Ultra Slow Muon Microscopy for Nano-science

Y. Miyake¹,², N. Nishida³, J. Yoshino³, W. Higemoto²,⁴, E. Torikai⁵, K. Shimomura¹,², Y. Ikedo¹,², N. Kawamura¹,², P. Strasser¹,², S. Makimura¹,², H. Fujimori¹,², K. Nakahara¹,²,⁸, A. Koda¹,², Y. Kobayashi¹,², K. Nishiyama¹,², R. Kadono¹,², T. Ogitsu²,⁶, Y. Makida²,⁷, K. Sasaki²,⁶, T. Adachi², and K. Nagamine¹,⁹

¹ Muon Science Laboratory, High Energy Accelerator Research Organization, Tokai, Ibaraki 319-1106, Japan
² Muon section, Materials and Life Science division, J-PARC Center, Tokai, Ibaraki 319-1106, Japan
³ Department of Physics, Faculty of Science, Tokyo Institute of Technology, 201201 O-okayama Meguro-ku, Tokyo 152, Japan
⁴ Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
⁵ Faculty of Engineering, Yamanashi University, Kofu, Yamanashi, 4008511, Japan
⁶ Cryogenic Science center, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 319-1106, Japan
⁷ Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, Tokai, Ibaraki 319-1106, Japan

Abstract. The surface muon beam which has been used for the studies of condensed matter physics or chemistry is conventionally obtained from the decay of positive pions (π⁺) stopped near the surface of the pion production target in the proton beam line and has large energy broadening with an implantation depth of 0.1 to 1 mm. Despite the name of surface muon, it is used as a probe of bulk phenomena rather than surface phenomena. In these two decades, the new method to generate ultra-slow muon beam with energy 0.2 eV has been developed and successfully obtained by KEK and RIKEN group. When the production of intense ultra-slow muon source will be realized, the use of its short-range penetration depth will allow muon science to be expanded towards a variety of new nano-scientific fields, which we call "Ultra Slow Muon Microscope" such as, 1) Surface/boundary magnetism utilizing its spin polarization and unique time-window. 2) Surface chemistry, utilizing a feature of a light isotope of hydrogen; such as catalysis reactions. 3) Muon Microscopy, utilizing a feature of micron meter beam size, when ultra slow muon is accelerated. 4) Precise atomic physics testing QED, since Mu is the simplest lepton pair consisting µ⁺ and e⁻. 5) Ion sources for g-2 µ⁻ experiment, and towards µ⁺,µ⁻ collider experiments in high-energy physics. Int this paper, the latest status of the intense low-emittance ultra slow muon source and its scientific prospects will be reported.

1. Introduction
A muon is a kind of lepton. It has a spin, 1/2 and a mass about 1/9 of proton (207 times heavier than electron). There are two kind of muons, positively charged muon (µ⁺) and negatively...
charged muon ($\mu^-$). $\mu^+$ is a decay product of $\pi^+$, associated with $\nu_\mu$. $\mu^+$ is emitted towards the opposite direction from $\nu_\mu$ and hence, $\mu^+$ is spin polarized inherently, since $\nu_\mu$ has negative helicity. When $\mu^+$ is implanted into the materials, $\mu^+$ stops between atoms, and there, $\mu^+$ starts Lamour precession according to the local magnetic field. $\mu^+$ decays to $e^+$ and two neutrino, $\nu_e$ and anti-$\nu_\mu$ in a lifetime of 2.2 $\mu$s. $\mu^+$ emits positron preferentially to the direction when their spins were pointing upon decay. Therefore, spin evolution of $\mu^+$ can be observed in the time histogram, by detecting $e^+$ events by scintillation counters. This experimental technique is called as $\mu$SR.

The conventional muon beams are obtained from proton accelerators with proton energies higher than 400 MeV. According to the momentum of the generated muon beam these beams are usually referred to either as $\uparrow$ decay muon $\downarrow$ beam or $\uparrow$ surface muon $\downarrow$ beam. The decay muons are obtained through the in-flight decay of $\pi^+ / \pi^-$, confined by a strong longitudinal field of several T from a superconducting solenoid magnet. Muons obtained from the in-flight decay of $\pi^+ / \pi^-$ have high momentum, between 40 to several hundreds of MeV/c. Not only positive but also negative muon beam are available[1]. The surface muons, as the naming suggests, are obtained from the decay of positive pions ($\pi^+$) stopped near the surface of the pion production target in the proton beam line[2]. Compared to the decay muons which have a high momentum due to the in-flight decay of pions, the surface muons obtained from the decay of $\pi^+$ at rest have a low and unique kinetic energy of 4.1 MeV (corresponding to a momentum of 29.8 MeV/c). Since the negative pions ($\pi^-$) are easily captured by the nucleus, only positive surface muon beams ($\mu^+$) are available. The spin polarized surface muons are widely used as a magnetic microprobe in material science [3]. The surface muon beam has a lower energy compared to the decay muon beam and when injected into a bulk sample, they have, therefore, an implantation depth of just 0.1 to 1 mm. Despite the name $\uparrow$ surface $\downarrow$ muons, it is typically used as a probe to bulk phenomena rather than surface phenomena.

Lately, the studies of surface/subsurface, nano materials and multi layered thin films, are becoming increasingly important. However, for that purpose, we must have muon beam, that has sufficiently low energy to stop on or near the surface of the sample. To perform such studies, so called slow (low energy) muons are required with energy that is of the order of several eV to a few tens of keV, far lower than the energies available from the conventional muon beams.

2. J-PARC Facility
The accelerator complex of the Japan Proton Accelerator Complex (J-PARC) has been constructed in the south part of Tokai-JAEA site, and consists of a 181 MeV (400 MeV at Phase2) LINAC, and 3 GeV and 50 GeV proton synchrotron rings. About 90 % of the 3 GeV, 333 $\mu$A (1.0 MW) is sent to the Materials and Life Science facility (MLF) for the production of intense pulsed neutron and muon beams, while the remaining 10 % will be sent to the 50 GeV ring for further acceleration in order to produce a 15 $\mu$A, 50 GeV proton beam to be used for the kaon or neutrino physics programs[4].

3. J-PARC Muon Facility, MUSE
The muon science experimental area (MUSE) is located in the integrated building of MLF for the materials and life science program. The 3 GeV proton beam from the 3 GeV proton synchrotron ring will be transported through the 300 m long beam transport line into the MLF building. The beam will be focused on the muon target (installed upstream of the neutron target) with a size of approximately 24 mm in diameter. The repetition rate of the 3 GeV synchrotron is 25 Hz, with a pulse-separation of 40 ms. One proton pulse consists of two bunches which are separated by 600 ns with a full width of 100-120 ns. Construction of the MLF building was started in the beginning of 2004, and first muon beam was delivered in the autumn of 2008.
For Phase 1, we installed a superconducting decay/surface channel with a modest-acceptance (about 40 m sr) pion injector, where both surface muons, and decay muons can be extracted. In November 2009, the surface muons ($\mu^+$) extraction rate was recorded to be $1.8 \times 10^6$/s with use of a 120 kW proton beam from the RCS. The achieved intensity is equivalent or even larger than that at the RIKEN-RAL muon facility [5]. This is the reason why that the world strongest pulsed muon source was claimed to be achieved at MUSE, even if with use of a 120 kW proton beam intensity. This intensity would correspond to $1.5 \times 10^7$/s surface muons when in the future the proton beam will reach a power of 1 MW [6].

In addition to Phase 1, as one of the principal muon beam channel at MUSE, we are planning to install the Super Omega Muon beam channel, which consists of a large acceptance solenoid made of mineral insulation cables (MIC), a superconducting curved transport solenoid and a superconducting axial focusing magnets. There, we can collect either surface or cloud muons with a large acceptance of 400 mSr. Compared to conventional beamlines, the large acceptance of the front-end solenoid will allow for the capture of the highest intensity pulsed muon beam in the world. With a muon capture rate of $5 \times 10^8$ surface muons/s and an approximate transport efficiency of 80%, we can expect $4 \times 10^8$/s surface muons and $10^7$/s negative cloud muons in the experimental hall [7]. At the super omega channel, we are aiming to create a new type of muon source: the intense ultra-slow muon source. Fig. 1 shows a schematic view of the super omegamuon beam line.

**Figure 1.** A schematic view of the superomega muon beamline consisting of a axial focusing MIC solenoid, a superconducting curved solenoid magnet, a superconducting axial focusing magnets and a slow ion optics.
4. Slow muon
There are proposed two methods to generate slow muon beam. The one is the generation of low energy $\mu^+$ through the cryogenic moderation method using Van der Waals solids such as solid Ar or $N_2$, has been initiated at TRIUMF and is developed at PSI [8]. Another method is the Ultra slow muon generation through the resonant ionization of thermal Mu atoms, developed at KEK and RIKEN RAL pulsed muon facilities[9]. At J-PARC, we are proceeding the latter method to generate intense ultra slow muon source at J-PARC [10].

![Figure 2](image1.png)

**Figure 2.** A resonant ionization scheme via the $1S\rightarrow 2P\rightarrow$ unbound transition for Mu and the scheme for the Lyman-\(\alpha\) generation via the four-wave frequency mixing method using two 212.55 nm ($\omega_r$) photons for the two-photon resonant excitation of the $4P^55P[1/2]_0$ state in krypton, subtracted by a photon with a tunable difference wavelength $\omega_l$.

![Figure 3](image2.png)

**Figure 3.** A schematic view of generation of the ultra slow muon beam. Ultra slow muons generated by the resonant ionization of Mu are accelerated and transported by "Slow-Ion Optics" consisting of an immersion lens (SOA), an electrostatic mirror, etc.

4.1. EXPERIMENTAL TECHNIQUE OF THE ULTRA SLOW $\mu^+$ GENERATION BY RESONANT IONIZATION OF MU
The ultra slow pulsed muons are generated by the resonant ionization of thermal Muonium (resignatated by Mu) atoms generated from the surface of a hot tungsten foil, placed at the intense surface muon beam line. In order to efficiently ionize the Mu near the W surface, a resonant ionization scheme via the $1S\rightarrow 2P\rightarrow$unbound transition was adopted. This requires a laser system to generate Lyman-\(\alpha\) photon (in the vacuum ultraviolet region around 120 nm) and 355 nm photon (for the ionization step from the 2P state). Lyman-\(\alpha\) photon is generated by the resonant four-wave mixing frequency, through a parametric process of adding energies of two 212.55 nm photons ($\omega_r$) and subtracting energy of one tunable infrared photon ($\omega_l$). ($\omega_{UV} = 2\omega_r - \omega_l$). Fig. 2 (left) shows a resonant ionization scheme via the $1S\rightarrow 2P\rightarrow$unbound transition for the hydrogen atom isotopes and the scheme for the Lyman-\(\alpha\) generation via the four-wave frequency mixing method using two 212.55 nm ($\omega_r$) photons for the two-photon resonant excitation of the $4P^55P[1/2,0]$ state in krypton, subtracted by a photon with a tunable difference wavelength. Fig. 2 (right) shows how to generate Lyman-\(\alpha\) light by the four wave mixing in Kr. Ultra Slow muons which is generated by ionization of Mu are accelerated and transported by "Slow-Ion Optics", which consists of an immersion lens (SOA), a magnetic bend for mass separation, an electrostatic deflector, and five sets of electrostatic quadrupoles. Fig. 3 shows a schematic view how to generate and transport ultra slow muon beam [9].
4.2. **UNIQUE FEATURES OF THE PULSED ULTRA SLOW $\mu^+$ BEAM**

One of the most important features of the ultra slow $\mu^+$ beam generated by the resonant laser ionization of Mu is its short pulse width. Regardless the temporal profile of the surface muon pulse with its double bunch structure consisting of 100 ns (FWHM) pulses separated by 320 ns at RIKEN-RAL, the pulse duration of the ultra slow muon beam is determined only by the duration of the laser pulse and by the transport properties of the low energy ion transport beamline. Consequently, at RIKEN-RAL the duration of the ultra slow $\mu^+$ pulse in the time-of-flight spectrum at the end of the transport beamline is just 7.5 ns (FWHM). In principle, the pulse duration can be reduced further to $\sim 1$ ns by using a laser with shorter pulse duration and optimizing the beamline transport [11].

Since the Mu atoms evaporate from the hot W (2300K) at thermal energies, the initial kinetic energy of the ultra slow $\mu^+$ generated by the laser resonant ionization is only 0.2 eV. Therefore the beam emittance of the ultra slow $\mu^+$ beam accelerated by SOA lens to 9 keV is so small that the beam can be focused onto a tiny spot on the sample. Compared to the size of the incident surface muon beam of 40 mm (FWHM), the resulting ultra slow $\mu^+$ beam it could be focused to a spot of just 3.3 mm (FWHM, horizontally) by 4.1 mm (FWHM, vertically) presently at RIKEN-RAL. In principle, the beam size is not limited by the beam emittance but by the transport characteristics of the beamline and by better optimization of the beamline spots as small as 1 mm (FWHM) can be potentially obtained, perhaps at a cost of reducing the transport efficiency.

4.3. **Yield of ultra slow Muon by the laser resonant ionization method**

At the RIKEN/RAL muon facility, 20 ultra slow $\mu^+$/s [11] at the sample out of $1.2 \times 10^6$ /s surface muons can be extracted. At the J-PARC MUSE Super Omega muon channel $4 \times 10^8$ surface muons/s can be extracted from a large acceptance of 400 msr. From the viewpoint of the intensity of the surface muon, we can gain a factor of 300. Taking into account the repetition rate of the pulsed laser system and the muon beam, we can gain a factor of two, since at J-PARC, both the laser and muon beams can be synchronized to 25 Hz, whereas at the RIKEN-RAL facility, the muon beam (50Hz) is synchronized to every second laser pulse. Therefore, we can expect $1.3 \times 10^4$ /s of the ultra slow $\mu^+$ without any additional laser development at J-PARC. Although more than 71 $\mu$J/cm$^2$ of the Lyman-$\alpha$ light is needed in order to saturate the transition of Mu from the 1S state to the 2P state, we are, at present, producing about 1 $\mu$J/cm$^2$ of the Lyman-$\alpha$ light through the Resonant Four-wave Frequency Mixing. With sufficient laser development, we can expect about 100 times gain. Finally, we are expecting a maximum rate of $1.3 \times 10^6$ /s ultra slow $\mu^+$ [10].

5. **Conclusion**

As one of the principal muon beam line at the J-PARC muon facility (MUSE), we are now constructing the Super Omega Muon beam line, which consists of a large acceptance solenoid made of mineral insulation cables (MIC) and a superconducting curved transport solenoid. There, we can extract $4 \times 10^8$ /s surface muons towards the experimental hall. At the super omega line, we are aiming to create a new type of muon source; the intense ultra-slow muon source by resonant ionization of thermal Muonium (designated as Mu; consisting of a $\mu^+$ and an $e^-$) atoms generated from the surface of a hot tungsten foil. When the production of intense ultra-slow muon source is realized, the use of its short-range penetration depth (eg. 1 nm resolution at a penetration of 1 nm, and 10 nm at a penetration of 6 nm in Gold) will allow muon science to be expanded towards a variety of new nano-scientific fields such as, 1) Surface/boundary magnetism utilizing its spin polarization and unique time-window. 2) Surface chemistry, utilizing a feature of a light isotope of hydrogen; such as catalysis reactions. 3) Muon Microscopy, utilizing a feature of micron meter beam size, when ultra slow muon is accelerated.
4) Precise atomic physics testing QED, since Mu is the simplest lepton pair consisting $\mu^+$ and $e^-$. 5) Ion sources for g-2 experiment, and towards $\mu^+\mu^-$ collider experiments in high-energy physics.

Table 1 shows a comparison of features between conventional surface muon and ultra slow muon.

|                       | Ultra Slow Muon | Surface Muon (ConventionalMuon) |
|-----------------------|-----------------|---------------------------------|
| Muon Beam Line        | J-PARC U-Line   | J-PARC D-Line                   |
| Implantation Energy   | 0.05 - 30 keV   | 4.1 MeV                         |
| Monochromacity        | 14 eV           | 0.4 MeV                         |
| Beam Size             | $\phi$ 1 - 4    | $\phi$ 50 - 70                  |
| Time Resolution       | sub ns - ns     | 100 - 150 ns                    |
| Polarization          | 50 %            | 100 %                           |
| Intensity             | $10^6$/s (@1MW) | $3 \times 10^7$/s (@1MW)        |

References

[1] Nagamine, K. 1981. Pulsed ⊞ SR facility at the KEK BOOSTER. Hyperfine Inter. 8: 787-796.
[2] Pifer, A.E., Bowen, T., Kendall, K.R. 1976. A high stopping density ⊞ + beam. Nucl. Instru. Metho. 135:39-46.
[3] Schenck, 1985. A. Muon Spin Rotation Spectroscopy. Adam Hilger Press, London.
[4] S. Nagamiya, T. Nagae, Y. Ooyama, Y. Miyake, H. Takano, J.R. Helliwell, J.C. Peng, Energy Review 19, 12(1999) 4-23
[5] K. Nagamine, T. Matsuzaki, K. Ishida, I. Watanabe, S.N. Nakamura, R. Kadono, N. Kawamura, S. Sakamoto, M. Iwasaki, M. Tanase, M. Kato, K. Kuroswa, G.H. Eaton, H.J. Jones, G. Thomas, and W.G. Williams, Hyperfine Interactions 101/102(1996)521
[6] Y. Miyake, K. Nishiyama, N. Kawamura, P. Strasser, S. Makimura, A. Koda, K. Shimomura, H Fujimori, N. Nakahara, R. Kadono, M. Kato, S Takeshita, W. Higemoto, K. Ishida, T. Matsuzaki, Y. Matsuda, and K. Nagamine, Nucl. Instr. and Meth. in Phys. Res. A 600(2009) 22-24
[7] K. Nakahara, Y. Miyake, K. Shimomura, P. Strasser, K. Nishiyama, N. Kawamura, H. Fujimori, S. Makimura, A. Koda, K. Nagamine, T. Ogitsu, A. Yamamoto, T. Adachi, K. Sasaki, T. Tanaka, N. Kimura, Y. Makida, Y. Ajima, K. Ishida, Y. Matsuda, AIP Conference Proceedings, 981(2007)312-314
[8] Morenzoni, E., Kottmann, F., Maden, D., Matthias, B., Meyberg, M., Prokscha, Th., Wutzke, Th., Zimmermann, 1994. U. Generation of Very Slow Polarized Positive Muons.Phys. Rev. Lett., 72,17: 2793-2796
[9] Nagamine, K., Miyake, Y., Shimomura, K., Birrer, P., Marangos, J.P., Iwasaki, M, Strasser, P., Kuga, T., Ultra slow Positive-Muon Generation by Laser Ionization of Thermal Muonium from Hot tungstum at Primary Proton Beam. 1995. Phys. Rev. Lett., 74,24: 4811-4814.
[10] Ultra Slow Muon Project at J-PARC, MUSE ⊞Y. Miyake, K. Nakahara, K. Shimomura, P. Strasser, N. Kawamura, A. Koda, S. Makimura, H. Fujimori, K. Nishiyama, Y. Matsuda, P. Bakule, T. Adachi, and T. Ogitsu, AIP Conference Proceedings1104 (2009) 47-52
[11] P. Bakule, Y. Matsuda, Y. Miyake, K. Nagamine, M. Iwasaki, Y. Ikedo, K. Shimomura, P. Strasser, S. Makimura, Nucl. Instr. and Meth. in Phys. Res. B266 (2008) 335-346