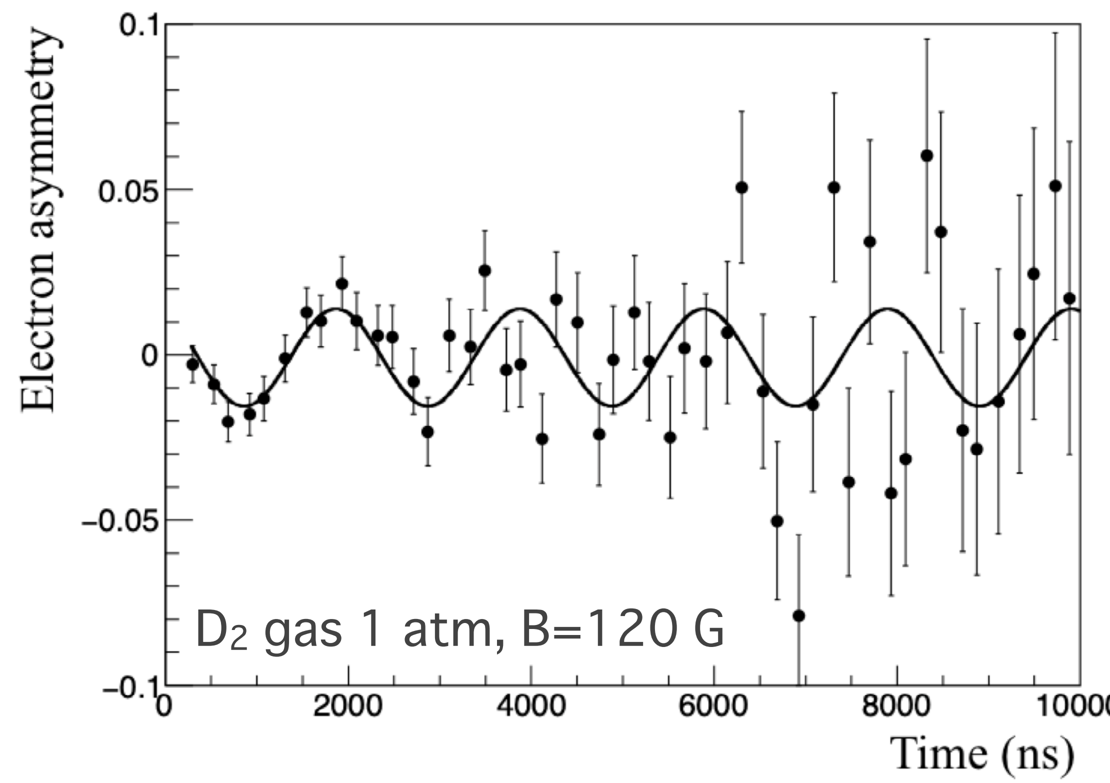
- Initial muon spin is polarized along the beam axis.
- Muon forms a muonic atom after stopping in the target.
- Muon spin rotates under a static magnetic field.
- Angular asymmetry in electron emission from muon decay is measured.

S. Kanda et al., J. of Phys. Conf. Ser., 1138 (2018).

Negative Muon Spin Rotation

of muonic carbon and muonic deuterium



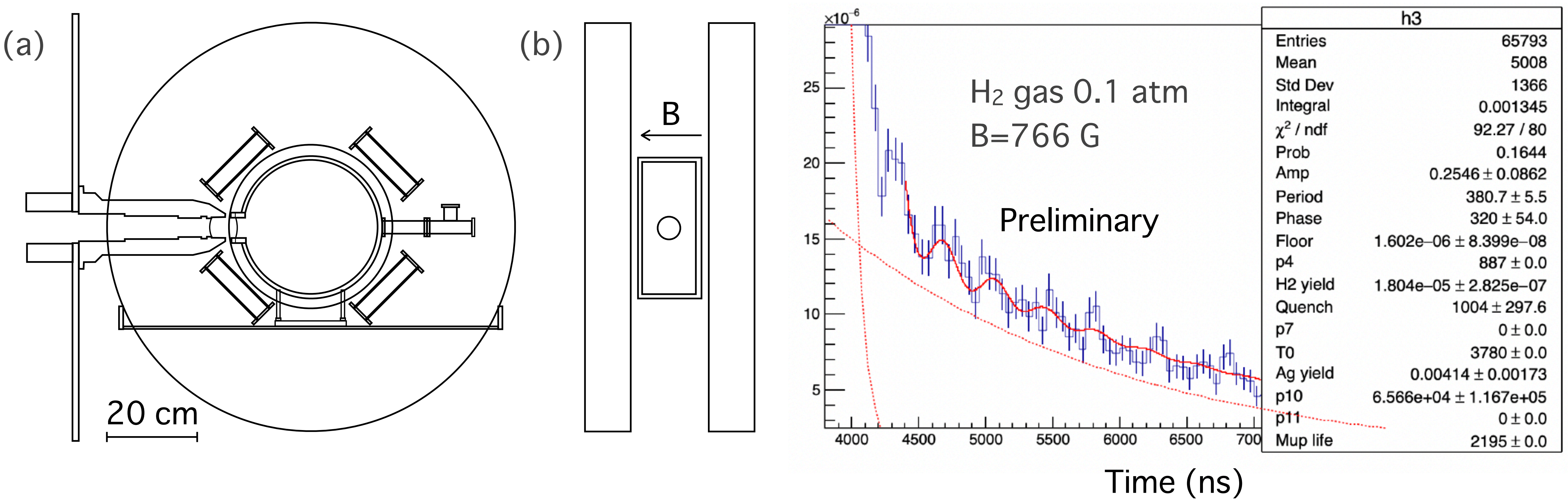


- Muon spin rotation in graphite was measured to calibrate the beam polarization and detector acceptance. The μSR amplitude was 0.045± 0.002, the beam polarization was estimated to be 95%.
- Using a deuterium gas target, an oscillation amplitude of 0.017±0.003 was obtained, then the residual polarization was 8.3%. Relaxation was too slow to evaluate.

Publication in preparation

Muonic Protium Spin Rotation

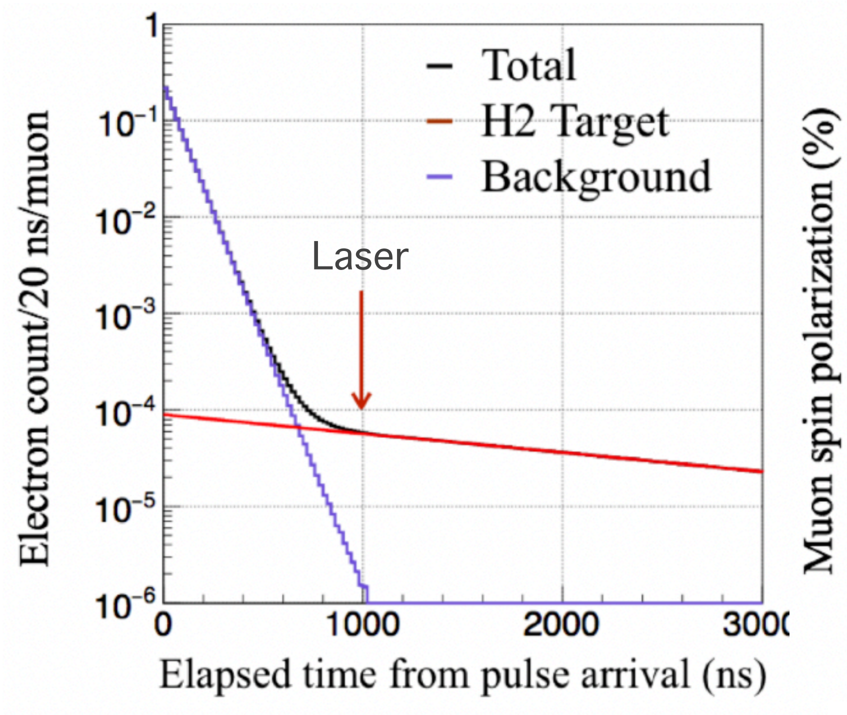
at RIKEN-RAL Muon Facility

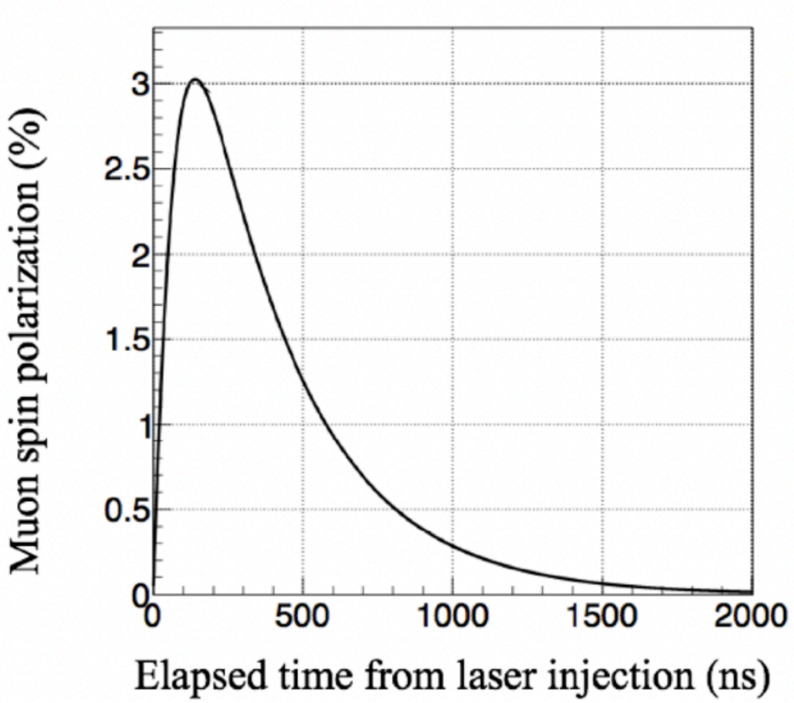


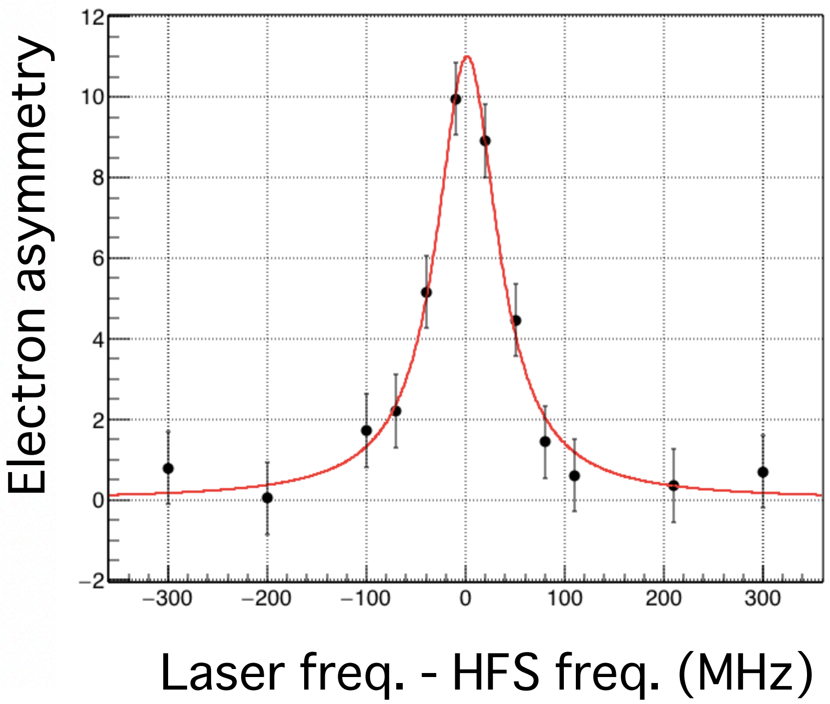
- Muon spin rotation with a low-density hydrogen gas target was performed using a new target chamber for better B-field uniformity.
- The low gas pressure of 0.1 atm was necessary, so the signal-to-noise ratio is small. Nevertheless, a spin rotation-like signal is visible, so careful analysis and detailed simulations are underway.

Feasibility of the Experiment

expectation on the statistical precision





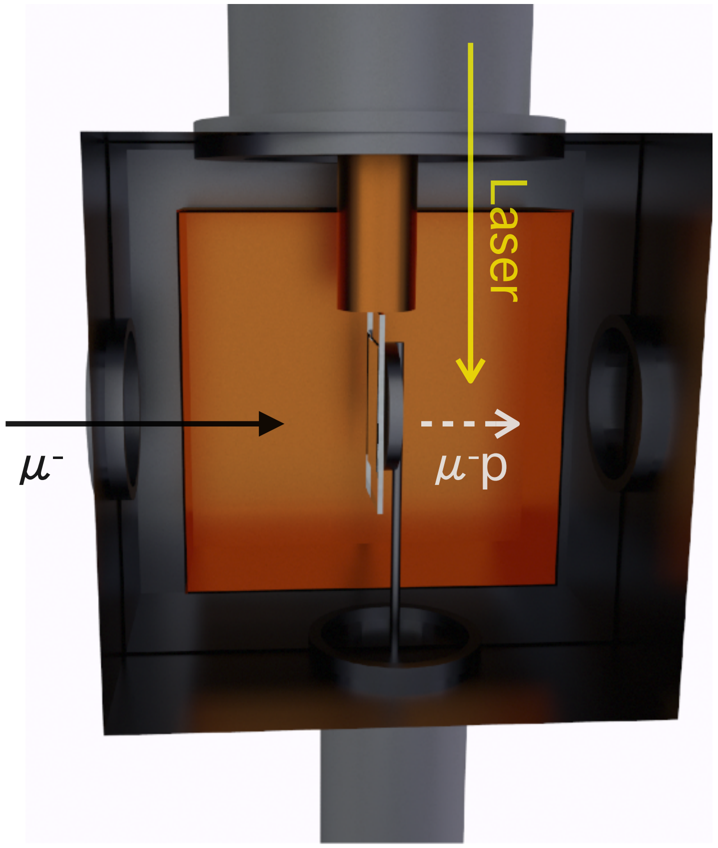


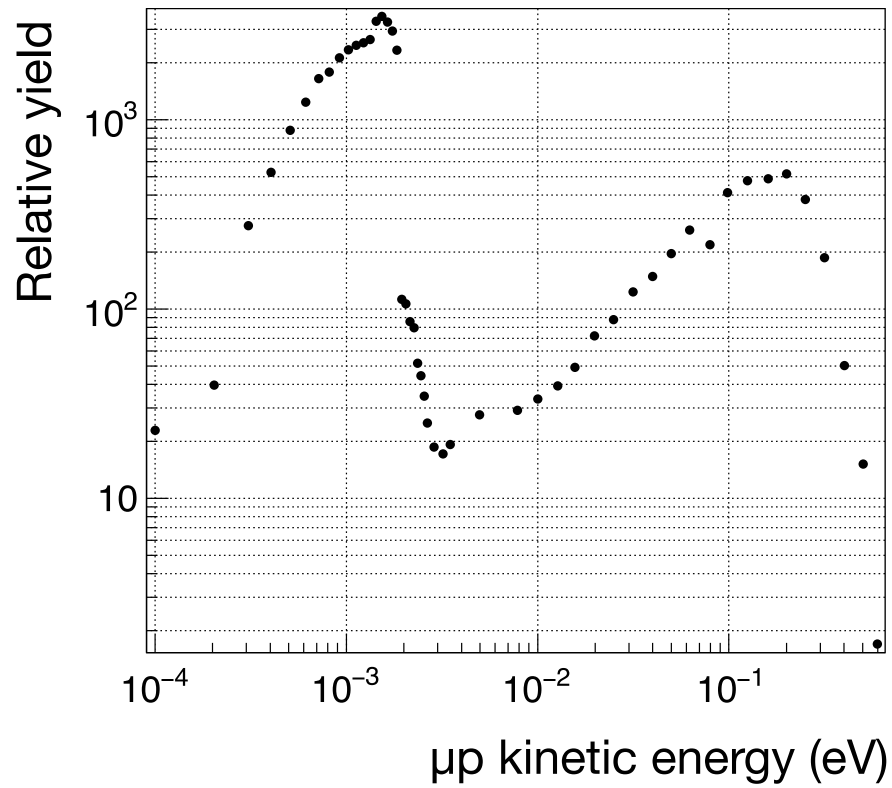
- The beam flux is 1x10^6 μ/s with the momentum of 40 MeV/c. About 0.05% of muons stop between the multipass-cell mirrors.
- The laser light is injected 1 μs after the muon pulse arrival. The averaged muon spin polarization will be 2% with the pulse energy of 20 mJ.
- The signal counting rate will be 0.14/s. A week of measurement is required for frequency scan.
- Completion of the high pulse-energy laser system is necessary. Improvement in the OPO and OPA is essential. Technically possible, mainly a matter of budget.

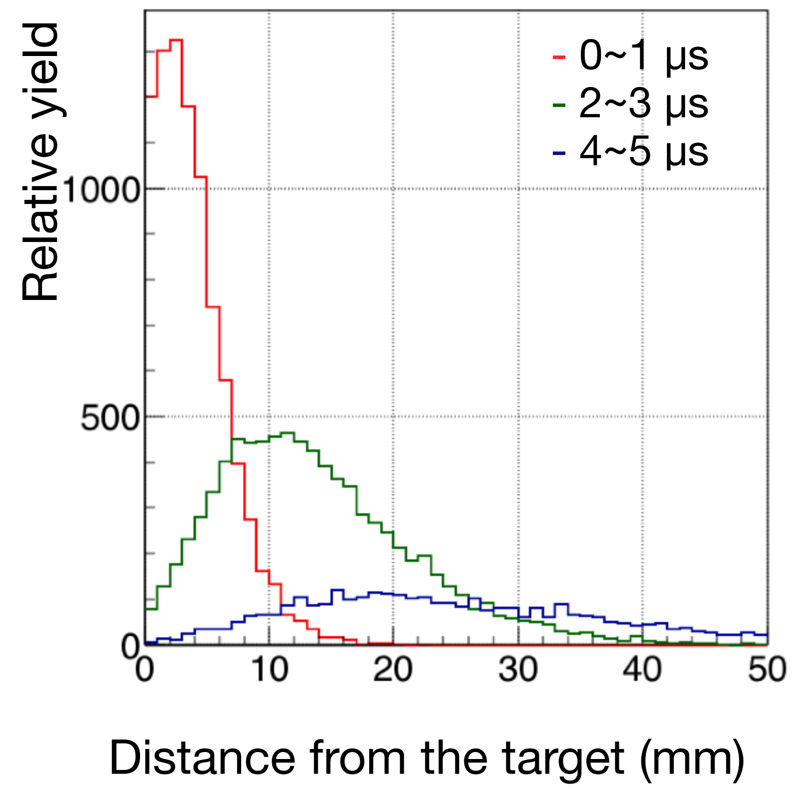
S. Kanda et al., Proceeding of Science, PoS(NuFACT2017)122 (2018).

Solid Hydrogen Target

for spectroscopy in vacuum





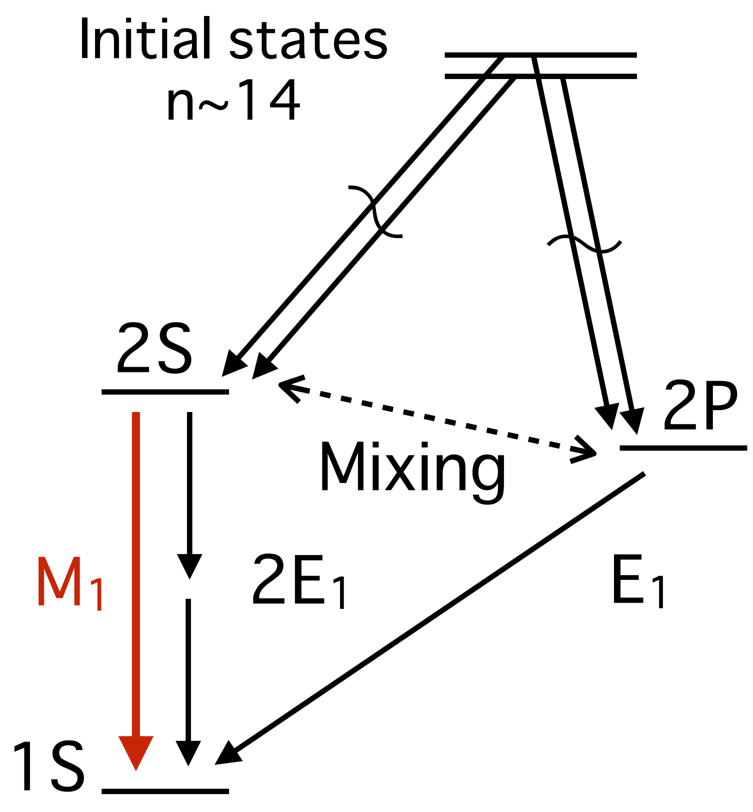


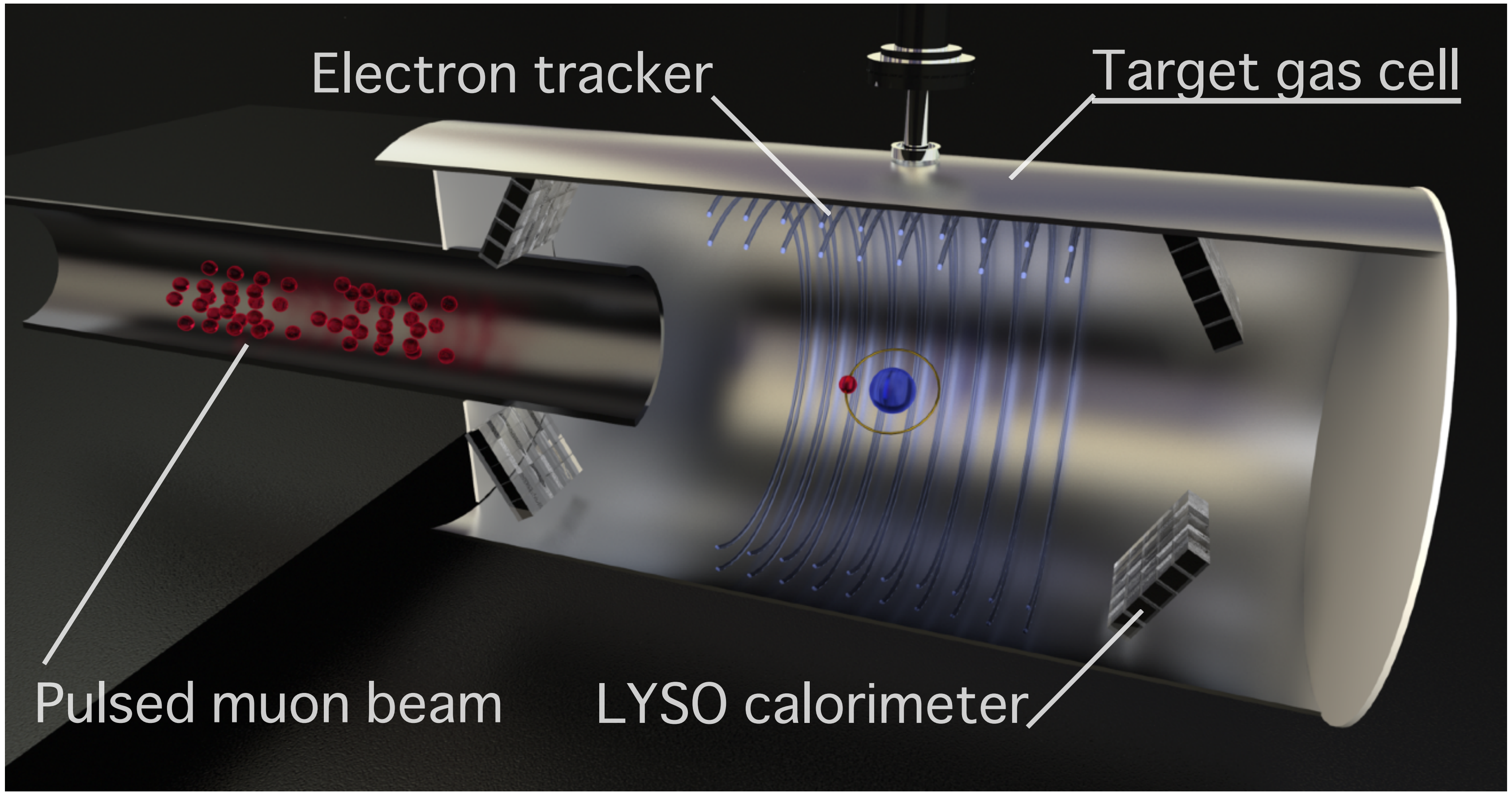
- Muonic hydrogen atoms are emitted from solid hydrogen in to a vacuum.
- Spectroscopy become possible without collisional quenching.
- Emission energy spectrum and space-time distribution were calculated.
- A solid hydrogen target is under development.

Model: J. Wozniak et al., Phys. Rev. A 68, 062502 (2003).

Atomic Parity Violation

a spin-off project from μp-HFS spectroscopy



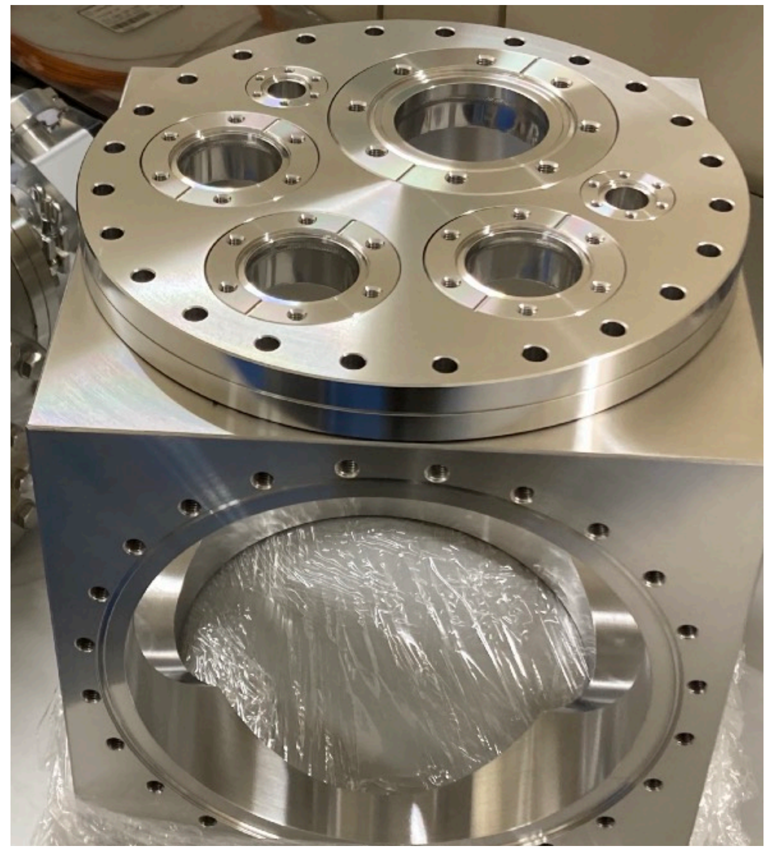


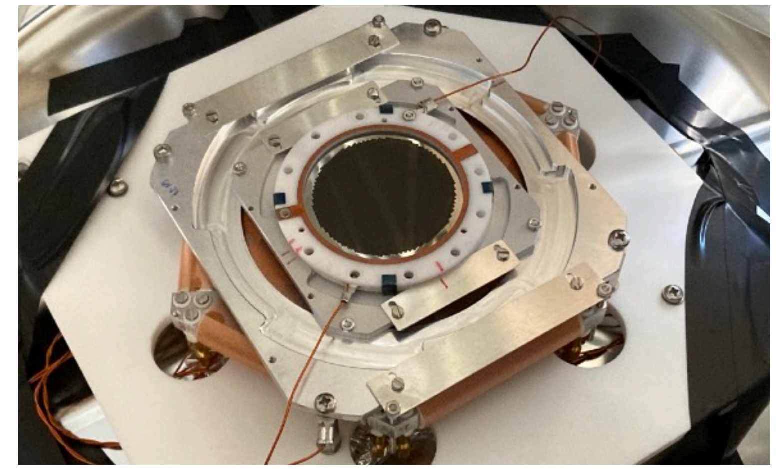
- A new measurement of the Weinberg angle using muonic atoms.
- Parity-violating mixing between 2S-2P states results in anisotropic single-photon emission (M1).
- Muonic X-rays are measured by a scintillator-based calorimeter.

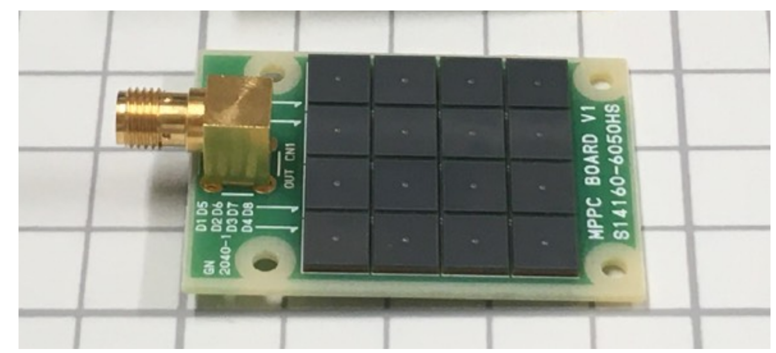
S. Kanda, EPJ Web Conf. 262, 01010 (2022).

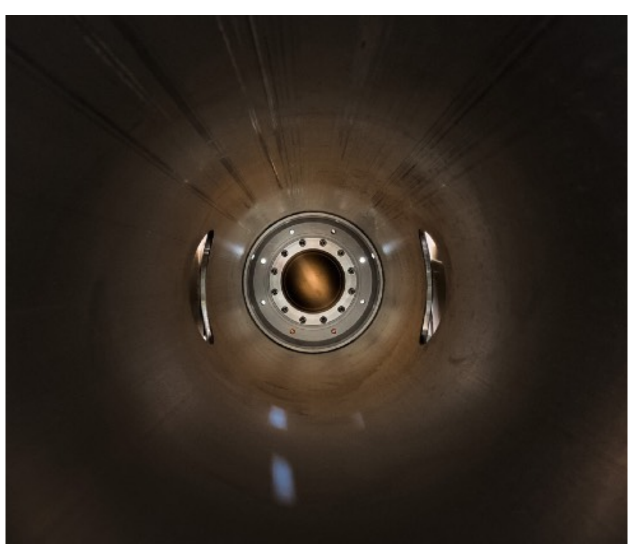
Reboot the project at J-PARC

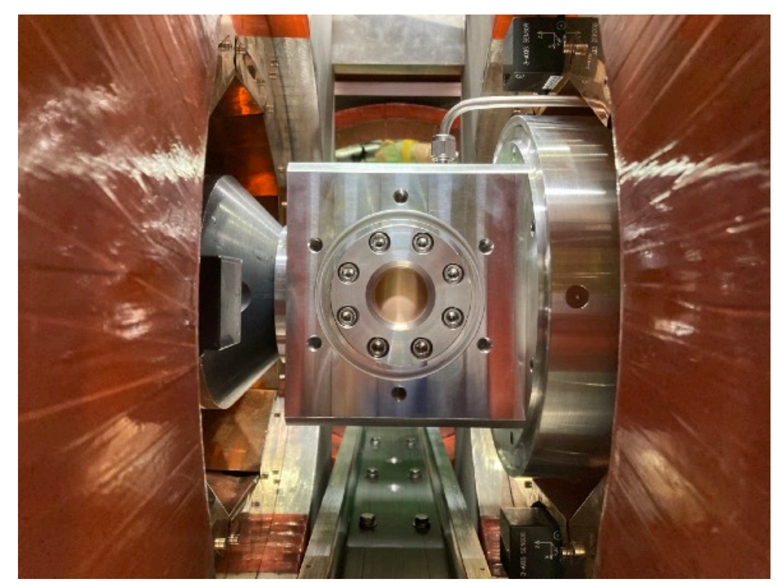
towards realizing the first spectroscopy











Summary

and outlooks

- For a deeper understanding of the proton radius, a new measurement of the ground-state hyperfine splitting in muonic hydrogen is in preparation.
- In the experiment, the angular asymmetry of muon decay electrons is to be measured for detection of the state transition.
- We are working to complete the apparatus developments and realize the experiment.
- Many thanks for Iwasaki-san and colleagues!