超低速ミュオンとその展開
（slowmuon project at RIKEN-RAL and beyond）

Yasuyuki Matsuda
(Grad. School of Arts and Sciences, Univ. of Tokyo)

First things first,…

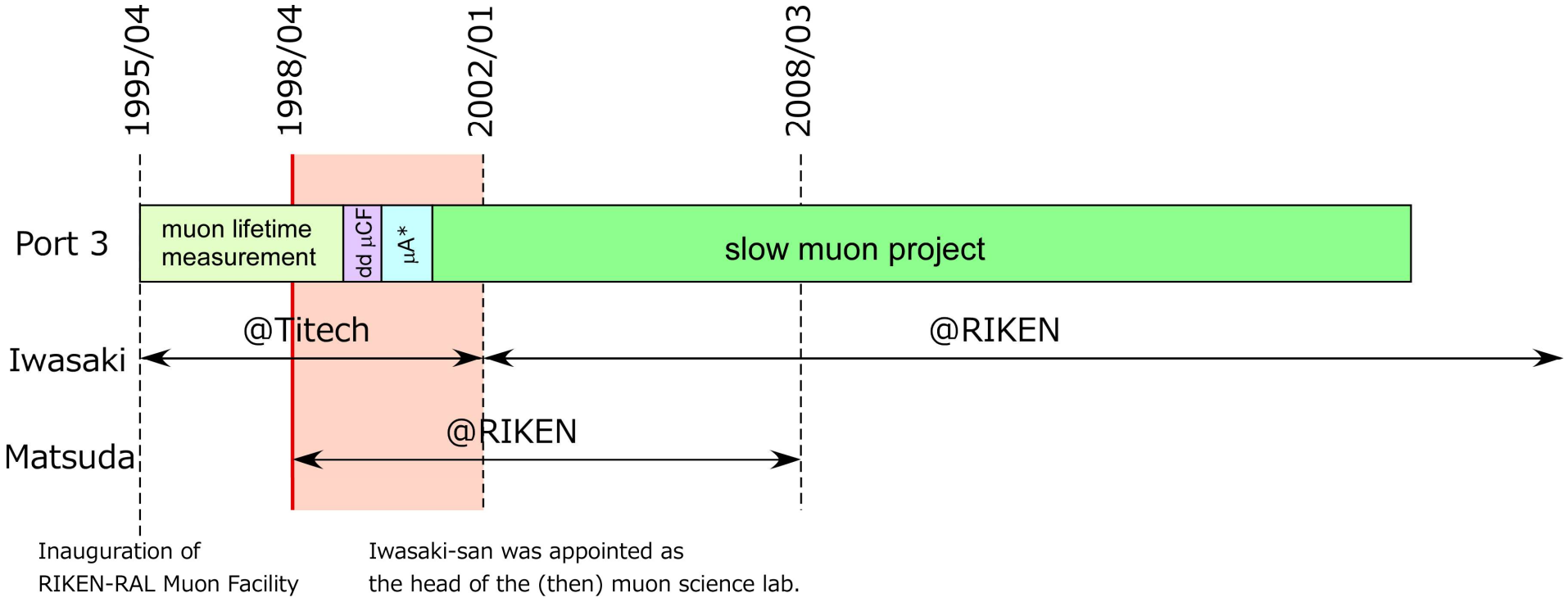
Congratulations for Happy Retirement!!

- I had worked at RIKEN with Iwasaki-san for only(!) 6 years, but it was really wonderful, exciting, and enjoyable years.

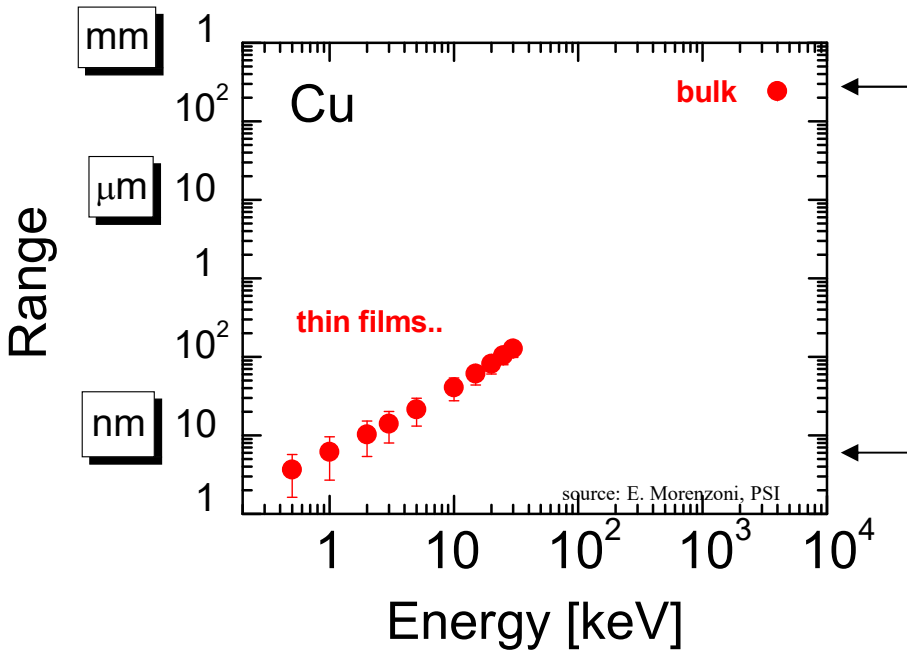
- When Itahashi-san asked me if I can give a talk on this occasion, I literally grabbed it!

  There are many contributors on the development of slow muon beam in Japan, I ask for their kind understanding on my giving talk on this subject !

Pre-Iwasaki era



slow muons



For "**surface muons**" with energy of 4 MeV the stopping range in a solid varies from 0.1 - 1 mm with a straggling of about 20% of the mean value.
Beam size 40-50 mm (FWHM)
Only bulk sample can be used

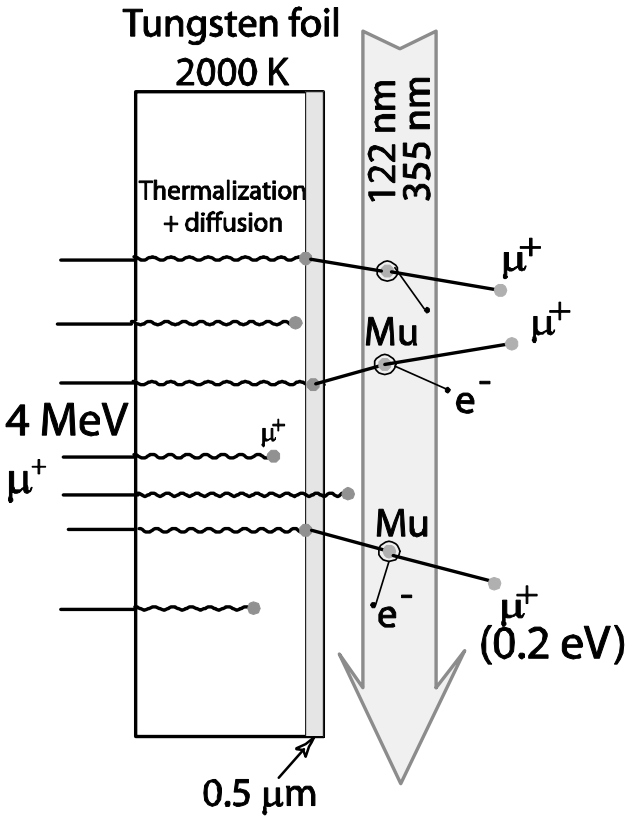
For "**slow muons (or LE muons)**" with energy 0.1-30 keV the stopping range in a solid varies from 1 - 200 nm. Implantation depth controlled on nm scale.
Beam size is small 4-5 mm (FWHM)

Slow muons allows…

- investigations of near-surface regions, thin films, interfaces and multi-layers, nanomaterials and of samples which can be grown only as thin films.
- to make depth resolved measurements.

Laser resonant ionization method

4 MeV muons ⟹ 0.2 eV thermal Mu ⟹ 0.2 eV μ^+



- Time width ~ a few ns

⇔ surface muon beam ~100ns

- Beam width ~ a few mm

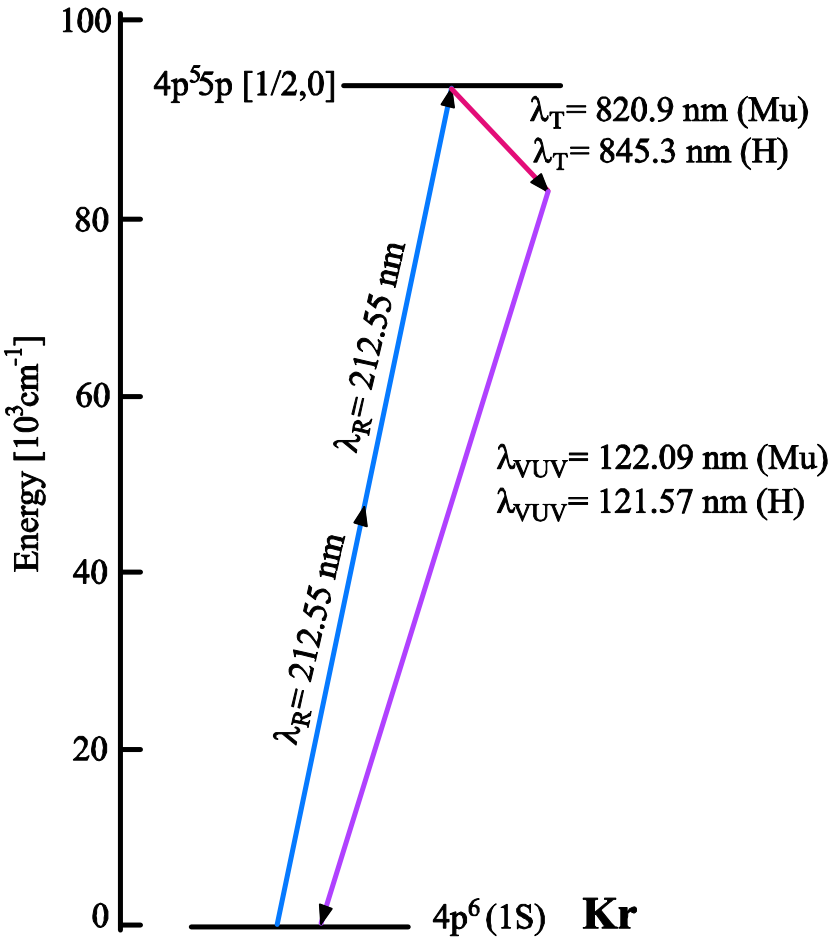
⇔ surface muon beam ~ a few cm

- 4MeV μ → 0.2eV Mu conversion eff. = ~1 %

→ potentially higher conversion efficiency to low energy muons (**if we can ionize Mu efficiently**)

K. Nagamine et al. Phys.Rev.Lett. 74, 4811(1995)

Lyman–α generation (sum-difference frequency mixing in Kr gas)

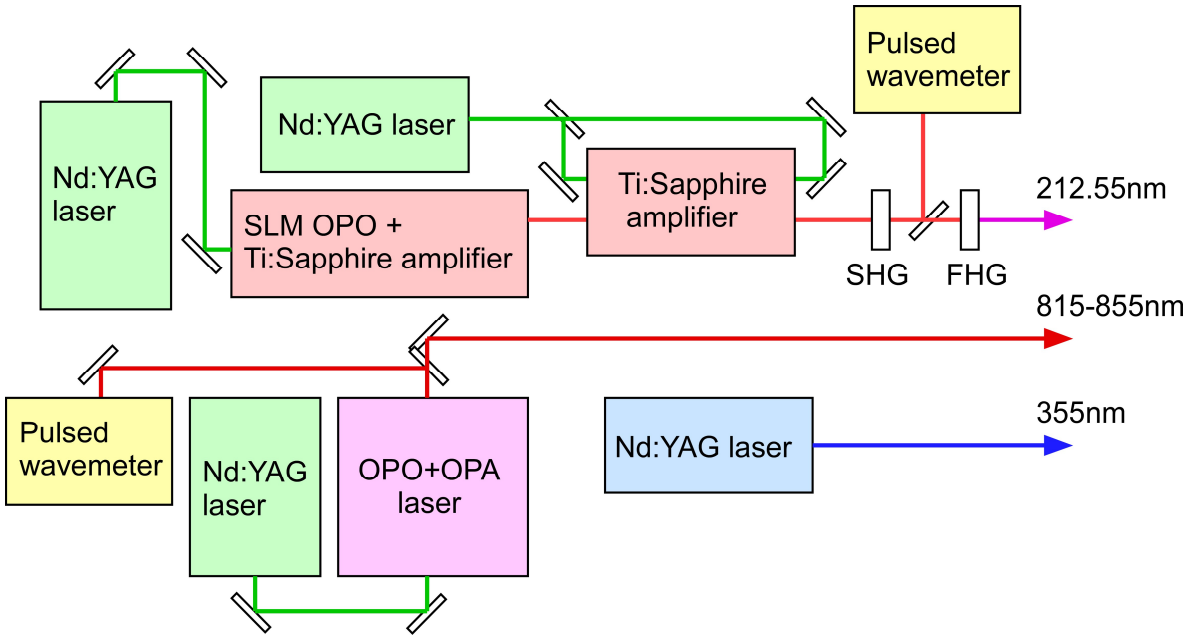


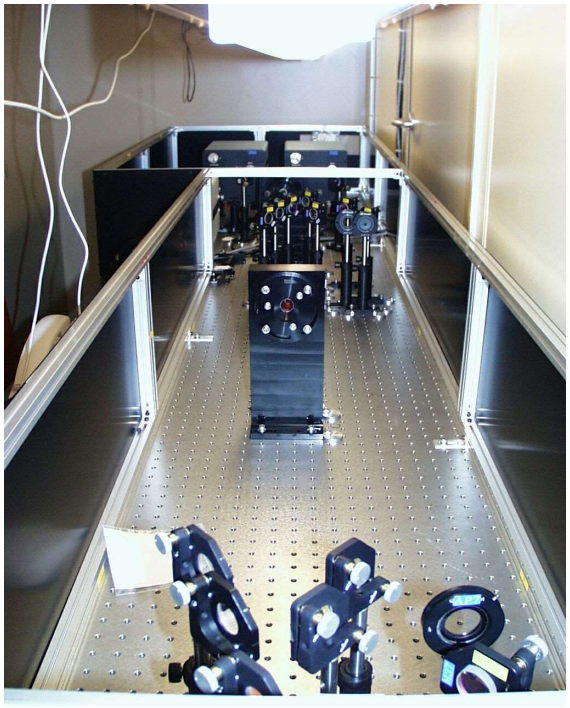
212.55 nm (single longitudinal mode) tuned to a resonance in Kr → yield resonantly enhanced

820 nm (844 nm for H or D) broadband to match Doppler broadening of 200 GHz

tuneable VUV output ~ **122 nm**
(with 200 GHz bandwidth)

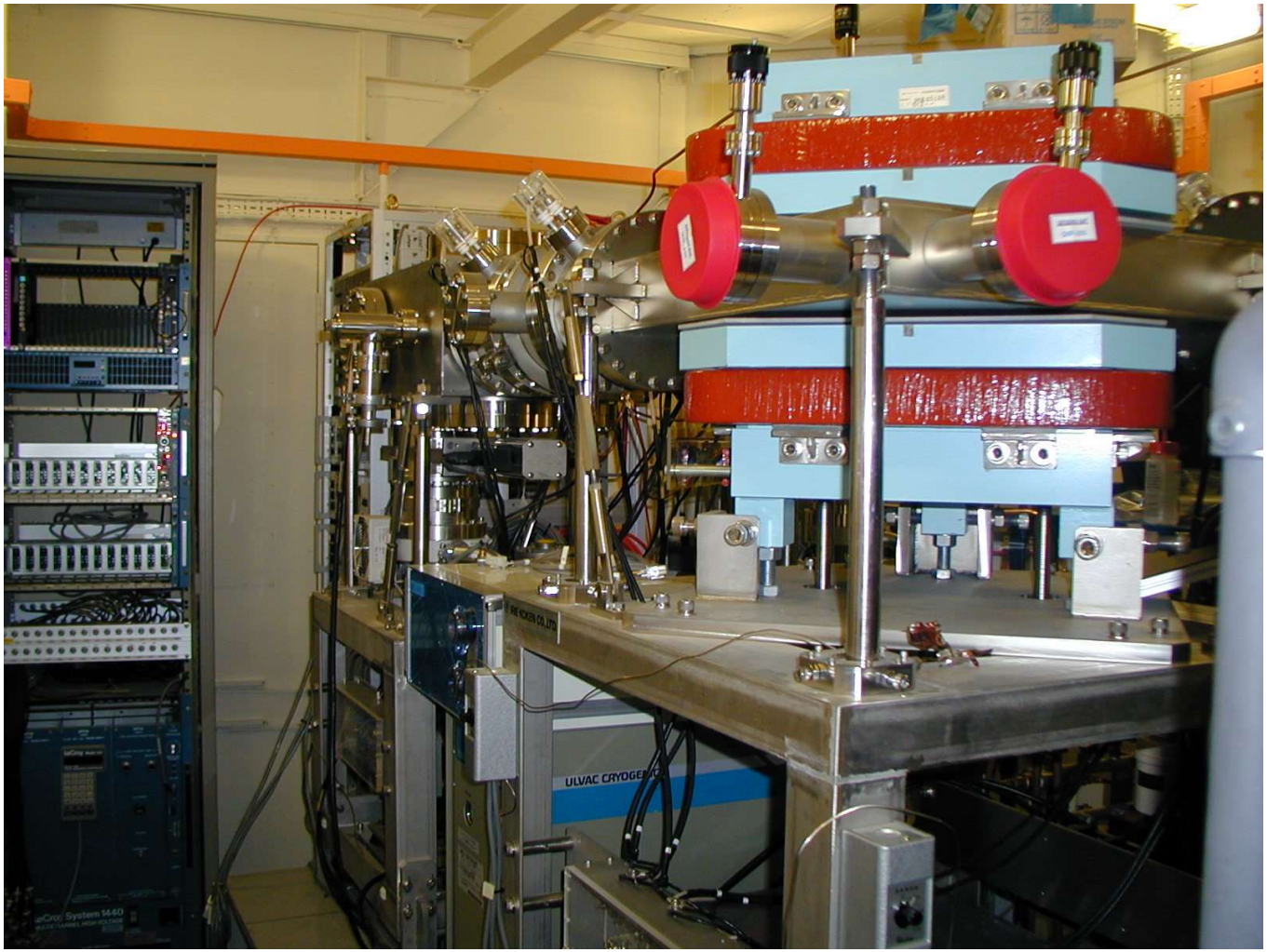
Diagram of the laser system





Laser system was fully installed in Feb 2001.
Successful generation of Lyman-α light was confirmed in Mar 2001.

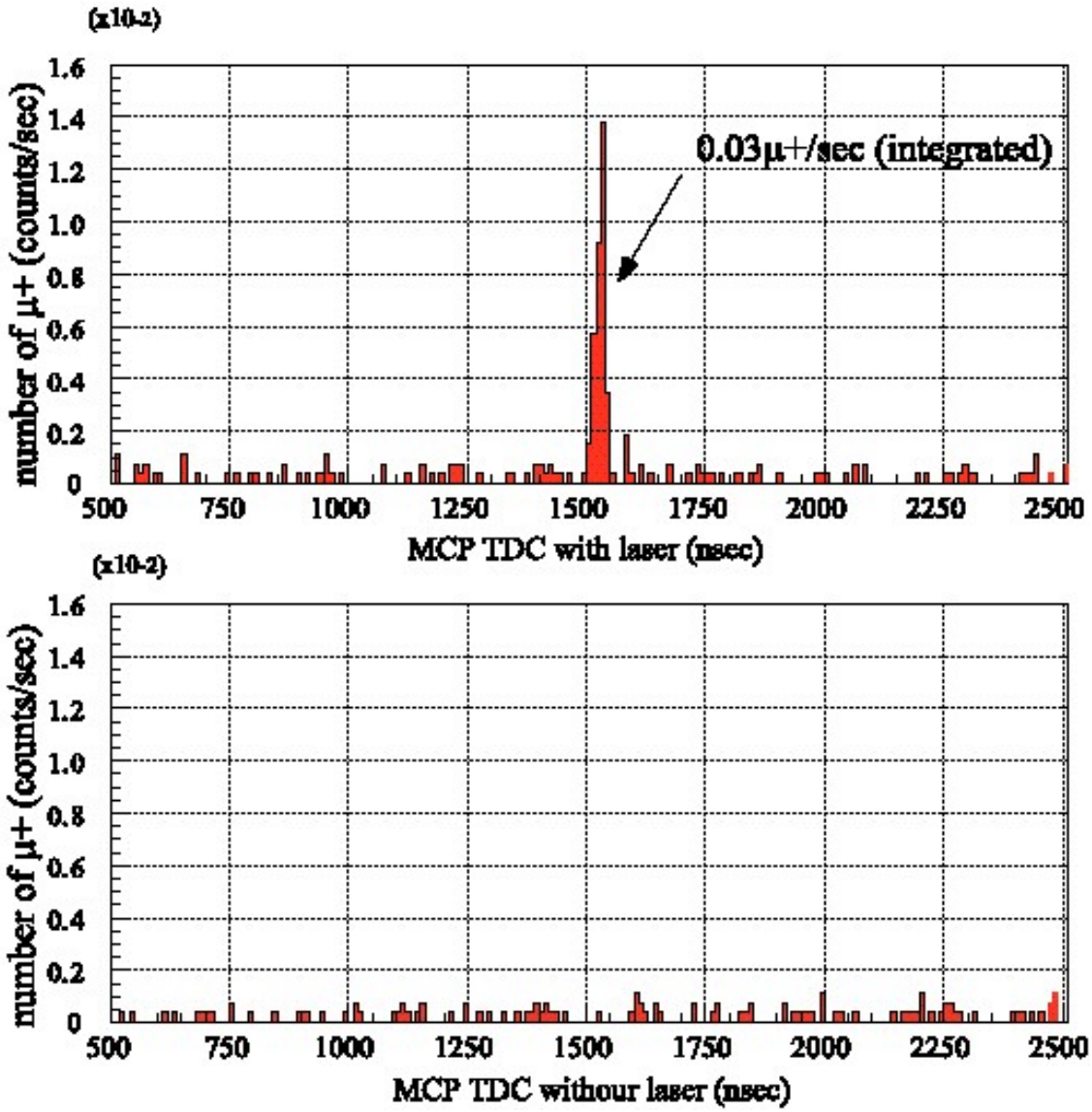
Slow muon beam line at Port 3



Slow muon beam line are installed in Dec 2000

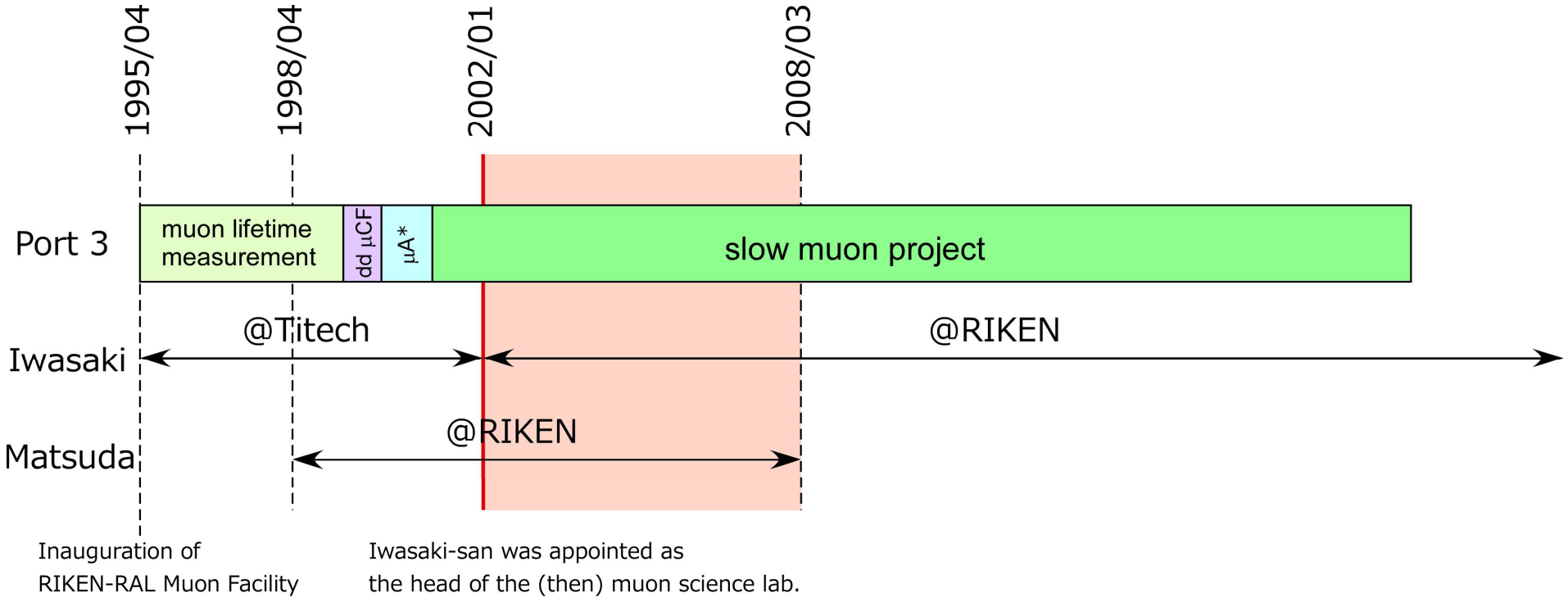
The first observation of slow muons at RIKEN-RAL

- Our first observation of slow muons (Summer 2001)
- Count rate was 0.03/sec
  ⇔ We expected 15/sec



Iwasaki era

- Iwasaki-san joined RIKEN on Jan 2002.



Iwasaki era

- The construction of J-PARC had started at Tokai when Iwasaki-san joined RIKEN in 2002 (and MLF was expected to be operational in 2007)

- “What is the role of RIKEN-RAL muon facility in muon science?”

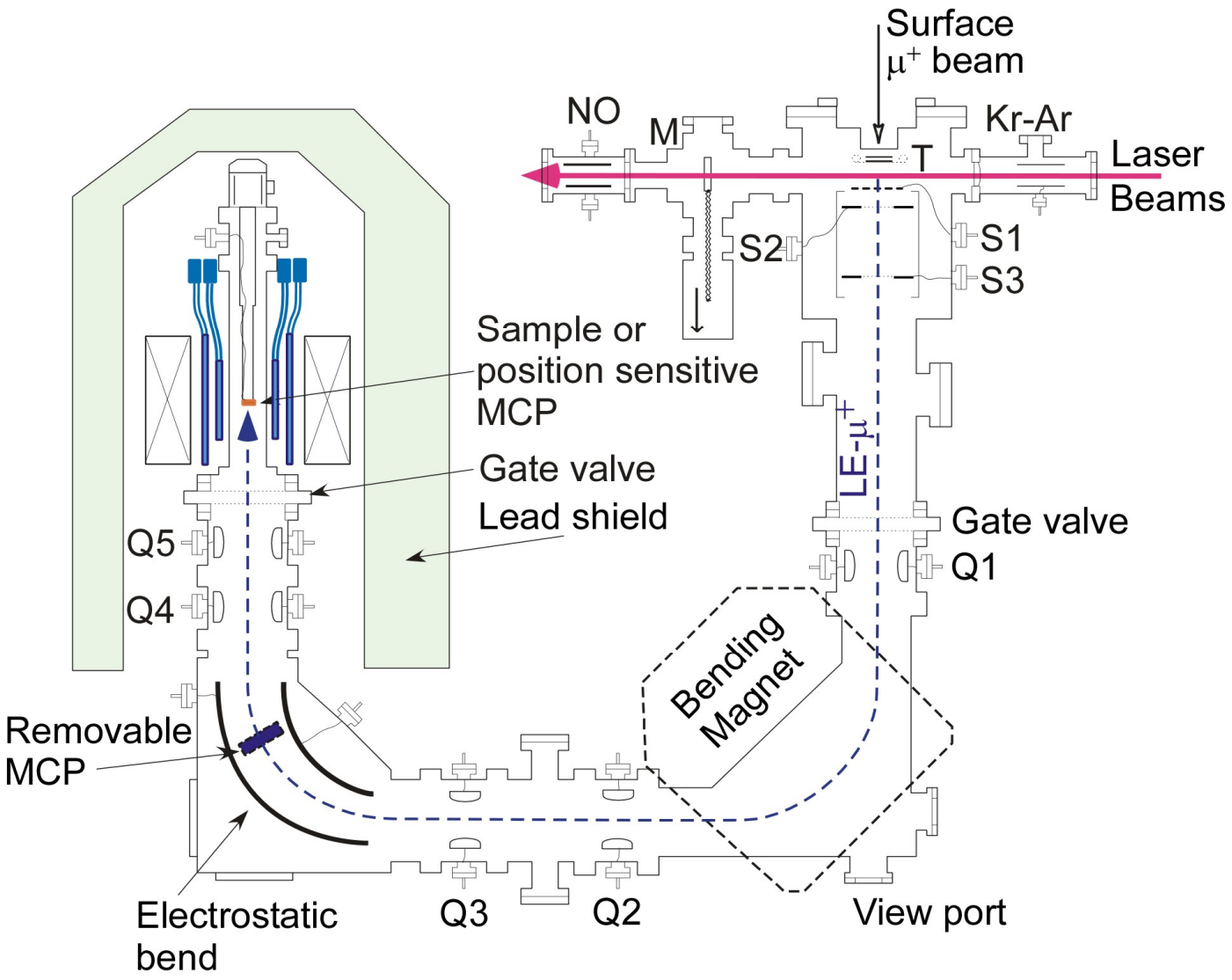
Iwasaki era

- The construction of J-PARC had started at Tokai when Iwasaki-san joined RIKEN in 2002 (and MLF was expected to be operational in 2007)
- "What is the role of RIKEN-RAL muon facility in muon science?"
- Iwasaki-san recognized slow muon project as "the future" of muon science, to be developed at RIKEN-RAL muon facility
- Iwasaki-san played a decisive role to move forward the collaboration between KEK and RIKEN

Iwasaki era

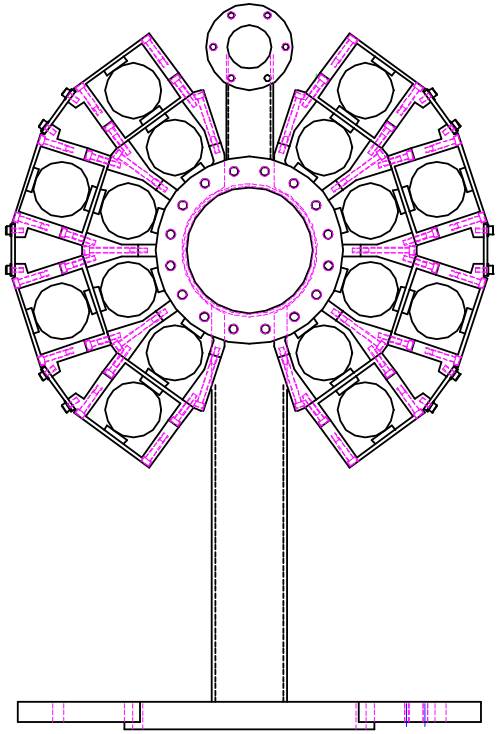
- slow muon μSR should be demonstrated
- Problems to be addressed
  - Efficiency of muonium production to be improved
  - Power of lyman-α light to be increased
  - Slow muon beam profile to be optimized
  - Reliability of laser system to be improved
- Many ideas needed!

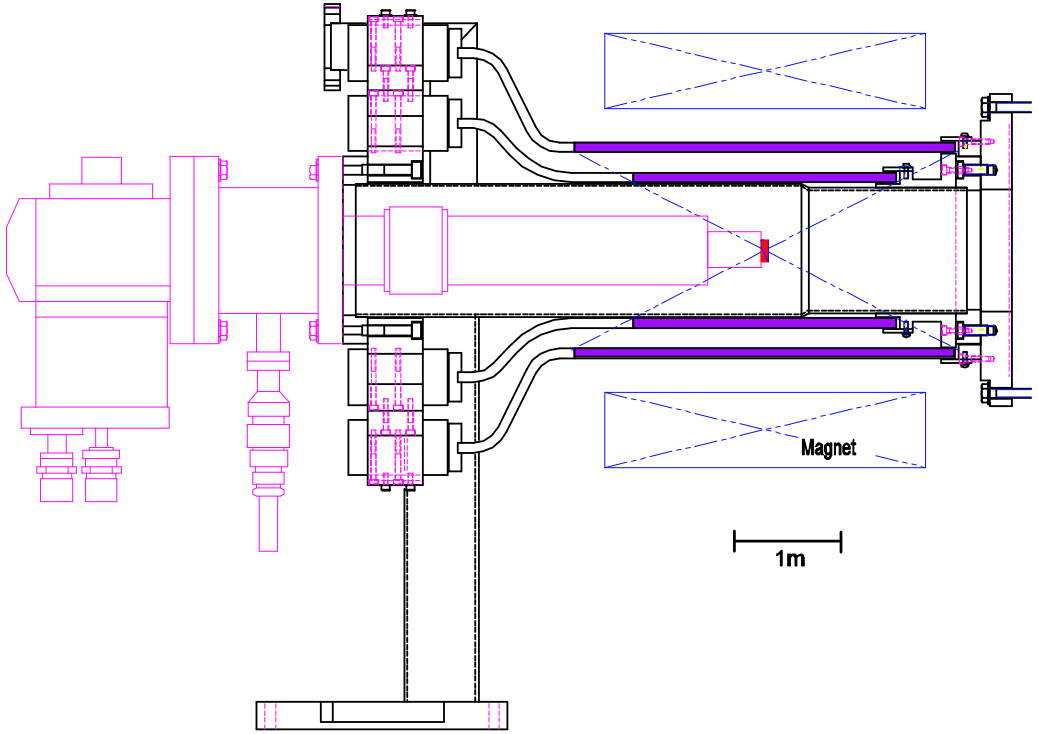
μSR setup with slow μ^+



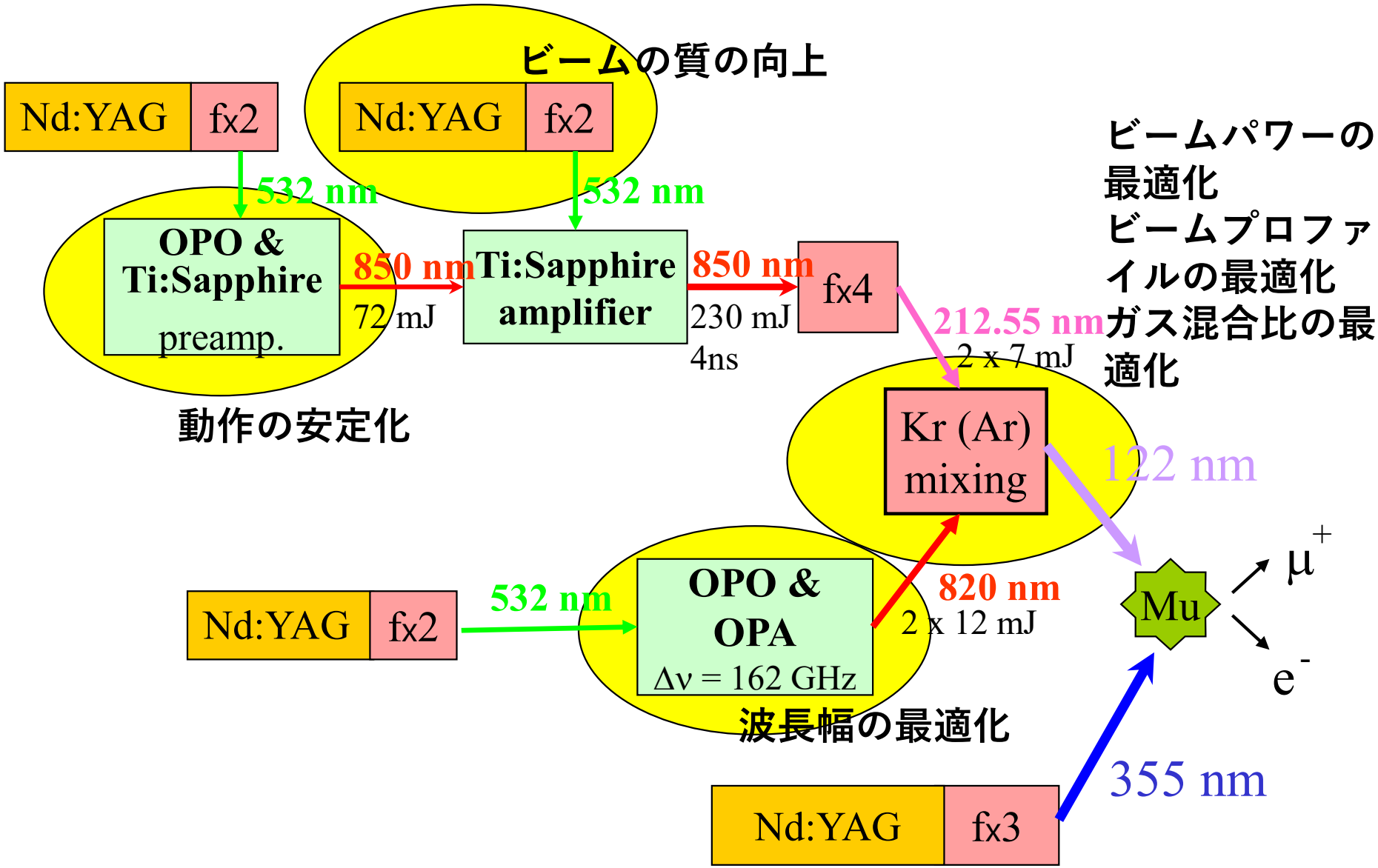
μSR spectrometer

- Large solid angle covered
- Zero-Field measurement and Transverse-Field measurement (~600G) can be done.
- Longitudinal-Field measurement under consideration.
  → installation finished in December 2005.



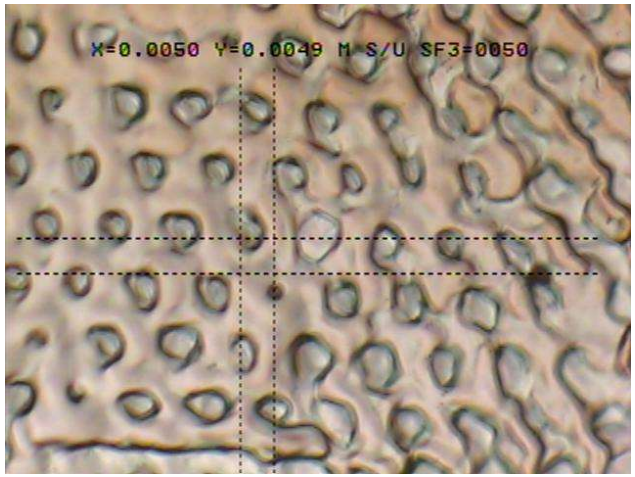


(2002/02 meeting memo)

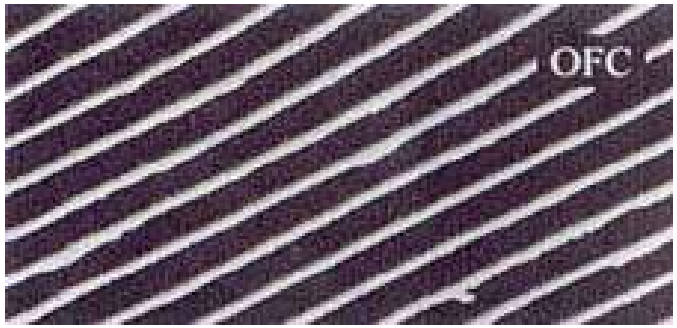


Efficiency of muonium production to be improved

- Micro-fabricated Tungsten target to increase surface area (~2005)

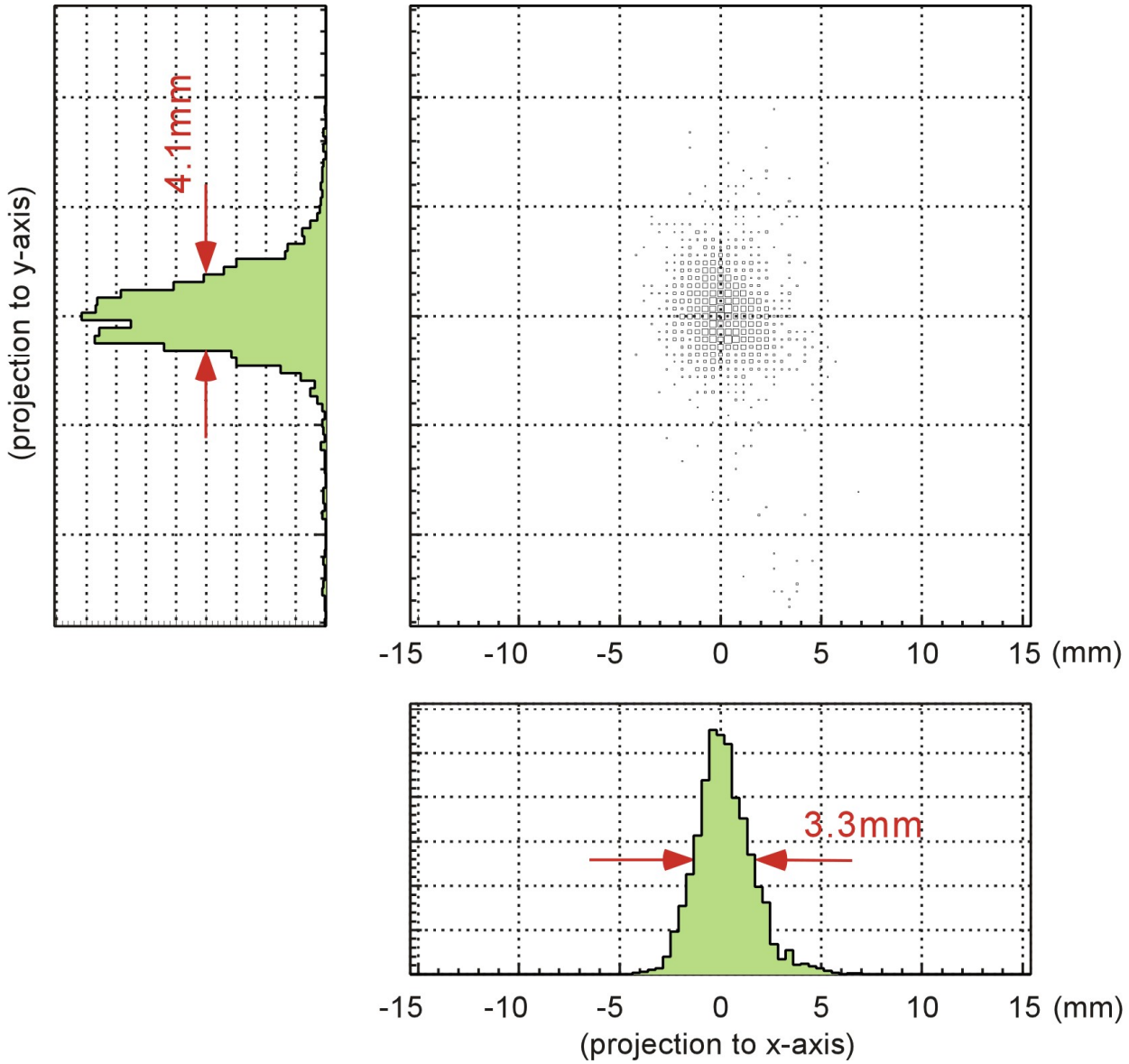


Laser micro-fablication (by Rosenetics Ltd.) we've got a modest increase of muonium yield.



Discussed possible microfabrication by a diamond cutter with Ohmori-lab (RIKEN) Difficulty to cut thin Tungsten film

Slow muon beam profile to be optimized

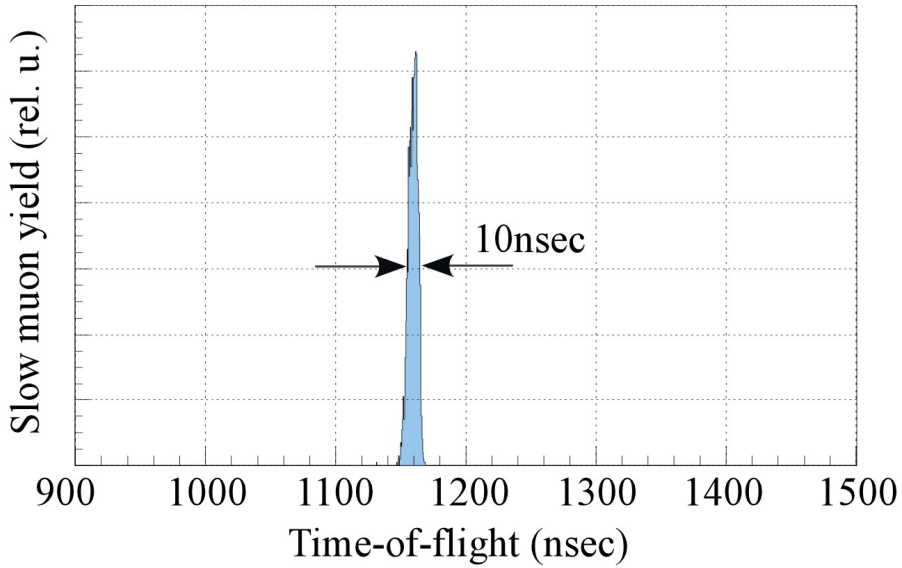


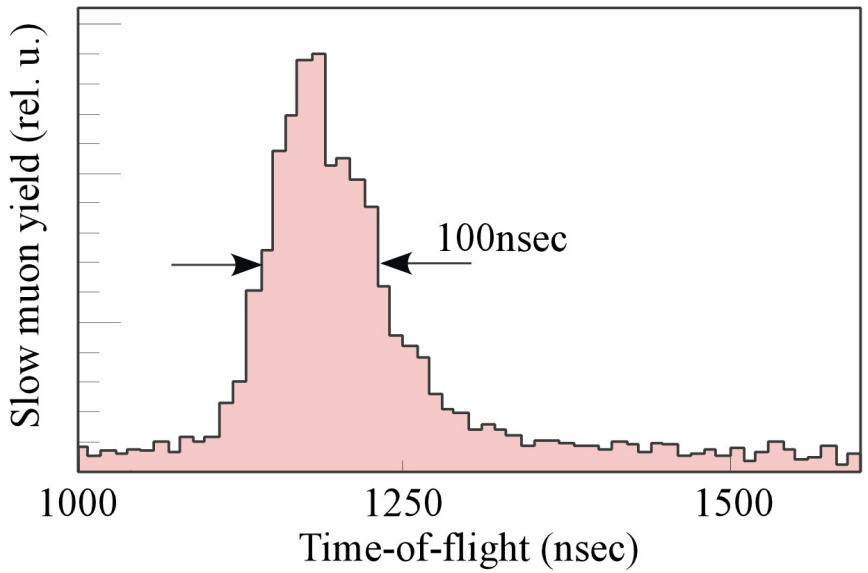
- Beam profile was measured using position sensitive MCP (Roentdek).
- The beam size was 4.1mm(x-axis) and 3.3mm(y-axis) at 9.0keV beam energy.

  (The size of original beam is about 3cmx3cm. 100times smaller beam)

- Small beam size allows us to measure **samples which can be made in only small quantity** with good S/N ratio.

Slow muon beam profile to be optimized





- The temporal width of LE-muon beam was about 10nsec. This is significantly narrower than that of initial muon beam (about 100nsec).
- This is because emitted muonium atoms are not accelerated until they are ionized by laser irradiation.
- Energy resolution is about 20eV

- Up : temporal resolution of slow muon beam generated by laser resonant ionization method
- Down : temporal resolution of slow muon beam generated by cryo-solid moderator method at ISIS muon beam line (Ph.D. Thesis, Dr. K. Trager, 1999)

Slow muon performance around 2008

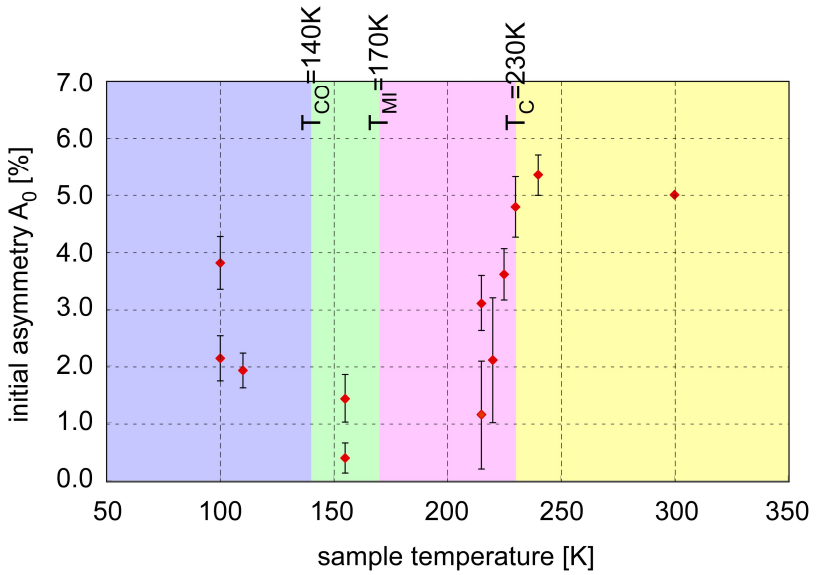
- **Slow muons at RIKEN-RAL muon facility have...**
  - Variable implantation energies
  - High time resolution (as well as high energy resolution)
  - Smaller beam size at sample position

	PSI	RIKEN-RAL	LE-muons @PSI	LE-muons @RIKEN-RAL
time structure	DC	pulsed	DC	pulsed
beam intensity	5×10^{7}/sec	10^{6}/sec	8×10^{3}/sec	2×10^{1}/sec
external trigger capability	No	Yes	No	Yes
polarization	100%	100%	100%	50%
time resolution	2nsec	100nsec	10nsec	10nsec
implantation energy	4.1MeV	4.1MeV	1～30keV	1～20keV
energy resolution	0.4MeV	0.4MeV	400eV	100eV
S/N (=N0/B0)	～150	～100000		～250
observable relaxation time	5～9000	200～32000		20～12000
beam size (FWHM)	30mm	30mm	15mm	4mm

Presented to RIKEN-RAL International Advisory Committee (Nov 2007)

Demonstration of LE-μSR at RIKEN-RAL

- μSR experiments for demonstration of performance of slow muon beam at RAL
  - "R285: μSR studies in a thin $Nd_{0.5}Sr_{0.5}MnO_3$ film grown on $SrTiO_3(011)$"
  - Got some interesting results, but statistics was poor (though we've used >3 weeks beam time)



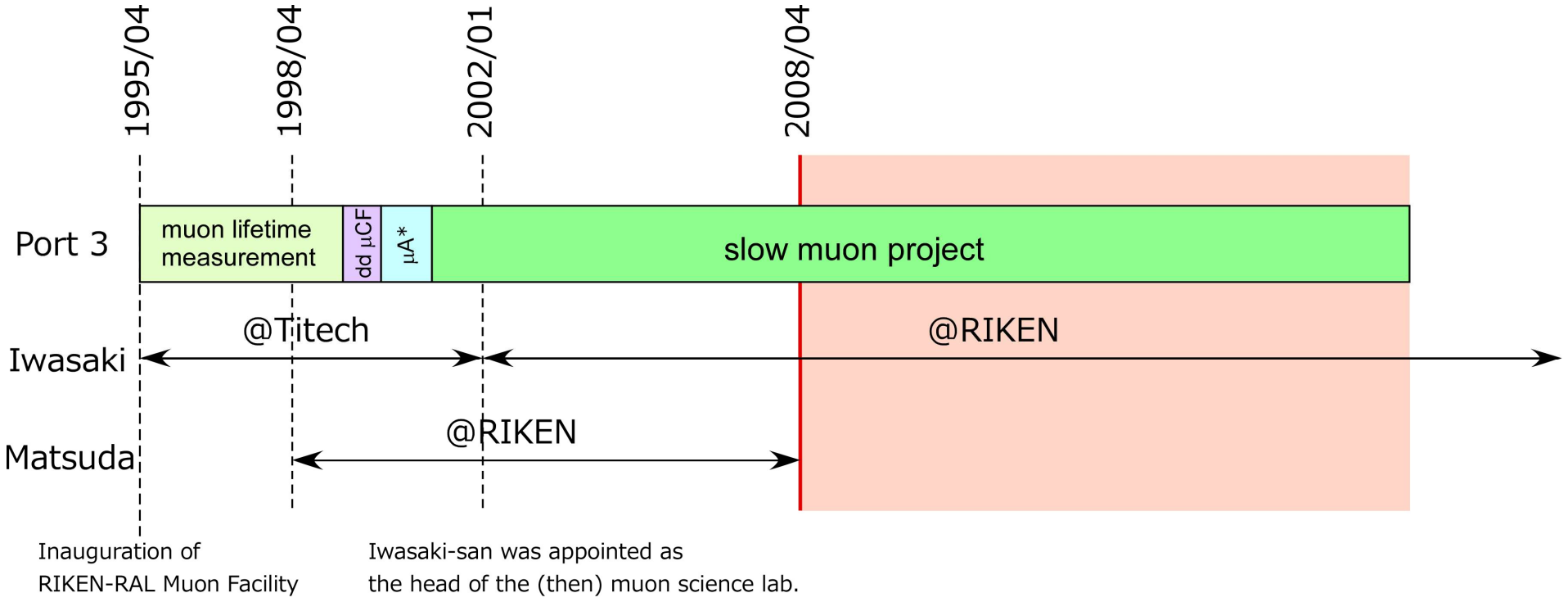
Slow muon performance around 2008

- We're suffering from the reliability of laser system
  - During breaks between beam times, we were busy to fix and tune the laser system, and didn't have much time to improve other apparatuses.

    We sometimes joked that every military campaign is limited by its logistic capability, and so is ours…

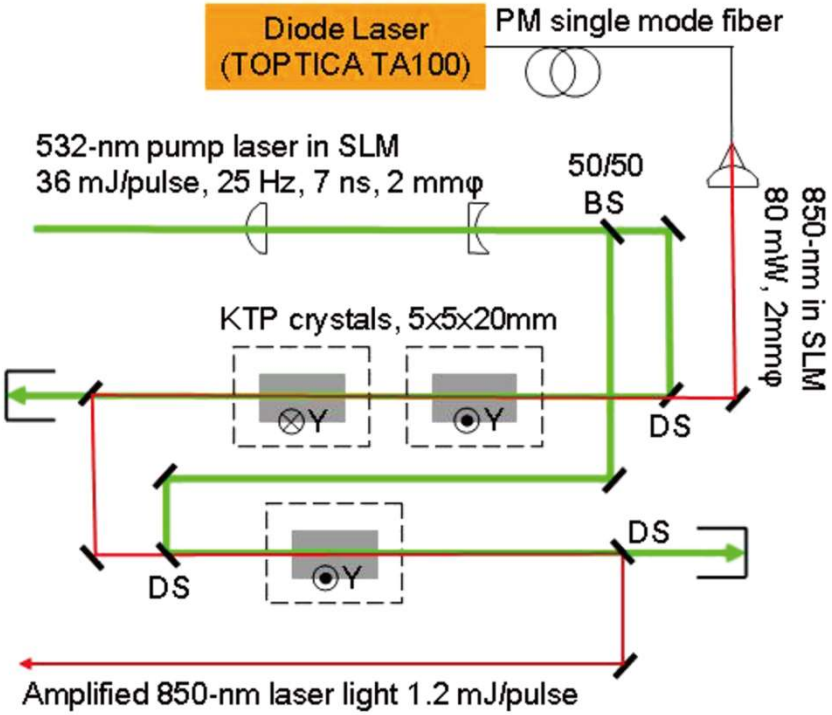
Iwasaki era

- Matsuda left RIKEN on Apr 2008.
  Iwasaki continued to drive the developing of slow muon



New Laser System

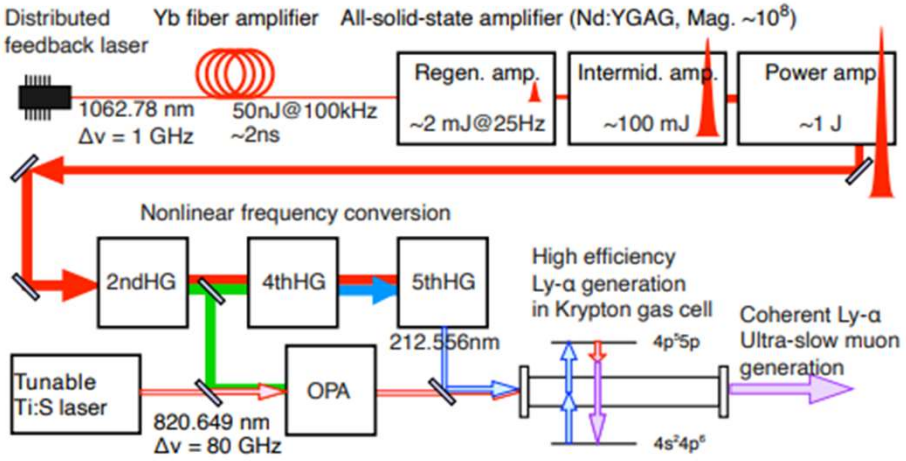
- A new scheme to generate 212.5nm wavelength to improve reliability of lyman-α generation
- Replace a 850nm-generating OPO with a seeding laser
- Collaboration with Wada-lab (RIKEN)



Yokoyama et al.
RIKEN Accel. Rep. 45, 182 (2012)

Another New Laser System

- Further development of the laser system was carried out, in collaboration with Wada-lab and KEK
- Adapted at J-PARC MUSE U-line
- Stable lyman-α output >10μJ/pulse



Y. Oishi et al.
J. Phys.: Conf. Ser. 2462 (2023) 012026

Oishi: "Just press a button, and you get lyman-α there"

Slow muon μSR at MUSE

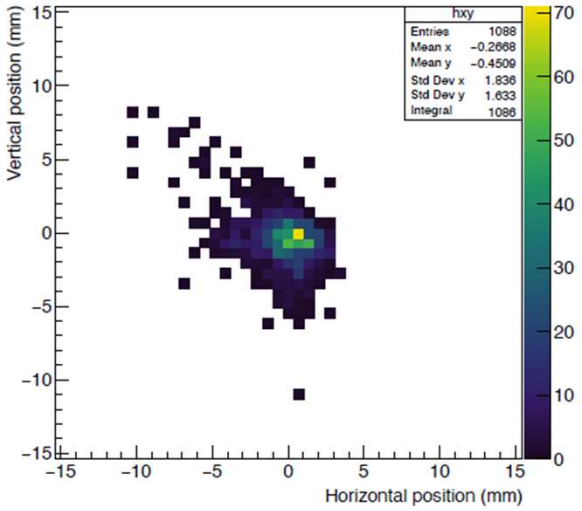


Figure 6. The USM beam profile at F3 after tuning. The beam widths were evaluated by assuming a two-dimensional Gaussian. The horizontal and vertical standard deviations were 1.6 mm and 1.8 mm, respectively.

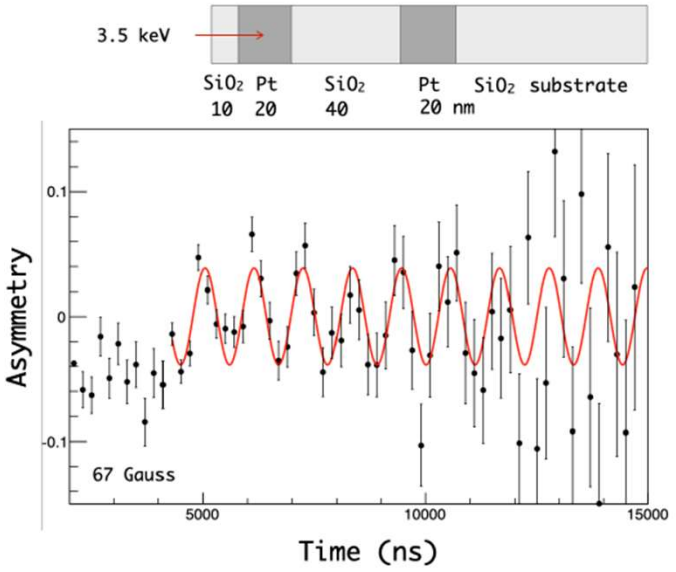


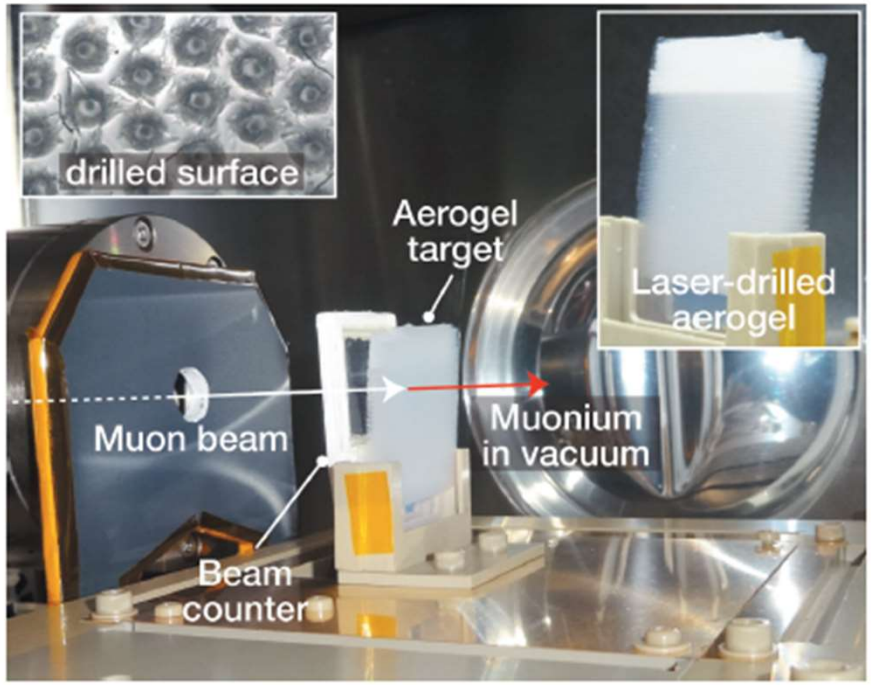
Figure 7. The μSR asymmetry measured by the spectrometer at U1A. USMs at 3.5 keV were implanted into a sample of alternating SiO_2 and platinum layers.

S. Kanda et al. J. Phys.: Conf. Ser. 2462 (2023) 012030

- Slow muon yield >300 /sec
- “real” scientific programs are underway.

New muonium production target

- Laser-microfablicated SiO_2 aerogel target
  - Lower initial emittance compared to tungsten target
  - Easier handling compared to SiO_2 powder
  - Increased surface area by laser ablation
- Collaboration with KEK, TRIUMF and other institutes
- Search for other production targets continues
  - Pant et al. Physica B 613 (2021) 412997
  - Pant et al. J. Phys. Conf. Ser. 2462 (2023) 012016
- Possible multi-layer configulation to increase yield
  - Zhang et al. NIMA 1042, 167443(2022)



Okada et al. RIKEN Accel. Rep. 47, 263 (2014)
Beare et al. PTEP 2020, 123C01 (2020)

and More...

- Possible re-polarization of muonium
  - 50% loss of polarization = 75% loss of FoM when muonium is formed
  - Possible re-polarization of muonium to recover polarization?
    - Das et al. J. Optical Society of America B 35, 1799 (2018)
- Re-acceleration of slow muon
  - muon linac for muon g-2 experiment

Iwasaki era

- “What is the role of RIKEN-RAL muon facility in muon science?”
- The RIKEN-RAL muon facility was an ideal breeding ground where any new ideas are encouraged, pursued, and developed!
- The development work under Iwasaki-san has laid the foundation of slow muon beam line at J-PARC MLF, which is now at fully operational

A big thank you to you, Iwasaki-san