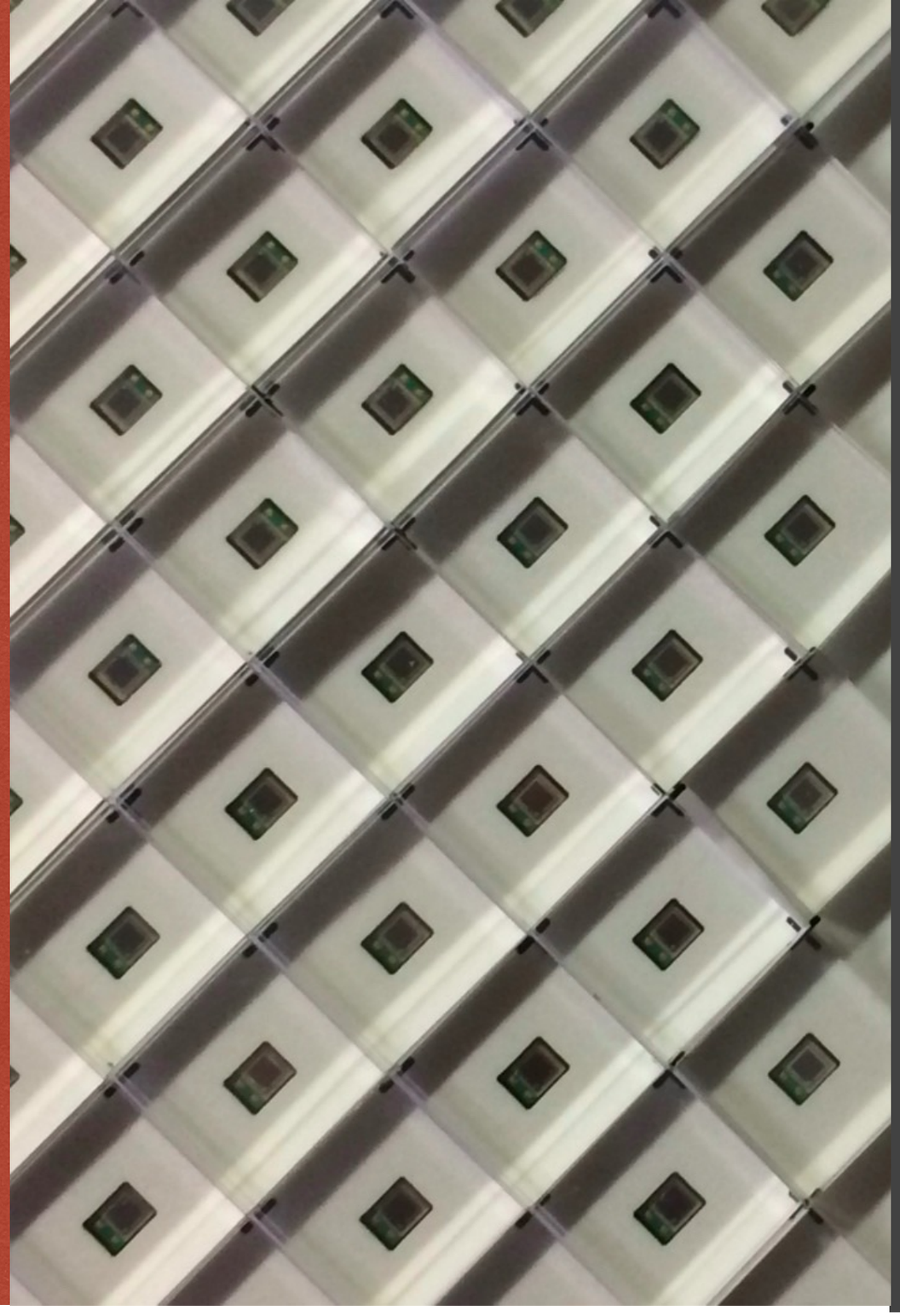
Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen utilizing muon spin repolarization with laser:

Preparation Status



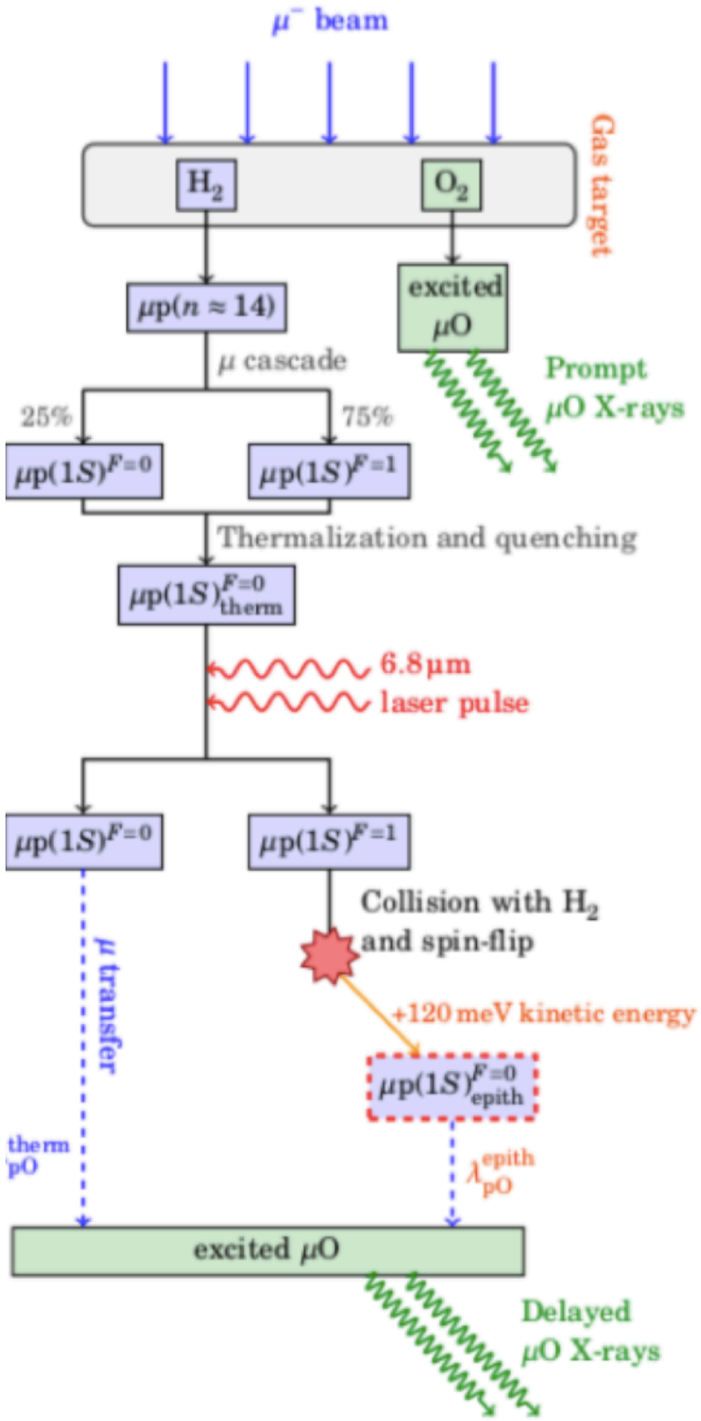
Sohtaro Kanda (神田 聡太郎) / RIKEN

sohtaro.kanda@riken.jp

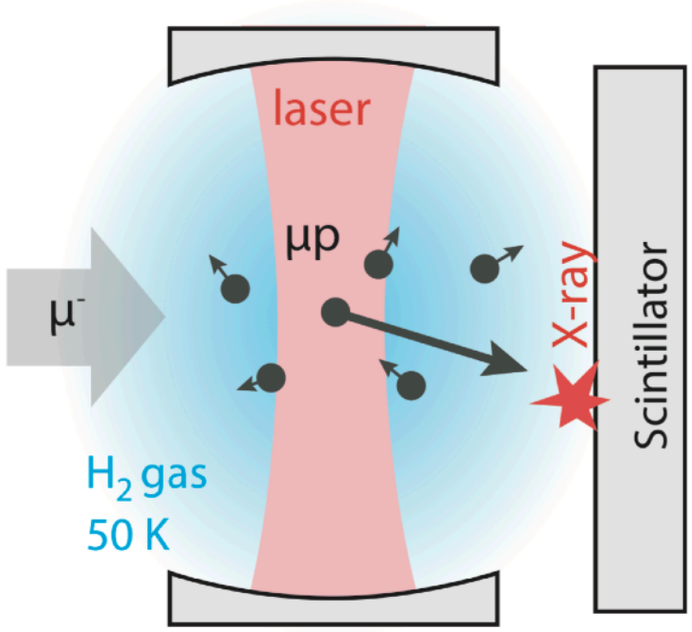
2019/09/16

Three μp-HFS Projects

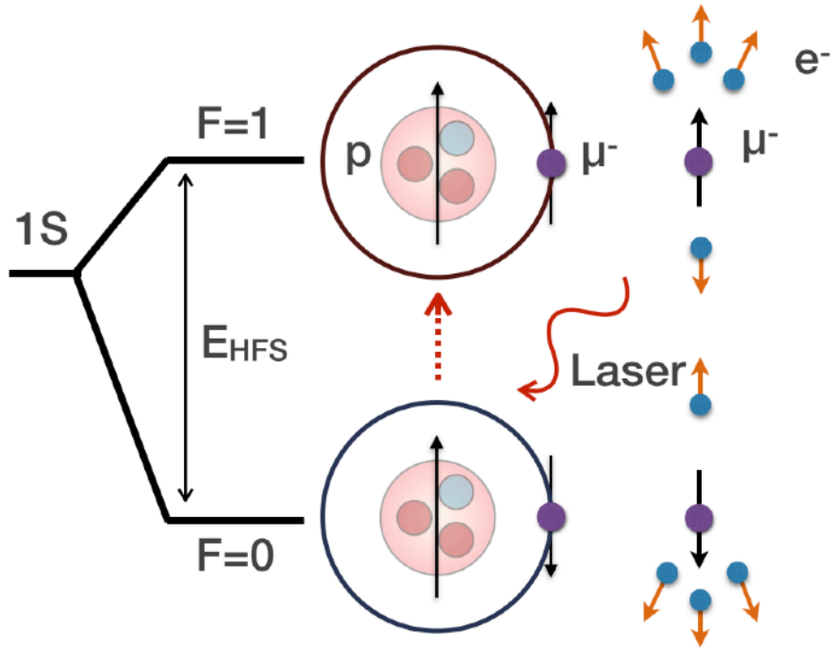
FAMU



PSI



RIKEN



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

Project Timeline of RIKEN Exp.

2013 2014 2015 2016 2017 2018 2019

The Puzzle

Proposal Submitted

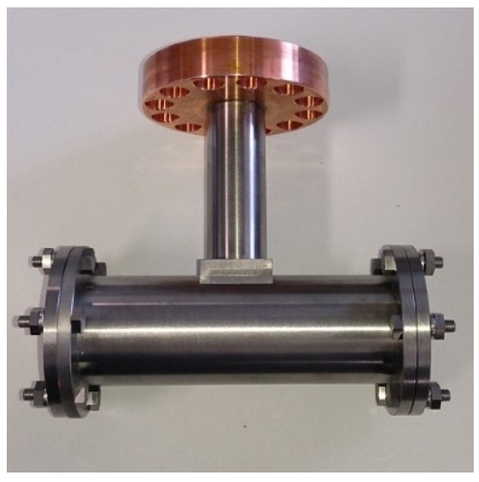
Target R&D

Detector R&D

Laser R&D

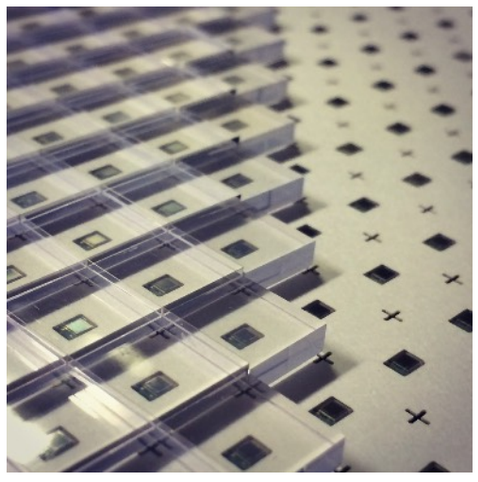
RAL Test1 RAL Test2 RAL Test3

J-PARC Test

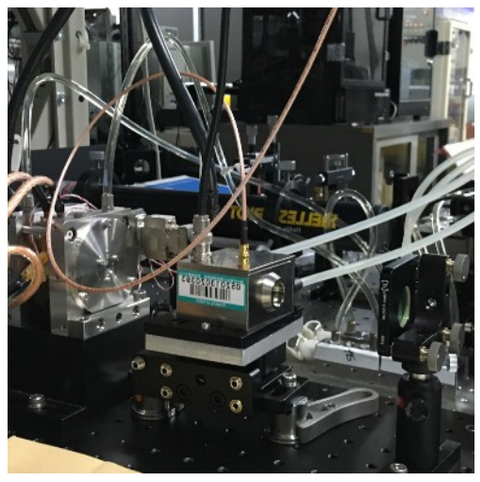


Target Cell

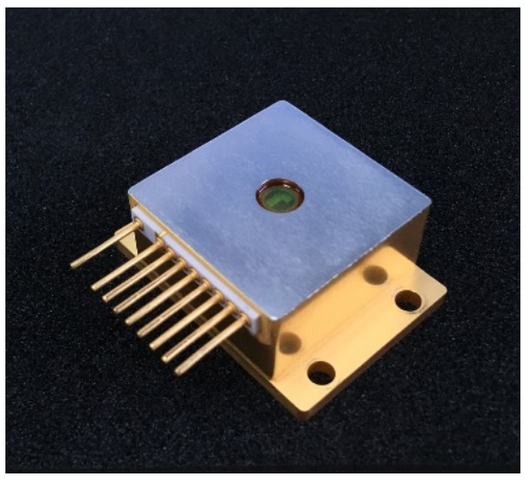
Gas Chamber



Detector



Pump Laser

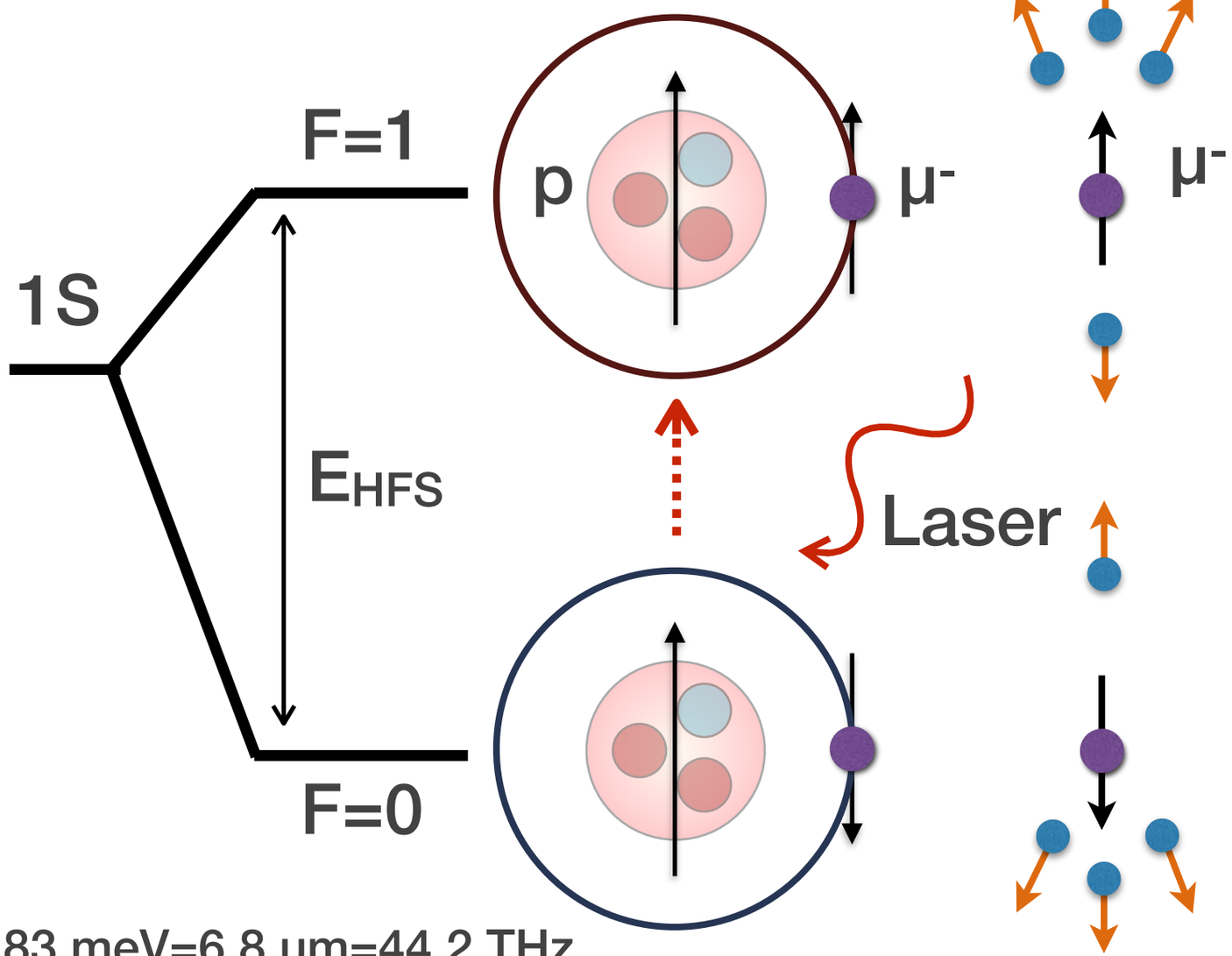


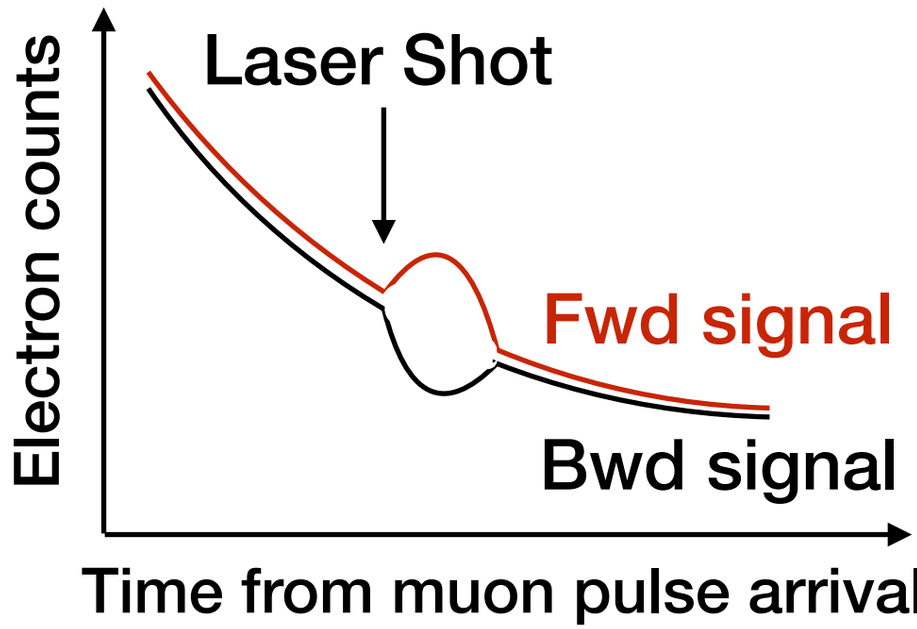
Seed Laser

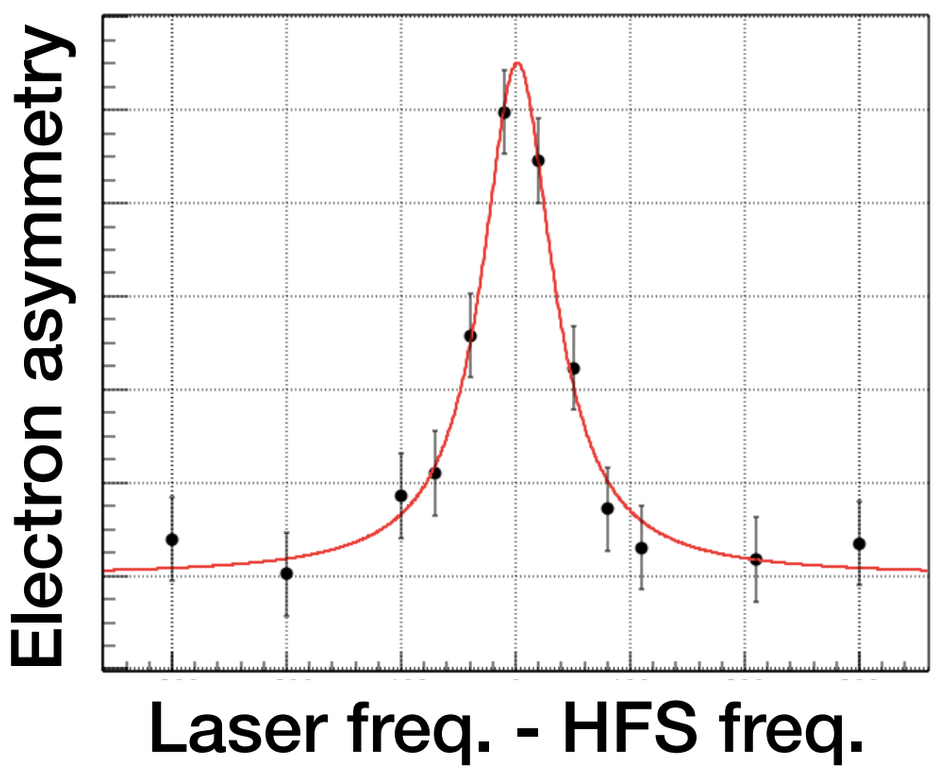
- **Our goal is the determination of μp-HFS with the precision of 2 ppm.**
- **Hydrogen target, transition laser, and electron detector are key components of the experiment.**

Laser Spectroscopy of μp HFS

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







Cryogenic hydrogen target

Segmented electron detector

μp atom

μ^- beam

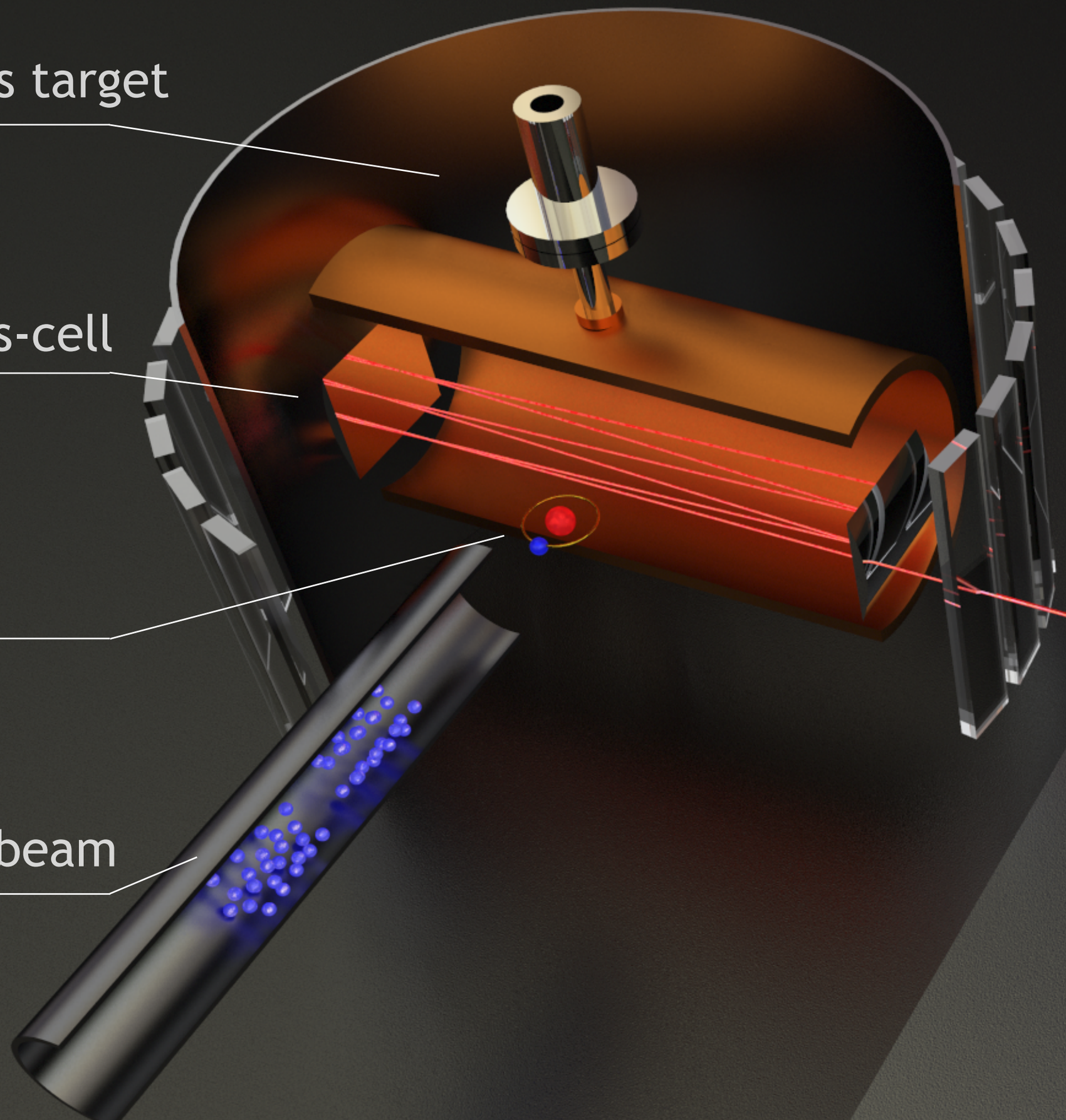
High pulse energy mid-IR laser

Cryogenic hydrogen gas target

Non-resonant multipass-cell

Muonic hydrogen atom

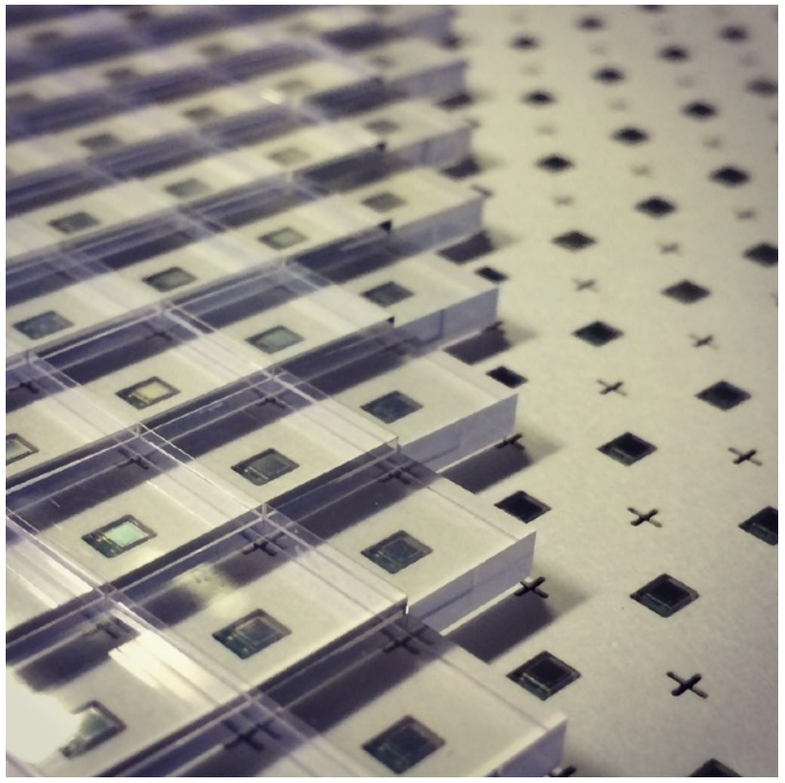
Pulsed negative muon beam

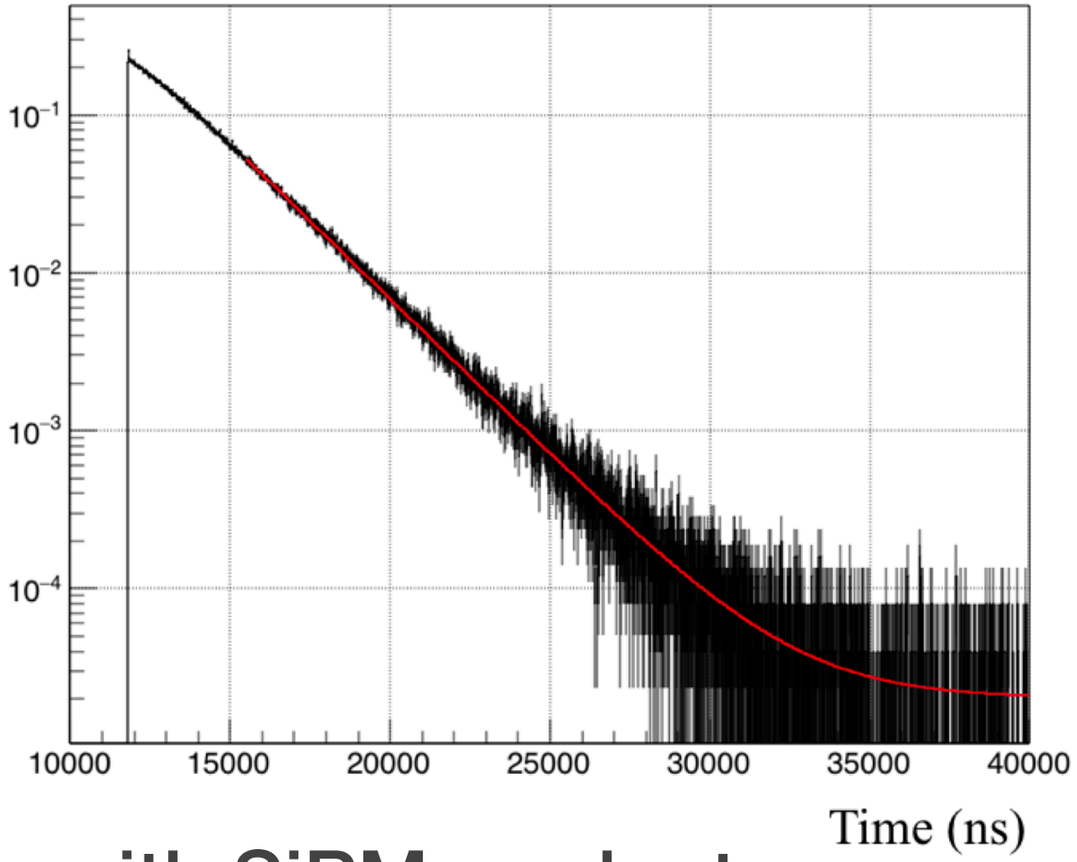


Particle Detectors

- Electron counter is necessary to detect laser-induced muon spin flip signal as the asymmetry in electron angular distribution.
- Requirements:
  - High-rate capability
  - High signal-to-noise ratio
- Muon beam monitor is needed for an optimization of measurement conditions.
- Requirements:
  - Pulse-by-pulse monitoring of beam profile and intensity
  - Minimum amount of material

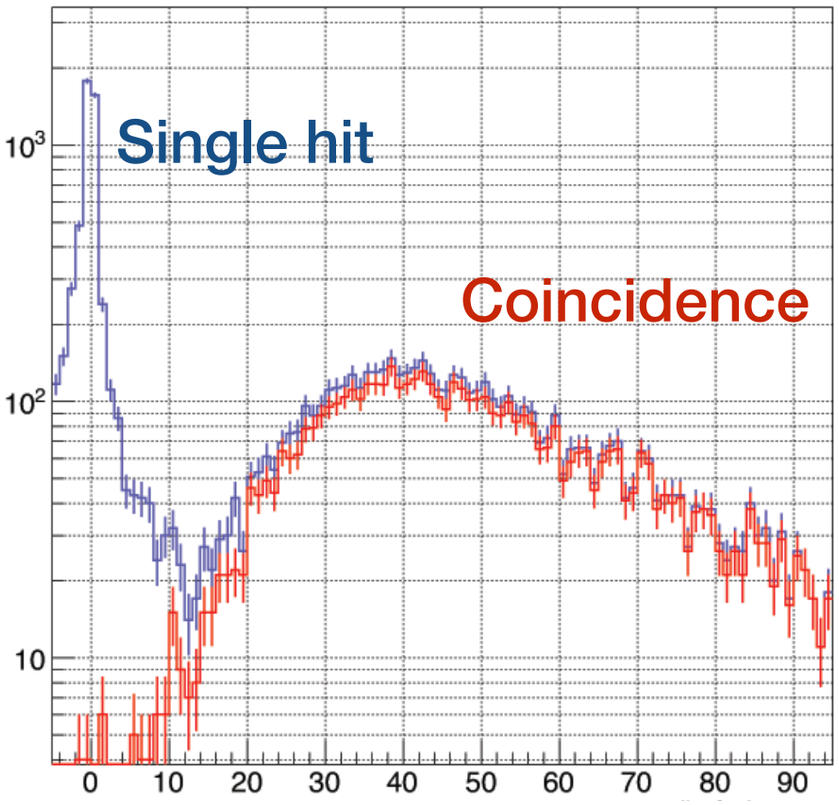
Electron Detector

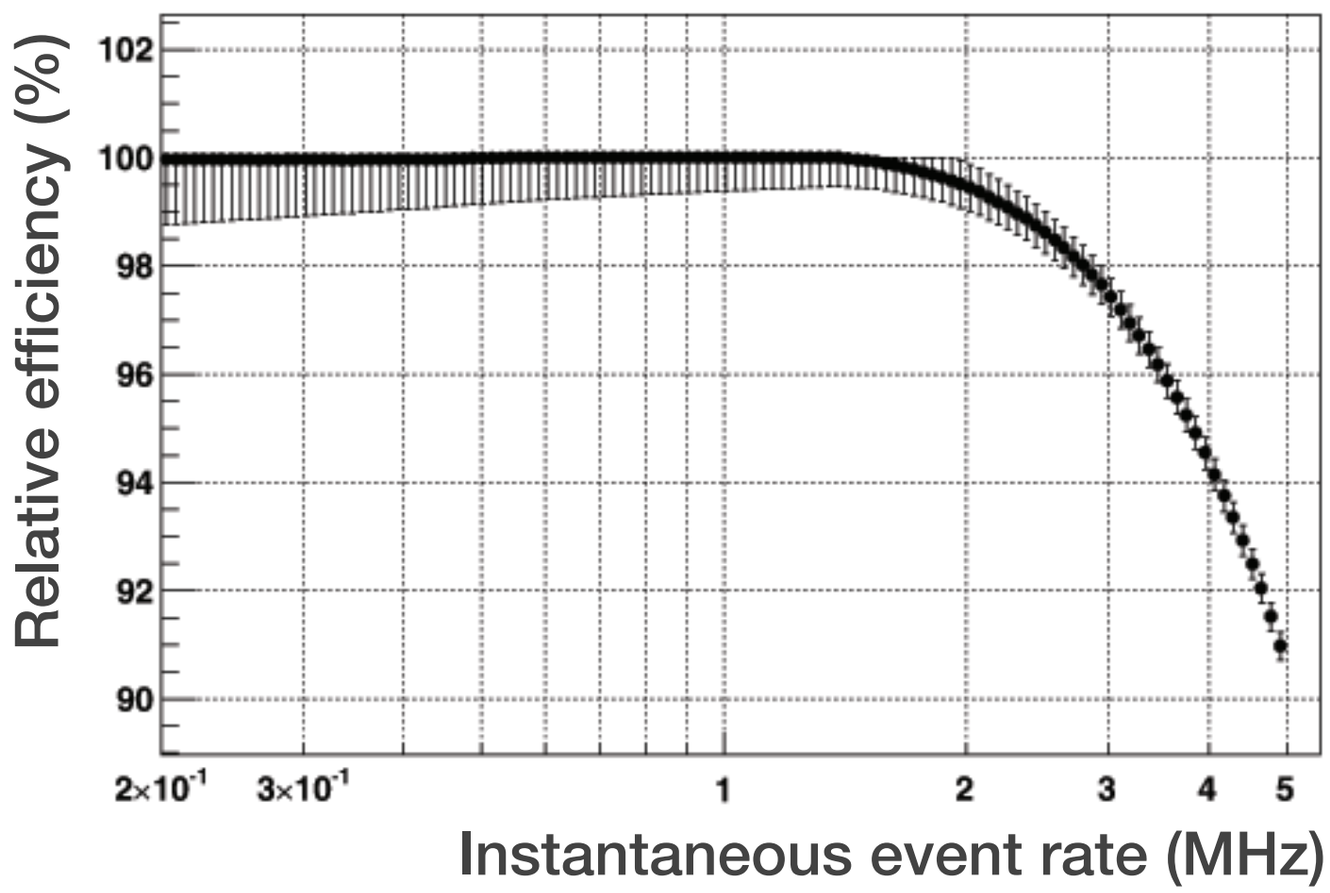




- Segmented scintillation counter with SiPM readout.
  - Unit cell has the dimension of 1 cm x 1 cm x 3 mmt.
  - 240 mm x 240 mm area, 1152 ch. in total.
- Amplifier, shaper, and discriminator in ASIC.
- FPGA-based multi-hit TDC.
- Developed for a muonium HFS experiment at J-PARC.
- S. Kanda, PoS(PhotoDet16)039 (2016).

Efficiency and Rate Capability



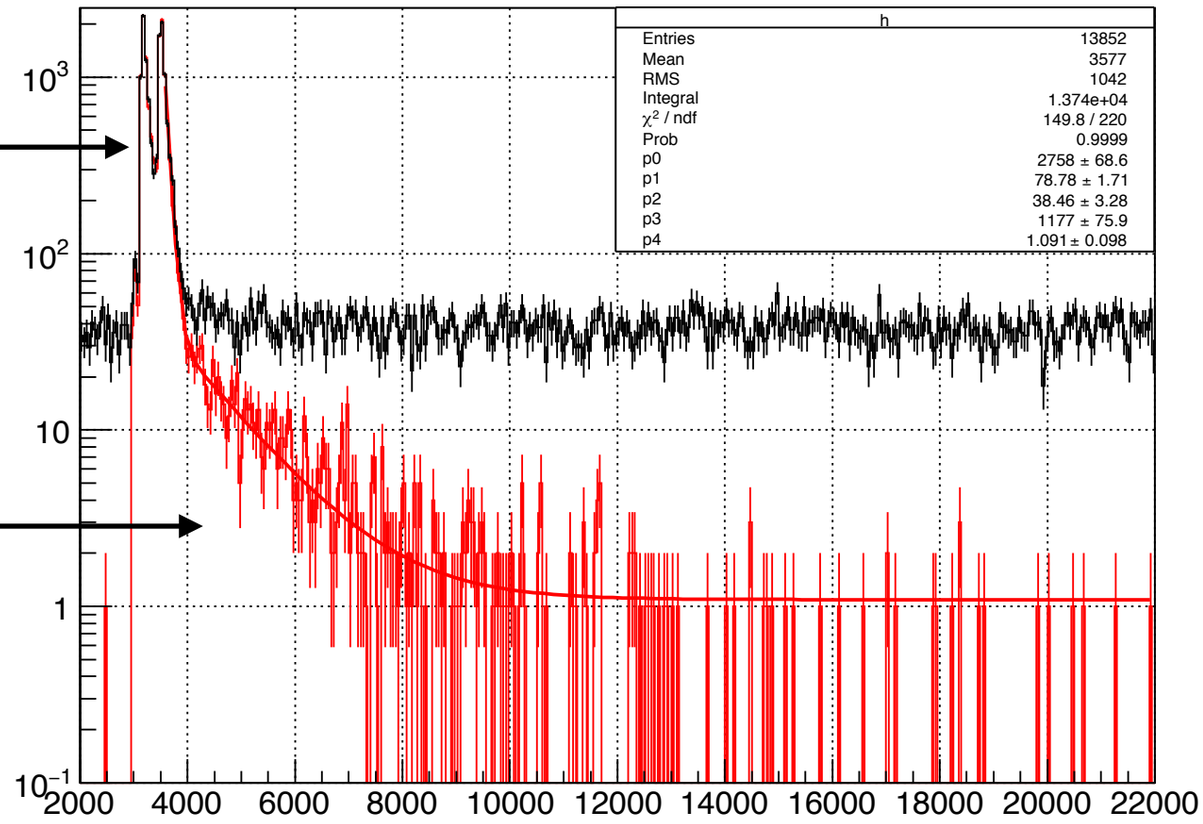


- Detection efficiency was obtained by photon counting measurement.
  - Efficiency > 98% for muon decay electron
- Rate capability was evaluated by event loss analysis
  - Pileup loss < 3% at 3 MHz instantaneous rate
- Detector performance is good enough for the experiment.

Signal-to-Noise Ratio

Sharp peaks come from muonic silver (Muon beam has double pulse timing structure)

Background events having long-lifetime

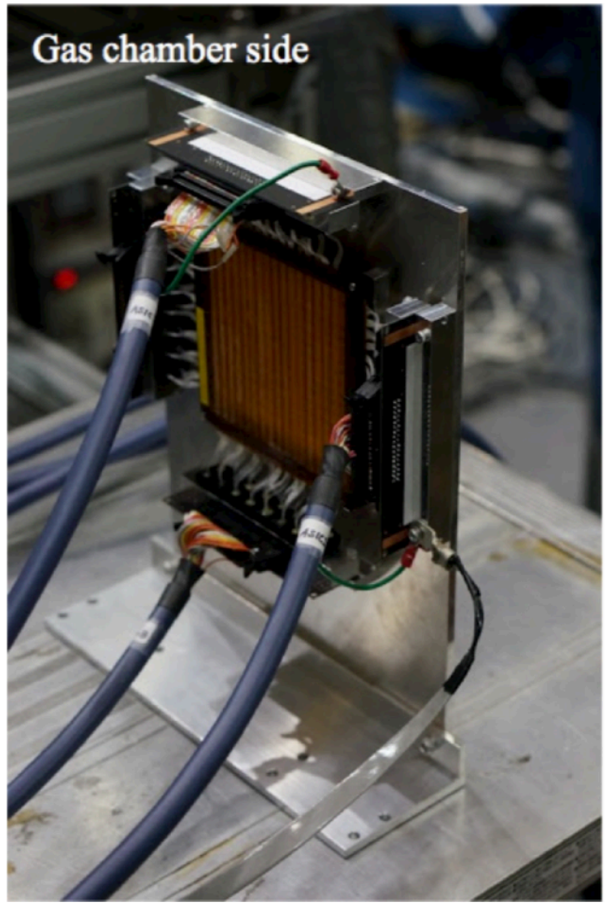


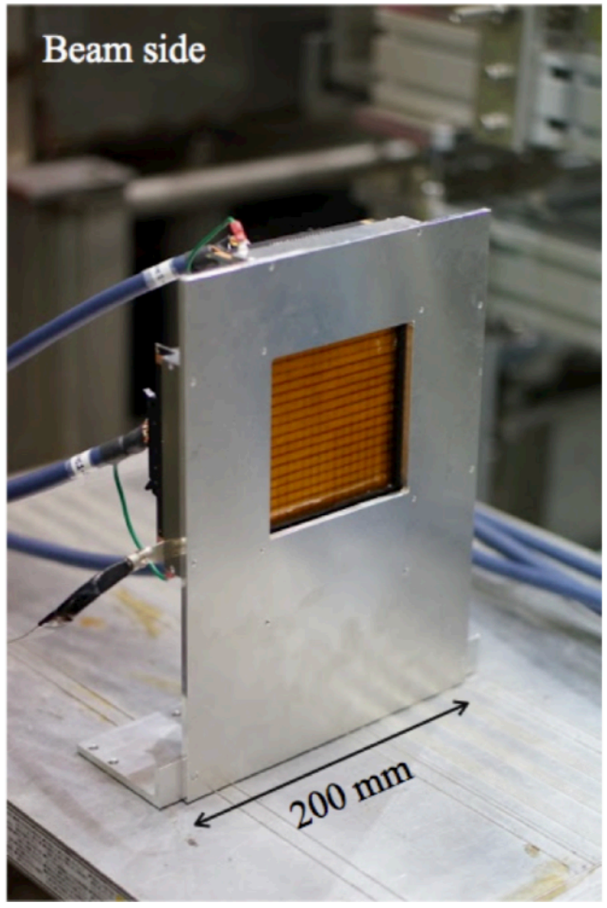
Single hit

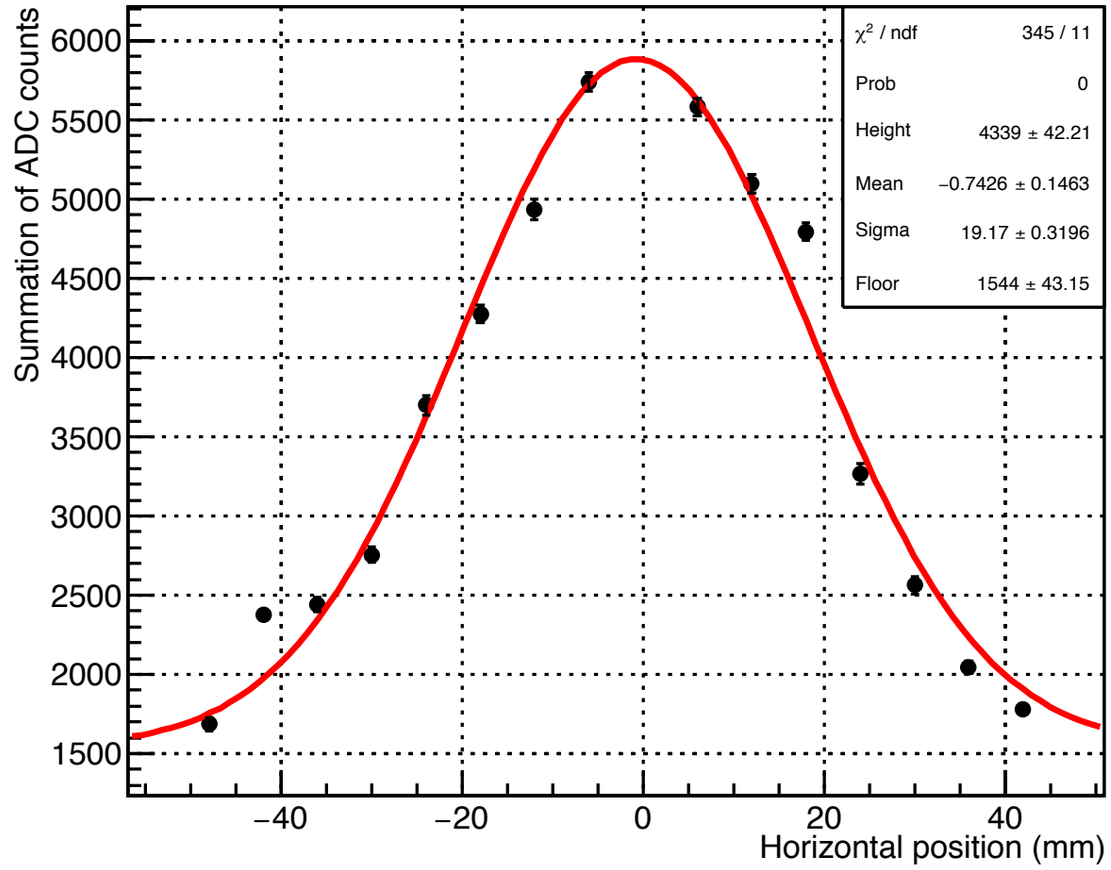
Coincidence

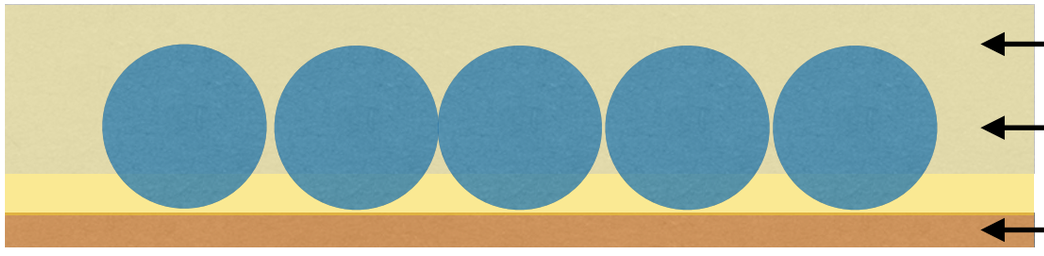
- In a spectroscopy measurement, laser light is injected after 1 μs passed since a muon beam pulse arrival.
- Inner walls of the target chamber is covered by silver plates to suppress background events.
- S/N was evaluated by time spectrum fitting.
- Expected S/N is 4 x10^4 , good enough for the experiment.

Muon Beam Profile Monitor

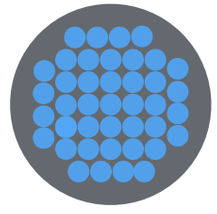








Fiber array layer structure

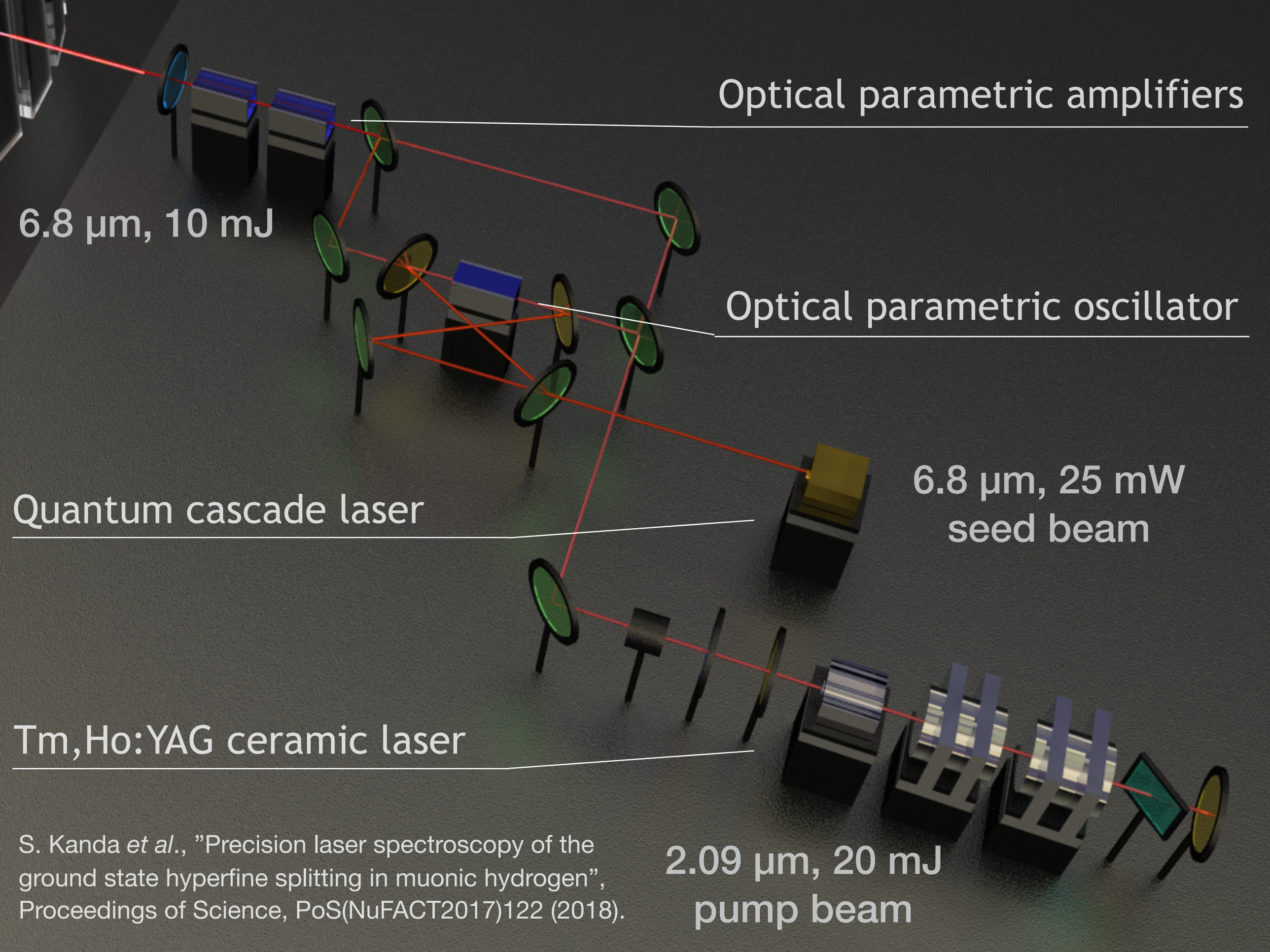


40 fibers are bundled for a ch. and connected to MPPC

- Cross-configured fiber hodoscope with SiPM readout.
- Online measurement of the beam profile and relative intensity.
- S. Kanda, RIKEN Accelerator Progress Report Vo. 48 (2015).

Transition Laser

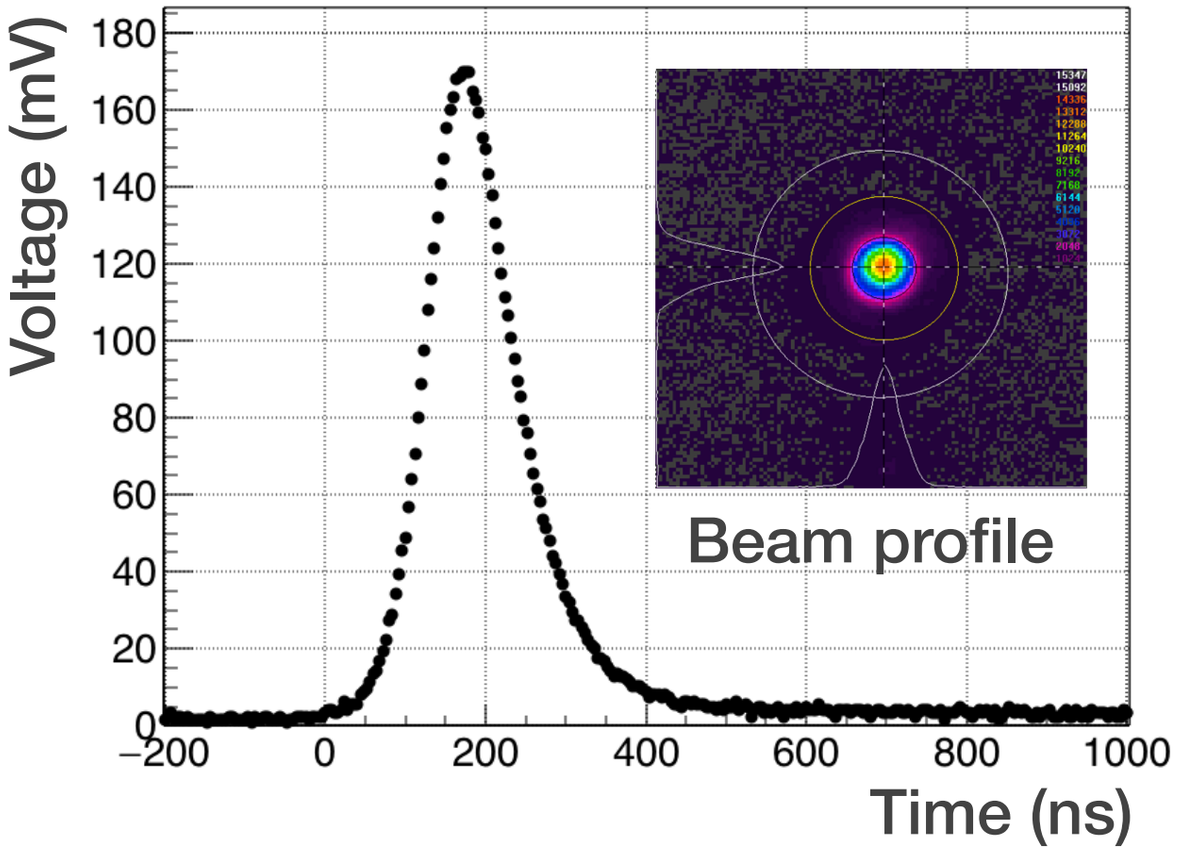
- HFS transition is optically suppressed by the selection rule, so high pulse energy is necessary.
- High-performance transition laser is required.
- Requirements:
  - Wavelength 6.8 μm (frequency 44.2 THz)
  - Stable, pulsed operation at 12.5 Hz
  - Wavelength tunability for a resonance scan
  - High pulse energy > 20 mJ
  - Narrow spectral linewidth < 150 MHz
  - Precise wavelength calibration (2 ppm)
  - Circular polarization



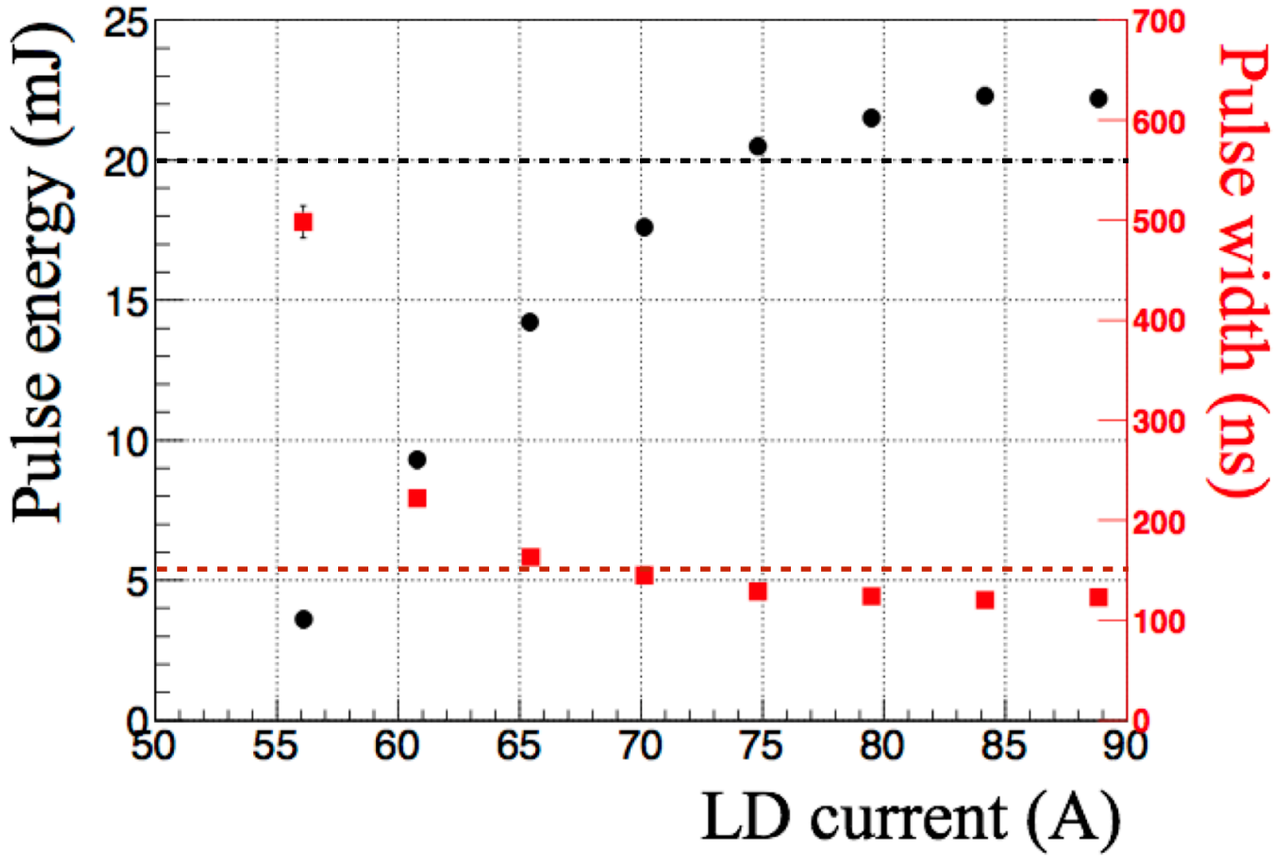
S. Kanda *et al*., ”Precision laser spectroscopy of the ground state hyperfine splitting in muonic hydrogen”, Proceedings of Science, PoS(NuFACT2017)122 (2018).

Tm,Ho:YAG Ceramic Laser

Waveform and beam profile



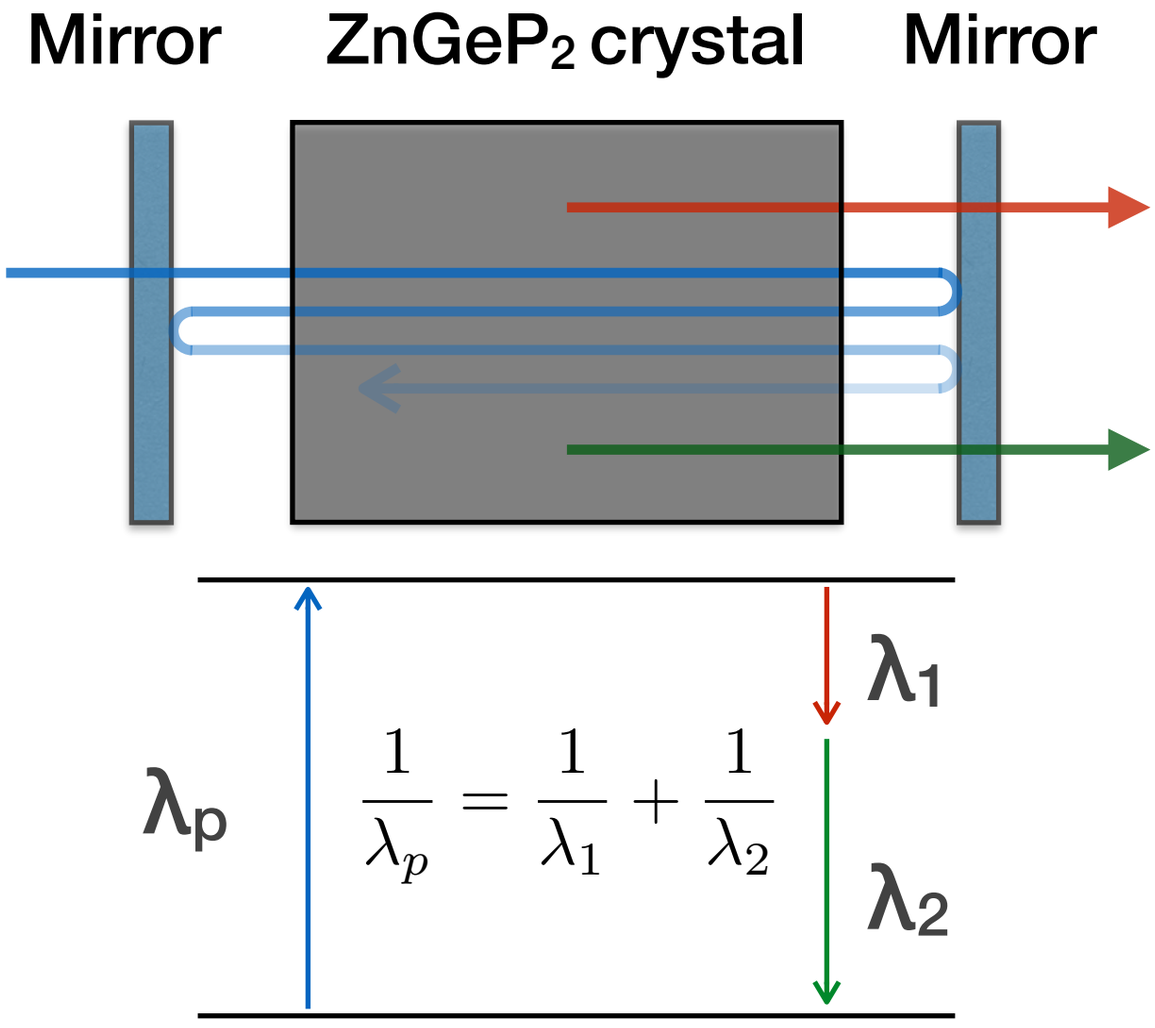
Pulse energy and width

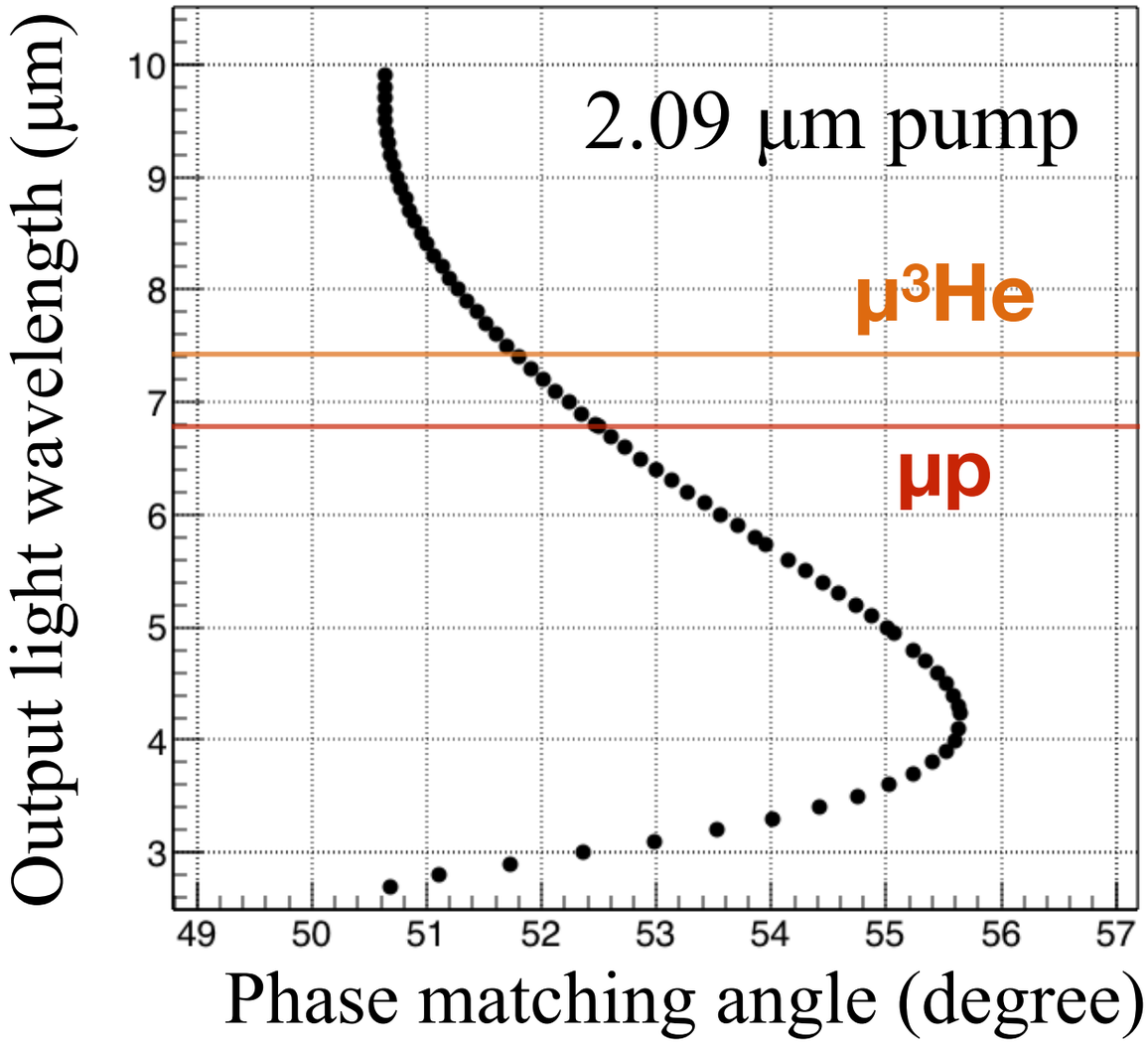


- 2.09 μm light is necessary for 6.8 μm light generation via OPO.
- LD pumped, Q-switching, Tm^{3+},Ho^{3+} co-doped YAG ceramic laser was developed.
- **Sufficient performance as a pumping beam for the ZGP-OPO was achieved (E>20 mJ, Width<150 ns).**

S. Kanda et al., RIKEN APR51 (2018).

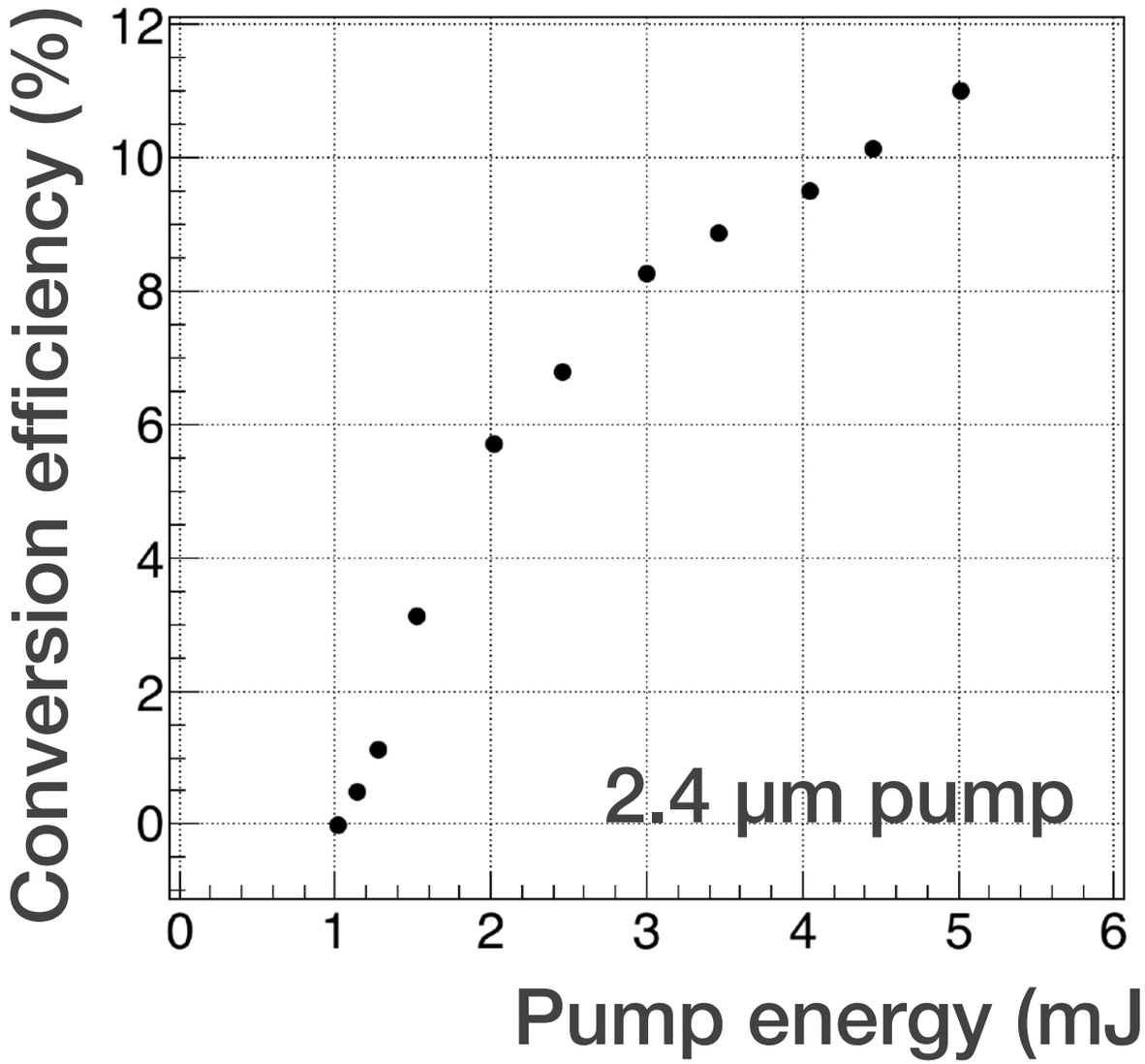
Optical Parametric Oscillation

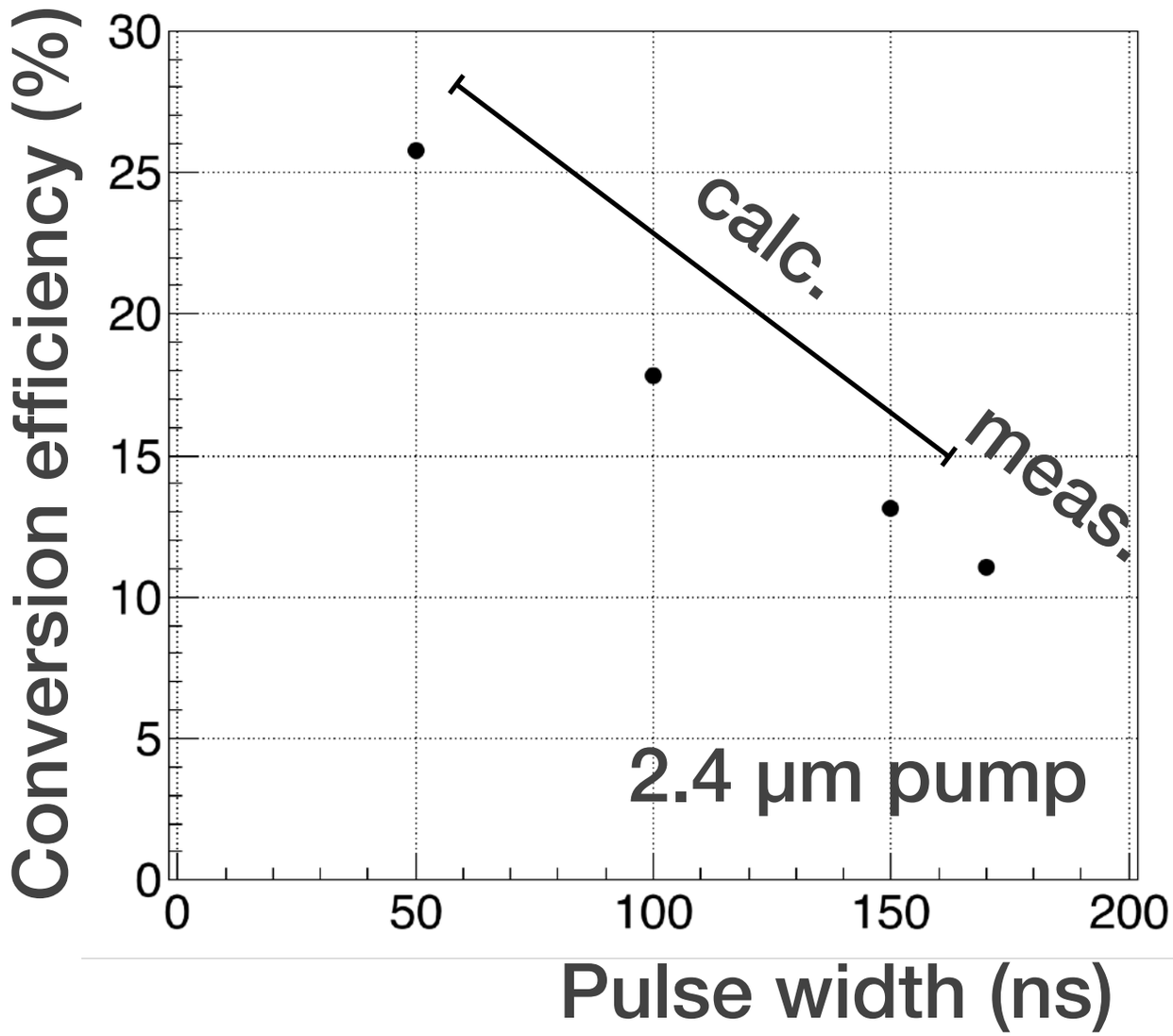




- **Optical parametric oscillator provides two lower frequency lights from a pumping light via non-linear optical effect.**
- **ZGP is an optimum from viewpoints of the damage threshold and non-linear optical coefficient.**
- **All-solid mid-infrared light source covers both μp 1S-HFS and μHe 2S-HFS at the same time by just changing of the crystal angle.**

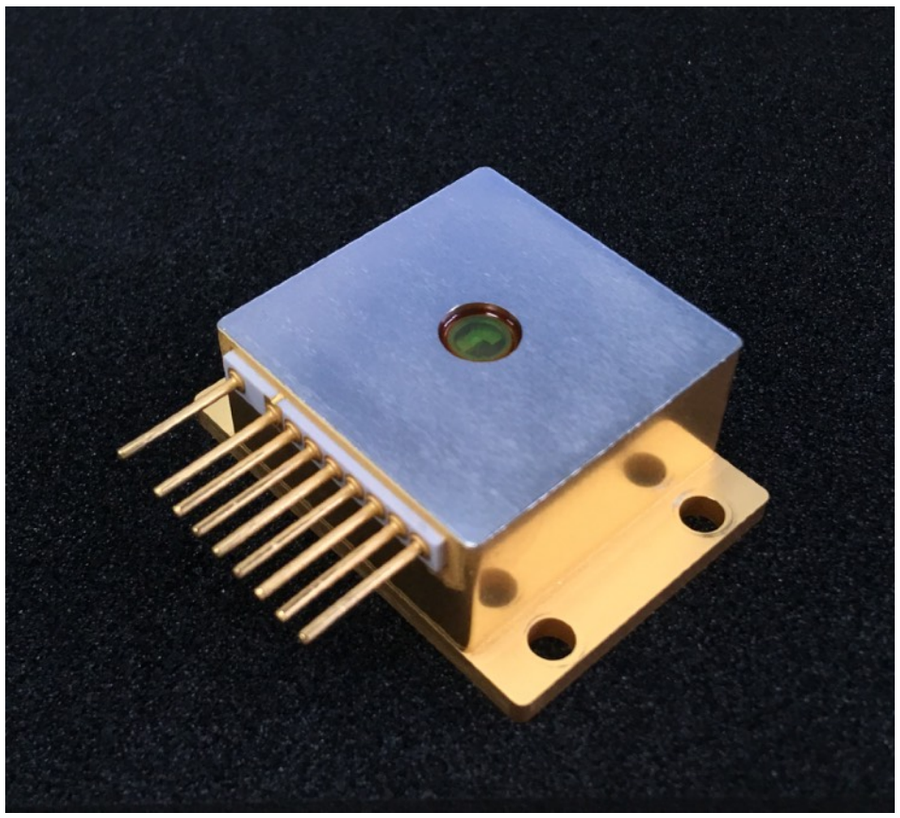
ZGP-OPO with 2.4 μm pump

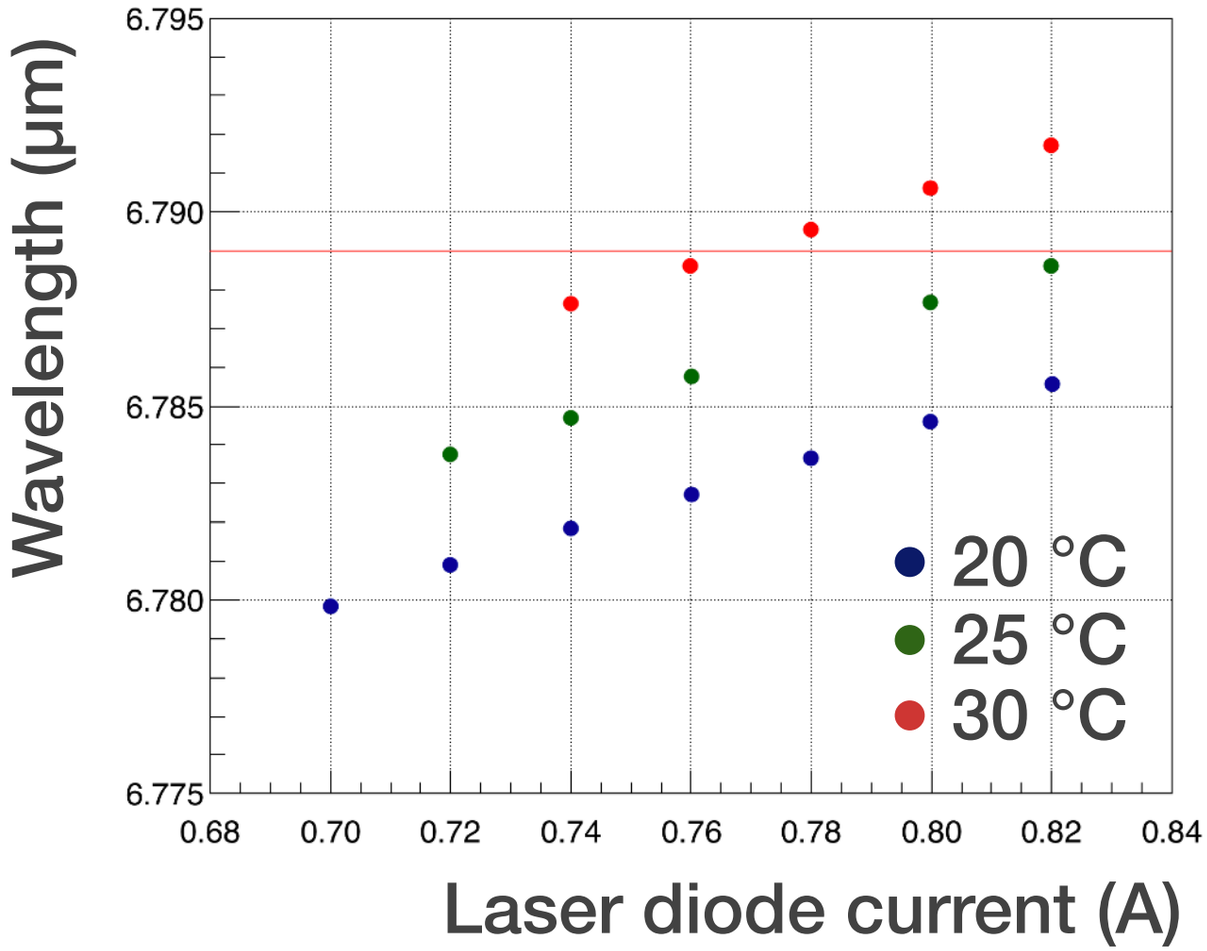




- **The ZGP-OPO was demonstrated with Cr:ZnSe laser (2.4 μm).**
- **Similar performance is expected with 2.09 μm pump.**
- **The conversion efficiency of 13% or above is achievable.**

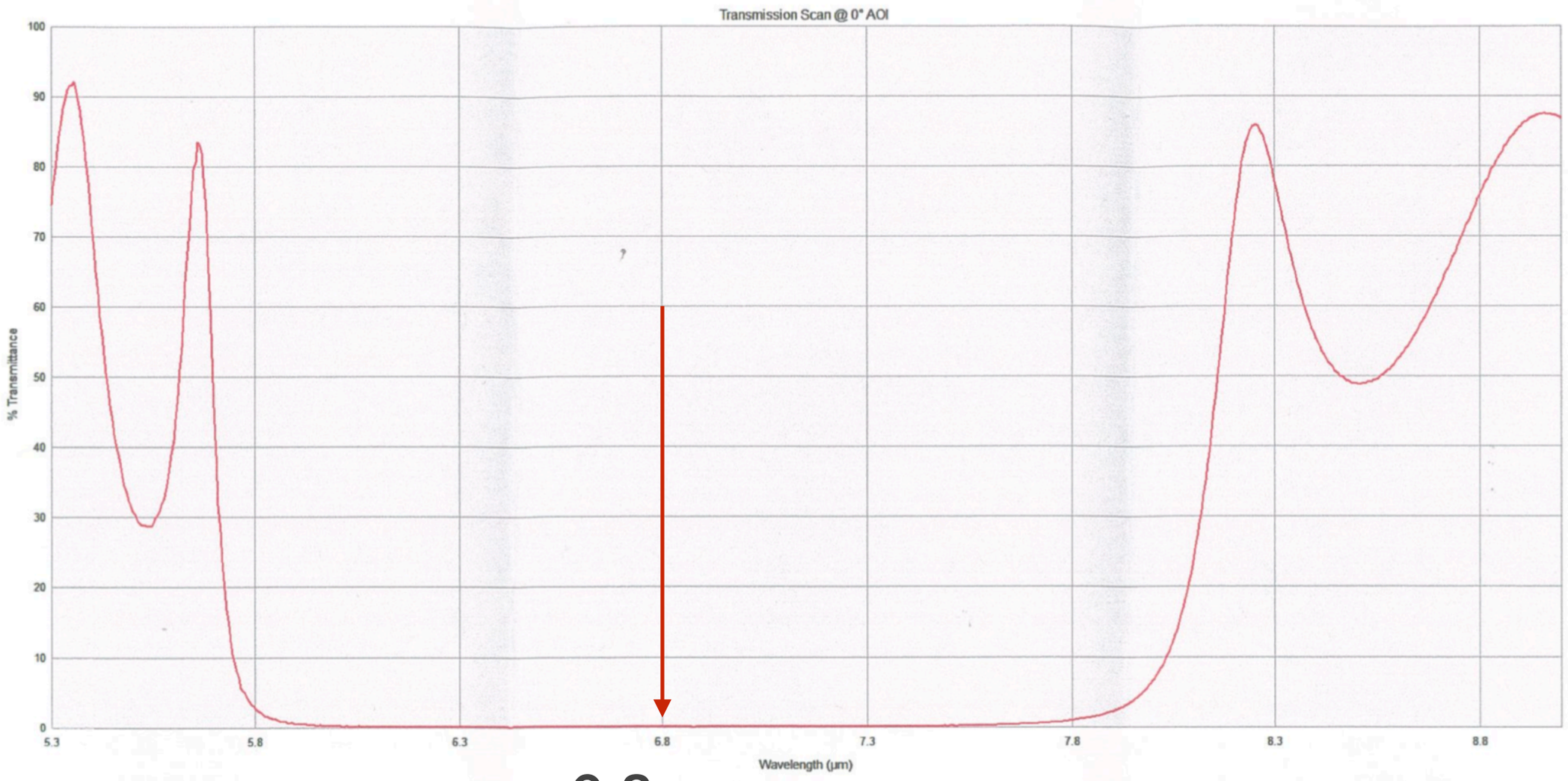
QCL-Seeder for ZGP-OPO





- 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).
- Spectral linewidth measurement is in preparation.

Multi-Pass Cell



6.8 µm

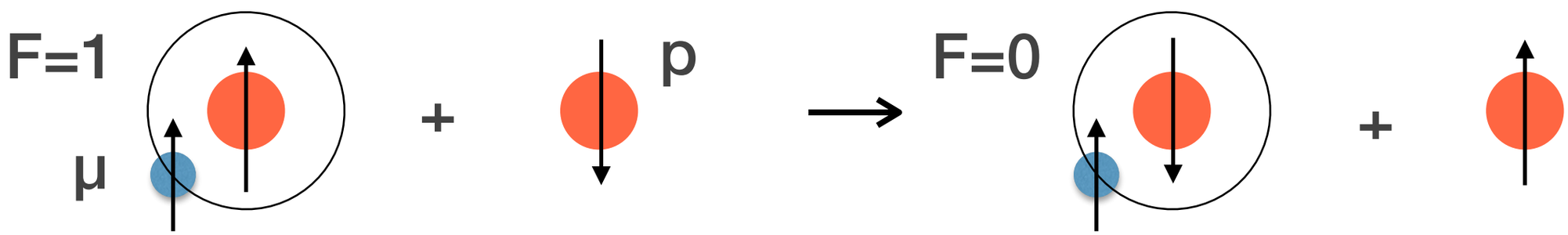
- Highly reflective mirrors for the multi-pass cell were developed.
- High reflection at 6.8 µm was confirmed.
- Cavity ring-down measurement is in preparation.

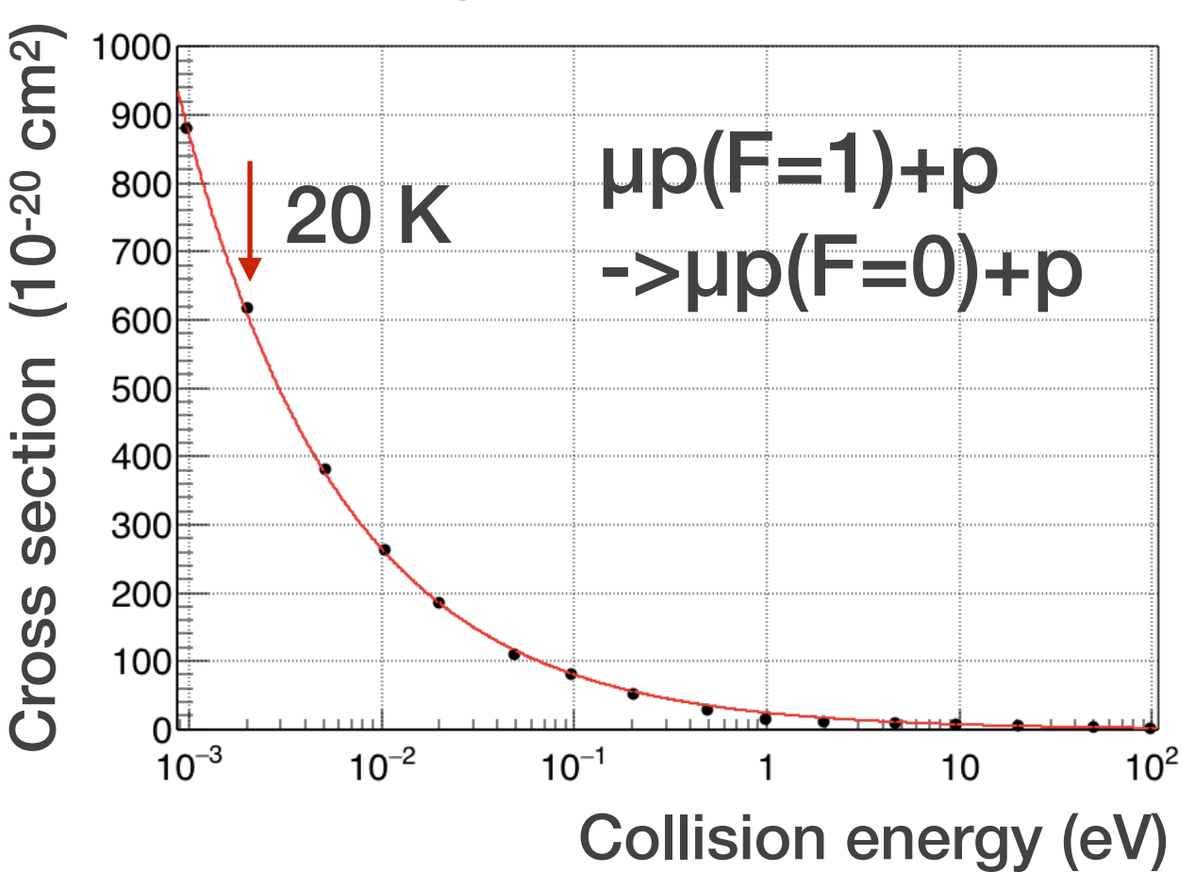
Hydrogen Target

- Muon stopping in target is needed for muonic hydrogen formation.
  - High density is efficient.
- Lifetime of the muon spin polarization is short due to inelastic scattering μp(F=1)+p->μp(F=0)+p.
  - Low density gives longer lifetime.
- Linewidth of the resonance is dominated by Doppler broadening effect.
  - Low temperature makes the linewidth narrower.
- Requirements:
  - Stable operation at 20 K and 0.1 atm.
  - High purity

Atomic Collisional Quenching

- 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.

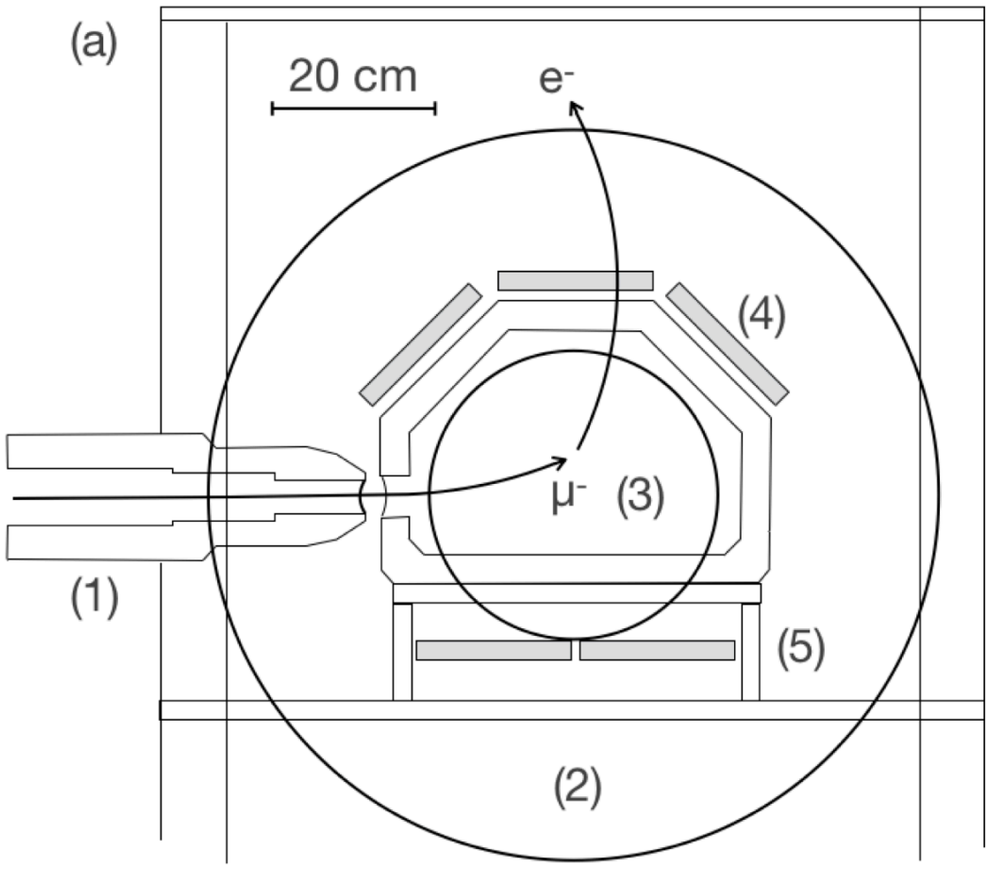




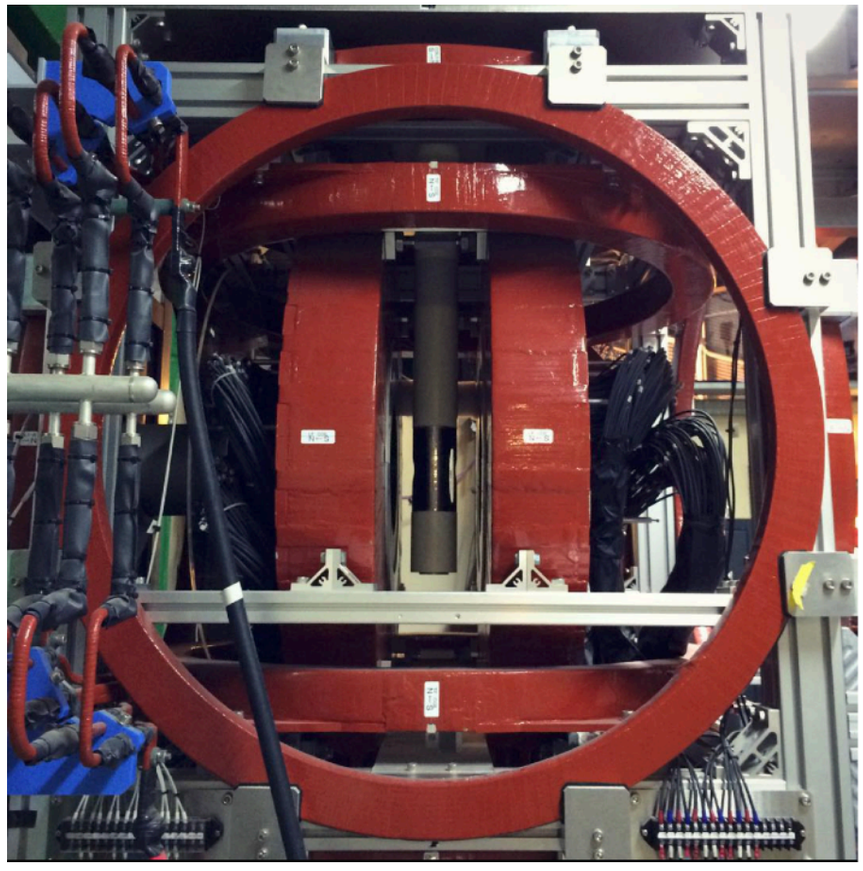
- Quenching rate depends on collision energy and gas pressure.
- Expected lifetime at 20 K, 0.06 atm is approximately 50 ns.
- A new experiment for direct measurement of the quenching rate was proposed.

J.S. Cohen, PRA 43, 3460 (1991).

Collisional Quenching Measurement



Experimental setup

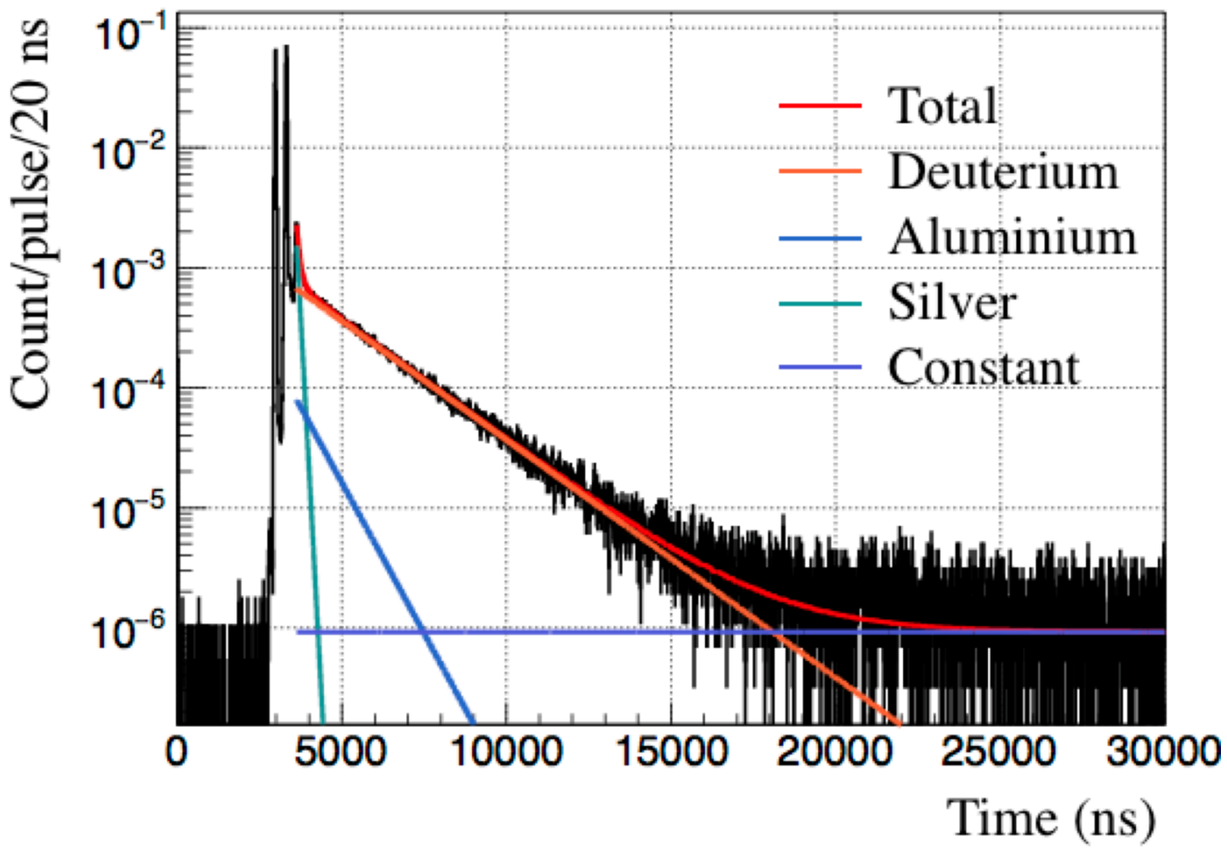


CHRONUS spectrometer

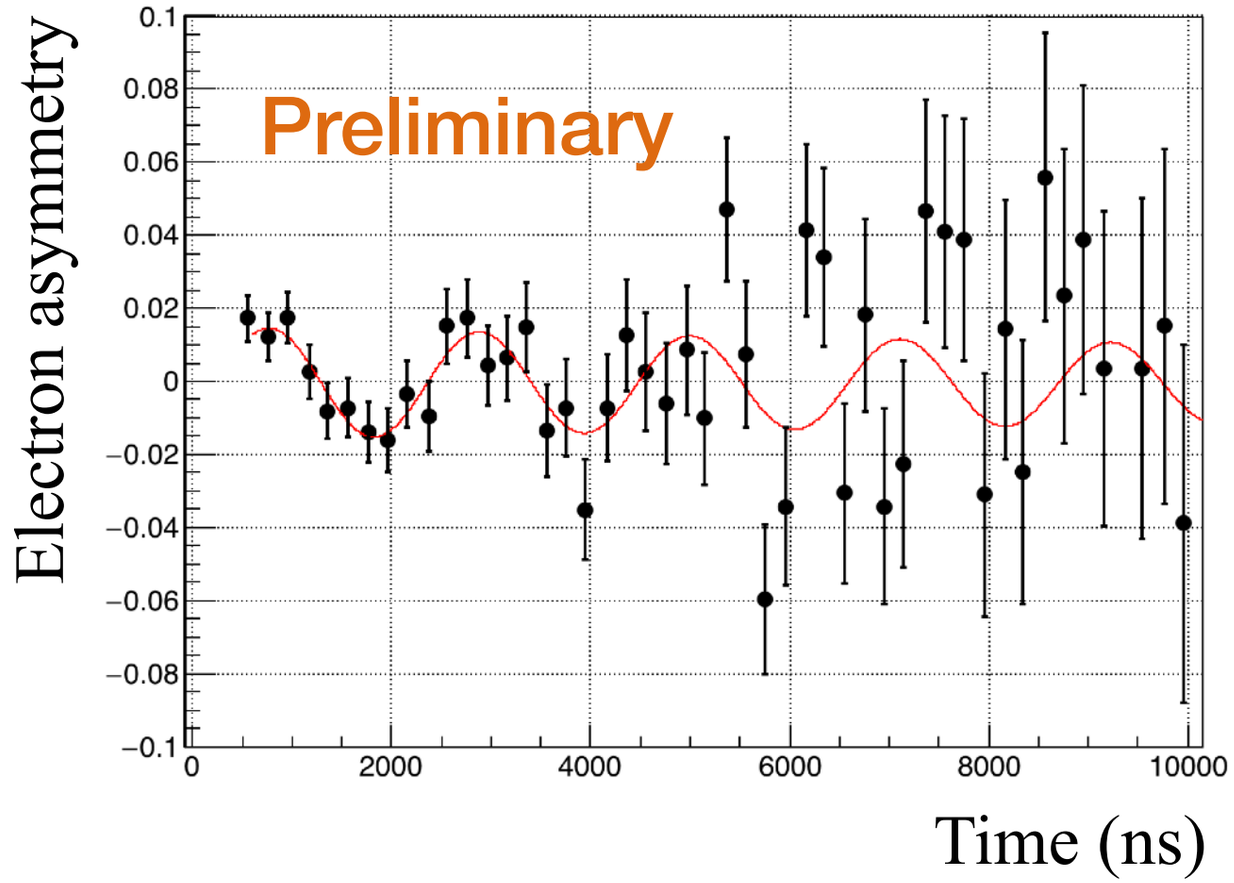
- Initial muon spin is polarized along the beam axis.
- Muon forms a muonic atom after stopping in the target.
- Muon spin rotates under a static magnetic field.
- Angular asymmetry in electron emission from muon decay is measured.

S. Kanda *et al*., “Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen atom”, Journal of Physics Conference Series, 1138 012009 (2018).

Muonic Deuterium μ-SR Result



Electron time spectrum
(zero field)

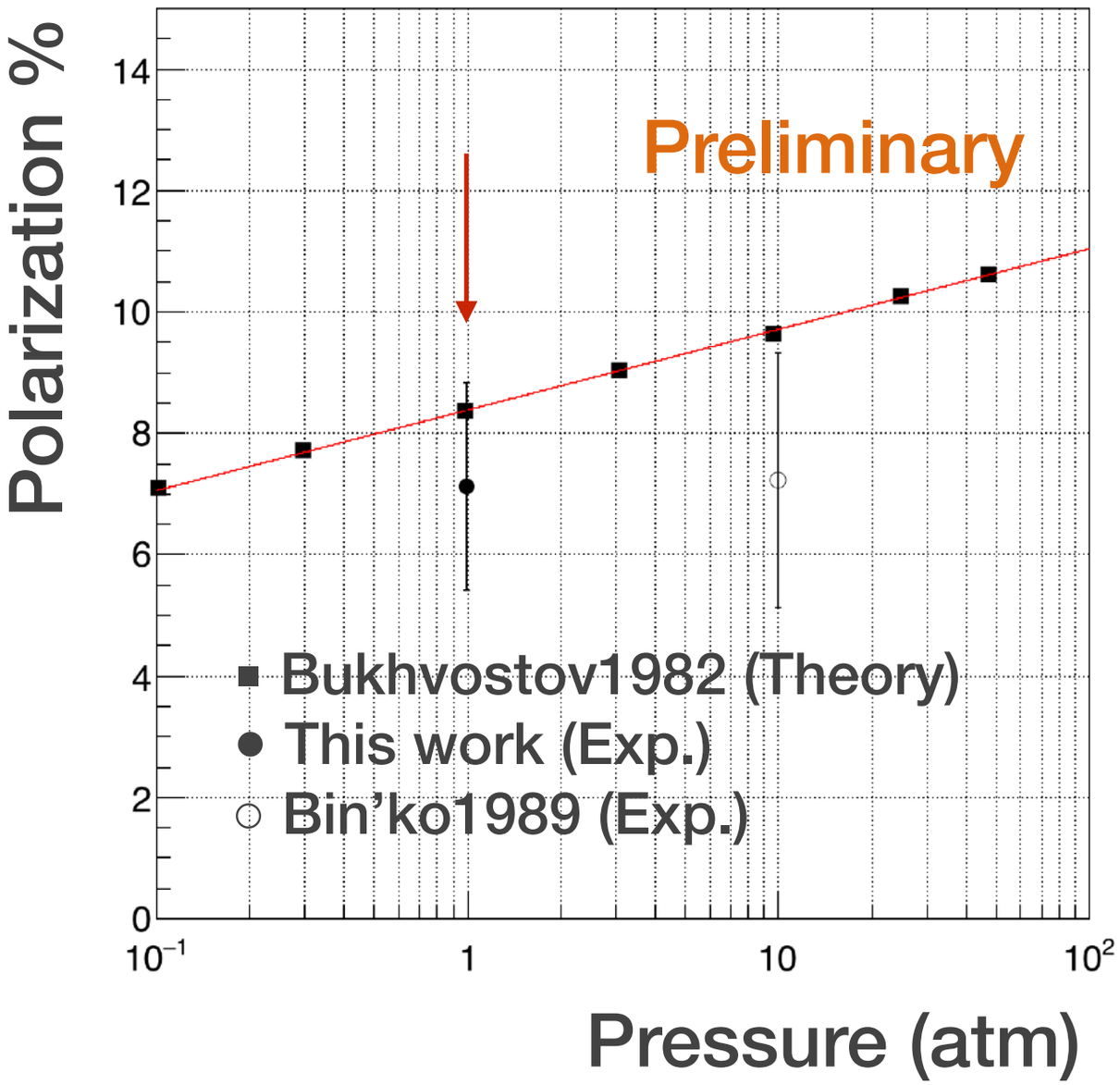


Electron asymmetry
(120 Gauss)

- Muon decay time spectrum was measured using the gaseous deuterium target at the pressure of 1 atm.
- Muon spin rotation was observed and the asymmetry was obtained.
- Residual polarization is calculated after corrections.

Comparison with Theory/Exp.

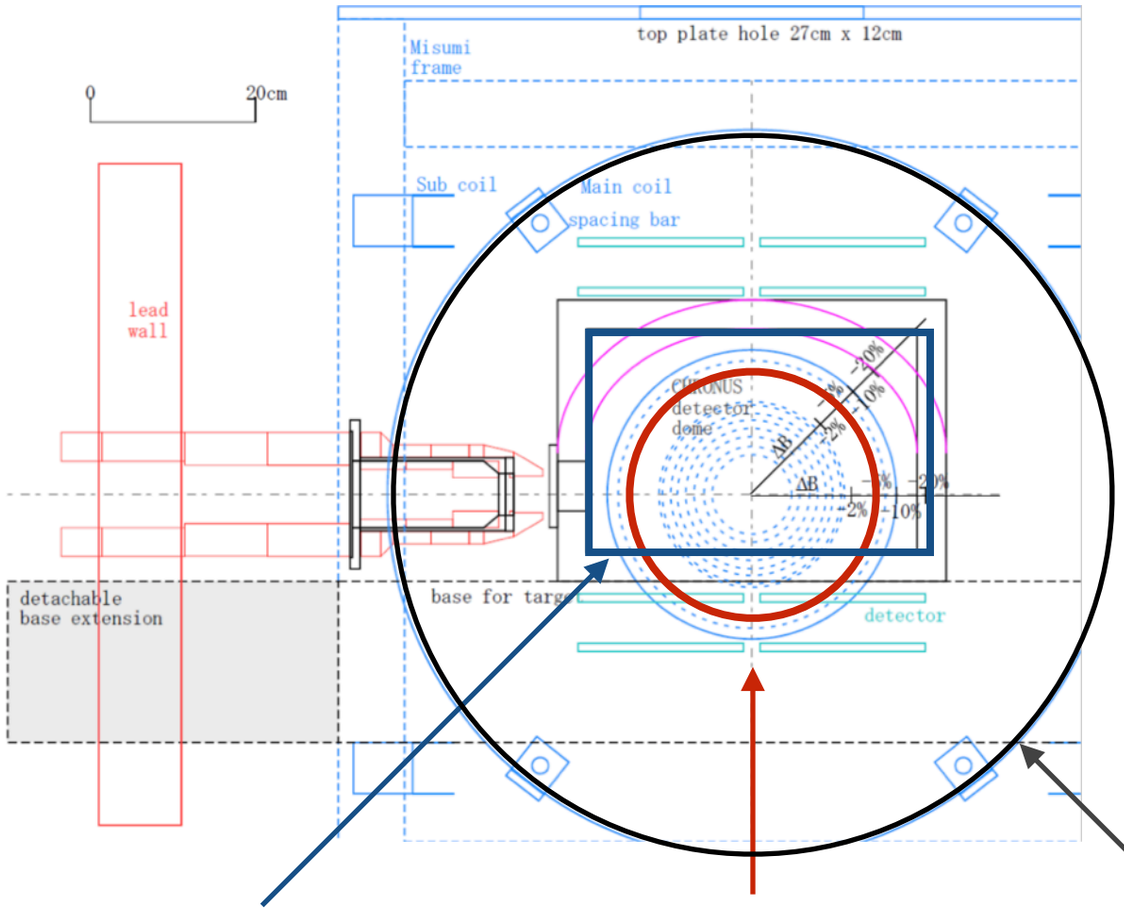
- On the residual polarization

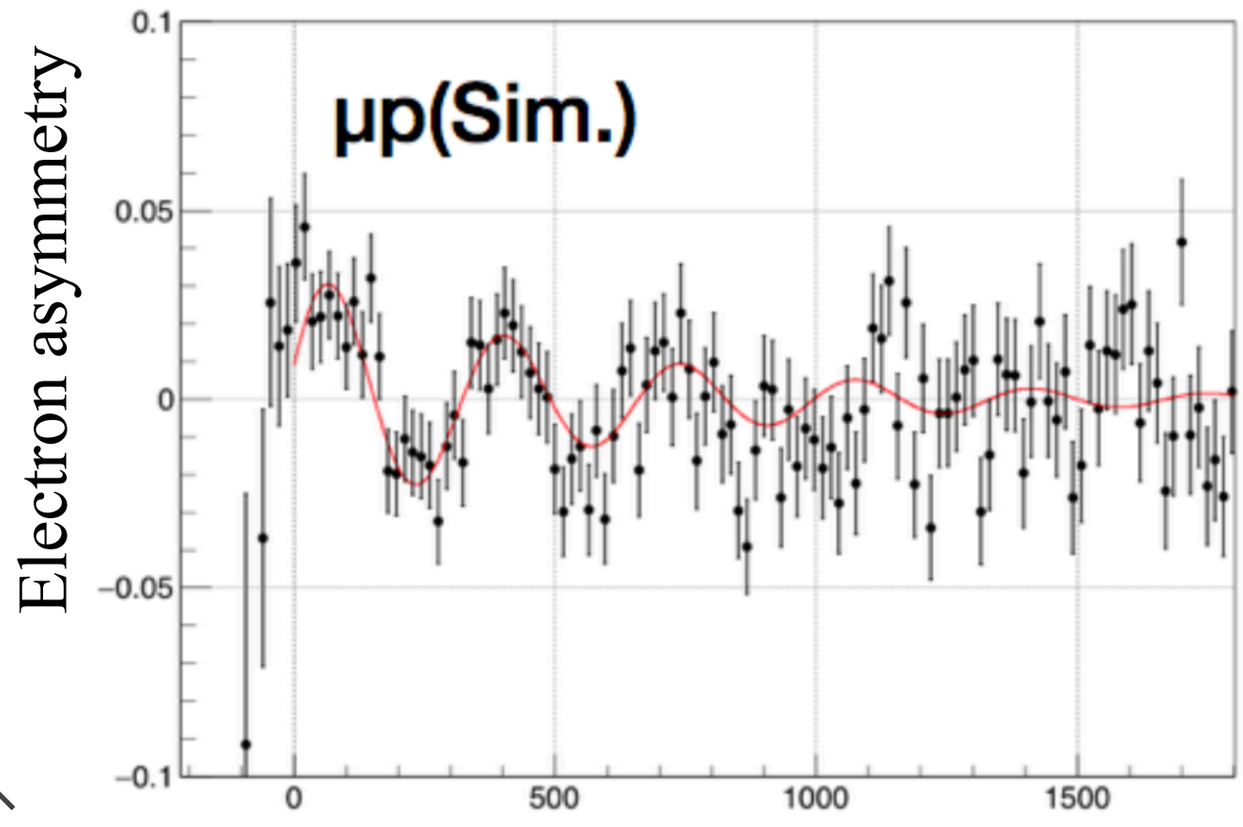


- Theoretical calculation (Bukhvostov1982)
  - 10.5% at 40 atm (λ=625 ns)
  - 9.7% at 10 atm (λ=2500 ns)
  - 8.4% at 1 atm (λ=25000 ns)
- Exp. results
  - D2 1 atm (This work)
    - 7.1%+-1.7%
  - D2 10 atm (Bin'ko1989)
    - 7.2%+-2.1%
  - D2 40 atm (Bystritskii1981)
    - Relaxation was too fast

The residual polarization is 7.1±1.7% and consistent with the theoretical prediction (8.4%).

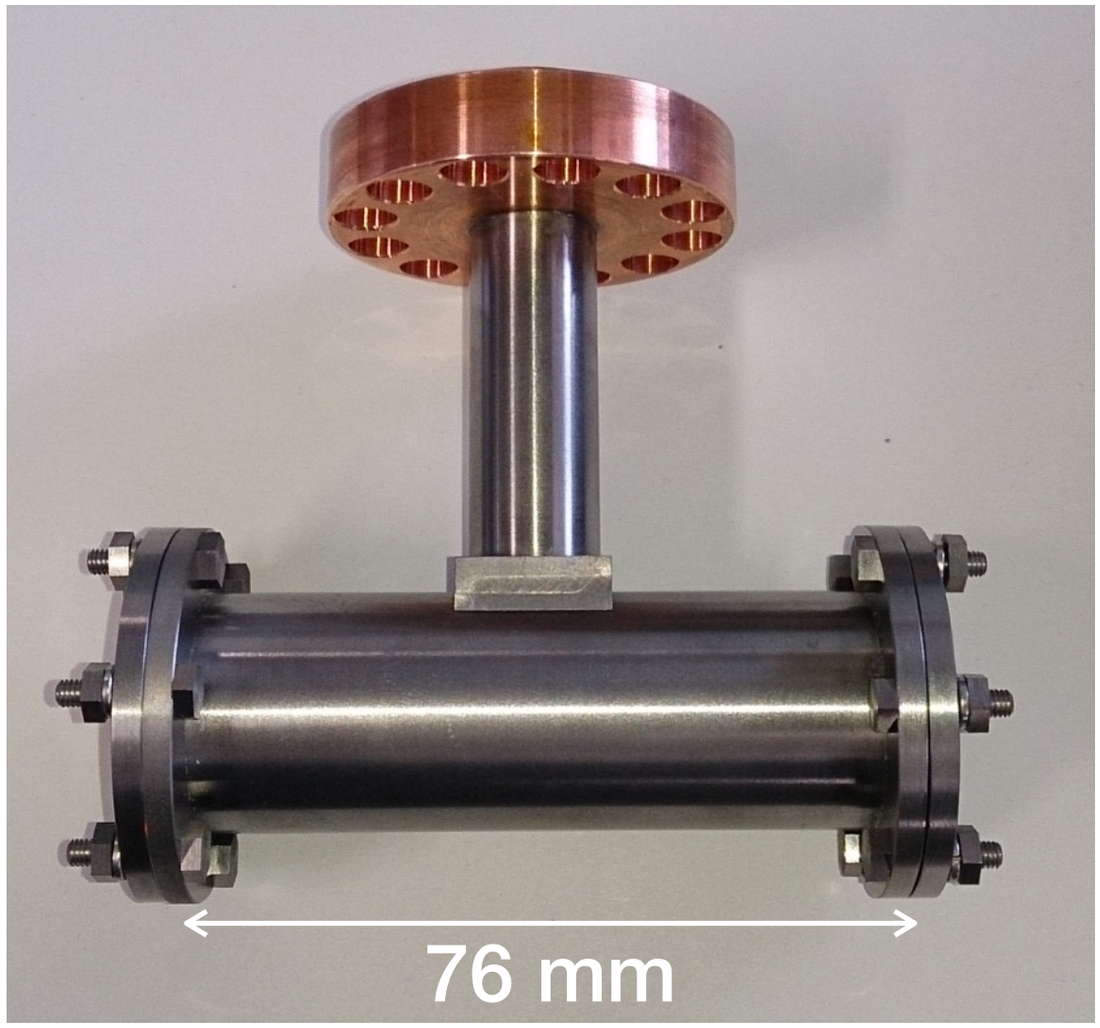
Upcoming Protium Exp.





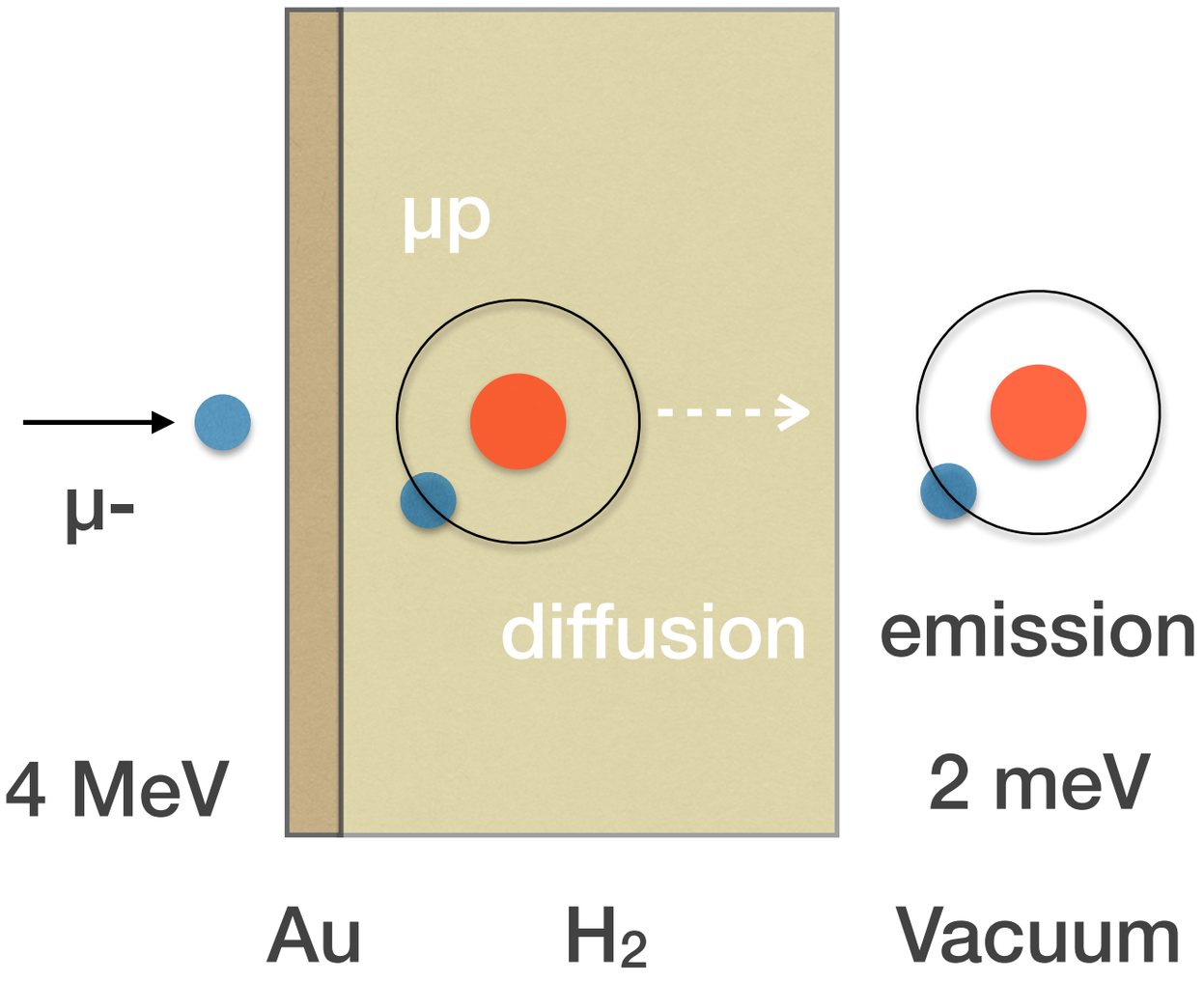
- New target chamber for better B-field uniformity was developed.
- Beam tuning and background study were done in this July.
- Spin precession measurement is scheduled in Nov.

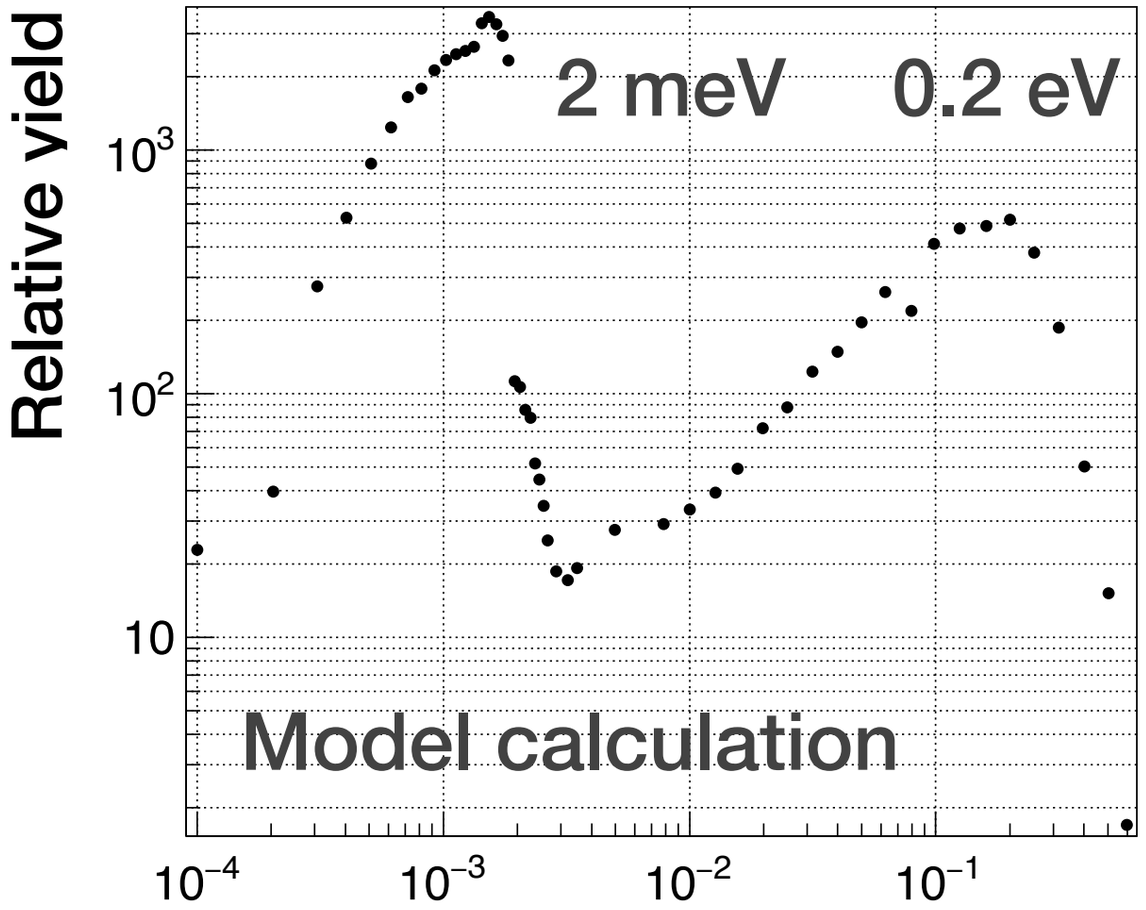
Hydrogen Target System



- Target temperature is controlled by using a GM cryostat.
- Temperature ranges from RT to 4 K.
- Gas density is monitored by a baratron pressure gauge.
- Target cell is made of tungsten for background suppression.
- Modifications for solid target is in preparation.

Alternative Idea: Solid Hydrogen

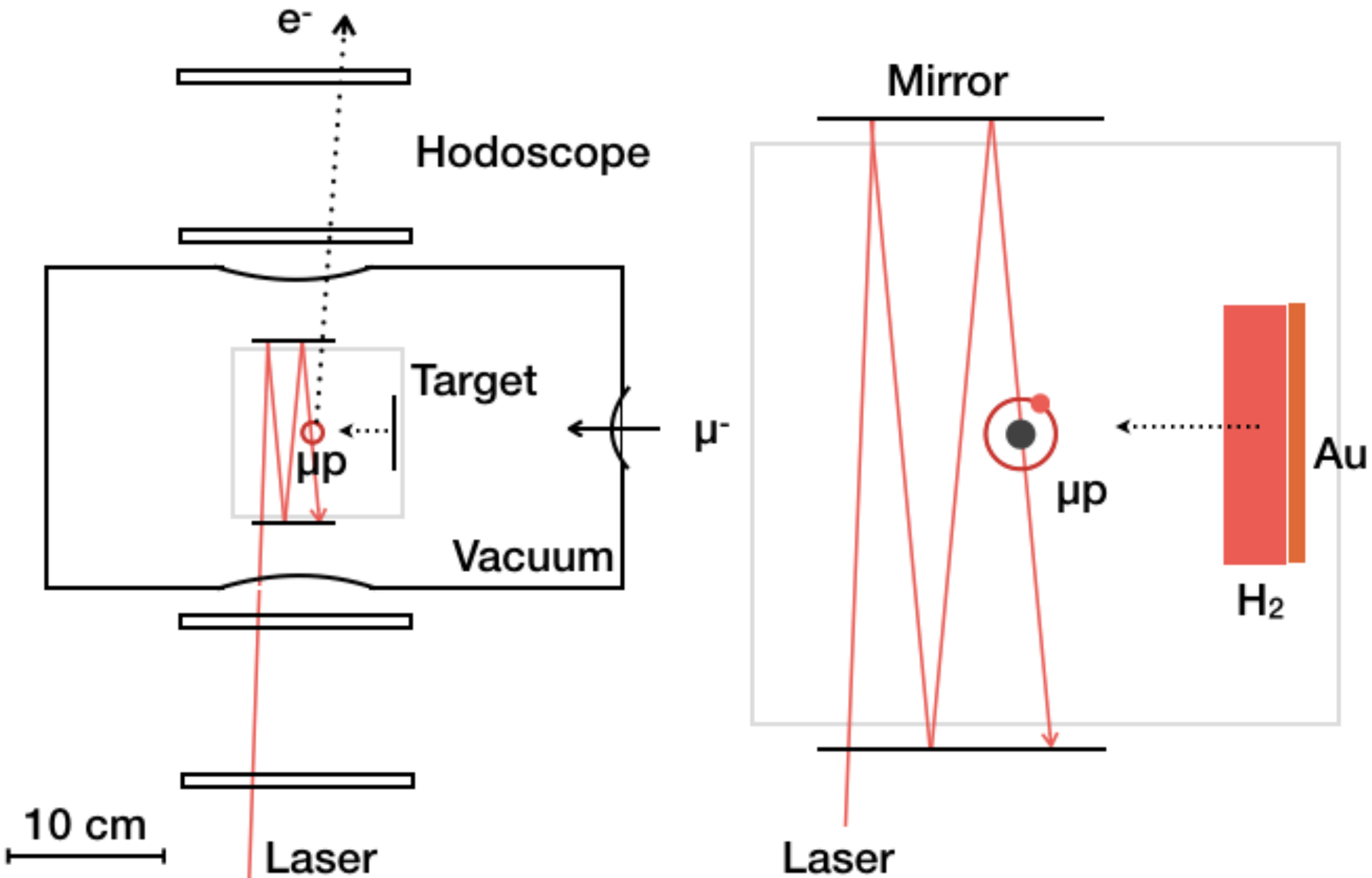




- Slow muonic hydrogen is emitted from solid hydrogen thin film.
- Emission energy has two components: 2 meV and 0.2 eV.
- Slow μp yield is approximately 0.5% of incident muons.

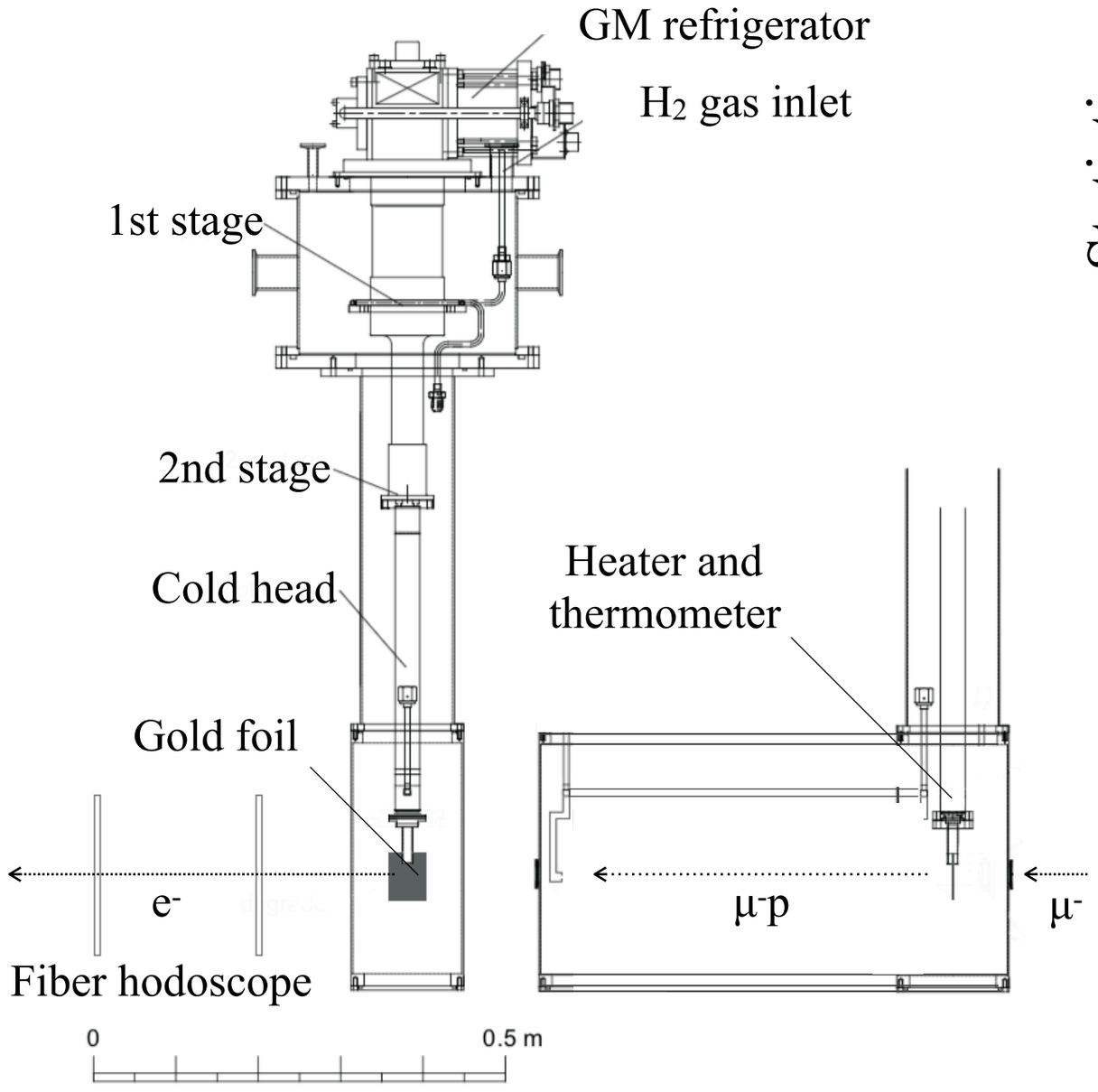
Theory: A. Adamczak, Hyperfine Interact. 119, 23 (1999).
Experiment: J. Woźniak *et al*., Phys. Rev. A 68, 062502 (2003).

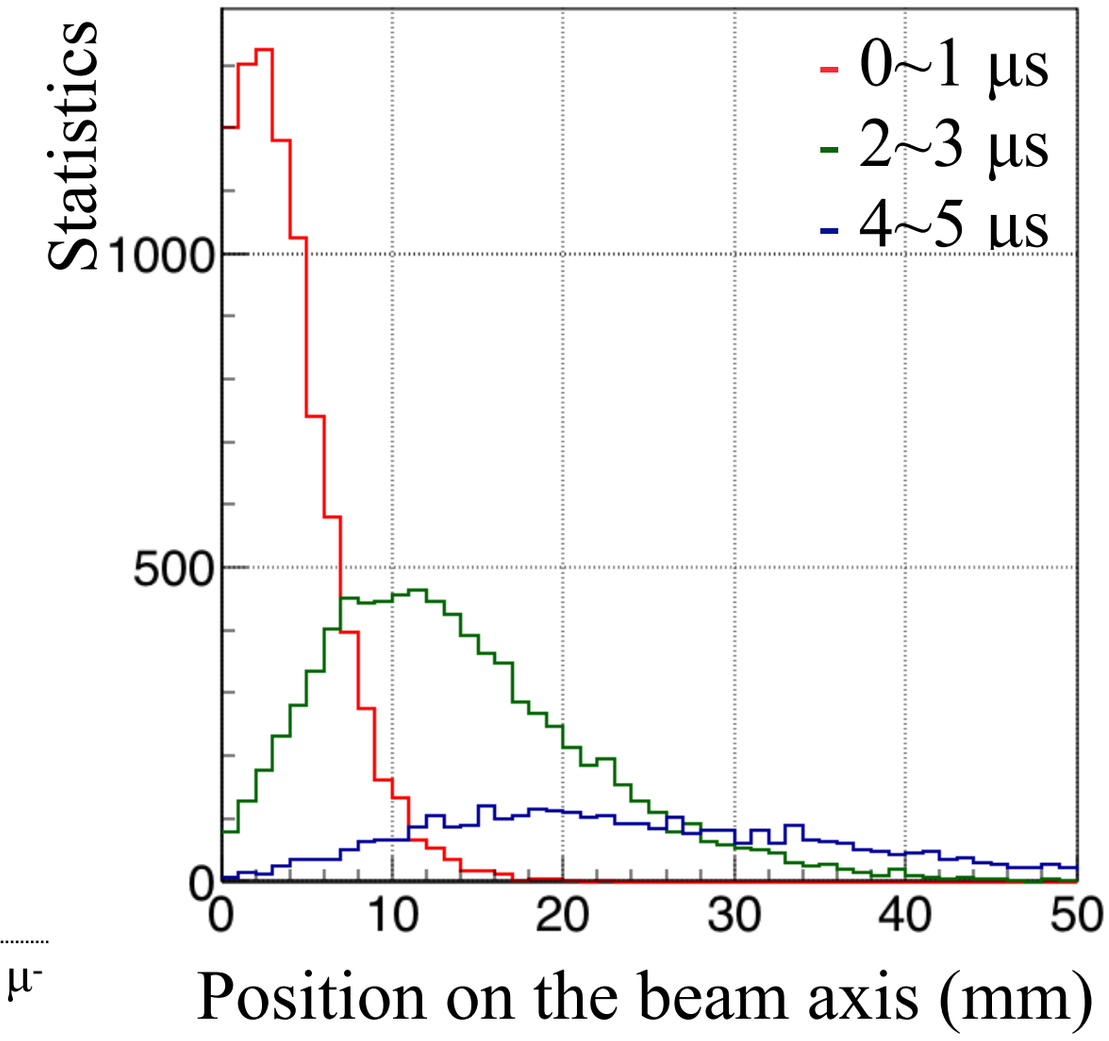
In-Flight Spectroscopy



- In-flight spectroscopy is free from the collisional quenching.
- Systematics is dominated by the Doppler effect
  - 500 MHz at 0.2 eV (7 mm/μs velocity).
- Electron tacking with fiber hodoscopes.

In-Flight Spectroscopy





Simulated μp positions in vac.

- Funding for a solid target development is secured.
- Preparation for a target chamber is in progress.
- Fiber hodoscope for electron tracking is to be developed.
- Next step is a measurement of the space-time distribution of μp.

Summary

- We proposed a new measurement of the HFS in muonic hydrogen atom.
- Hydrogen target, transition laser, and detectors are three key components of the experiment.
- Hydrogen target
  - Gaseous target is completed.
  - Solid target is in preparation as an alternative.
- Laser
  - Pump, and seed lasers are completed.
  - Improvement in OPO is in preparation.
  - Multi-pass cell is fabricated and to be tested.
- Detectors
  - Electron and muon detectors are completed.