

# Ultra Slow Muon Microscope at MUSE / J-PARC

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**Abstract.** We report current constructing states of the Ultra Slow Muon Beam at U-line / MUSE / J-PARC, which are supported by thermal muonium ( $\text{Mu}$ ,  $\mu^+e^-$ ) production with the most intense pulsed slow muon beam, laser resonant ionization, and transportation of Ultra Slow Muon Beam. A thermal  $\text{Mu}$  is produced by a hot tungsten foil in a  $\text{Mu}$ -production chamber. At the laser resonant ionization process, a thermal  $\text{Mu}$  is ionized by coherent vacuum ultraviolet radiation and coherent 355-nm radiation. The coherent radiation sources are developed at RIKEN, installed in a laser cabin, and connected via a VUV steering chamber with the  $\text{Mu}$ -production chamber.

## 1. Introduction

The Ultra Slow Muon (USM) Beam has been developed at MSL / KEK in Japan [1] and, RIKEN-RAL muon facility / ISIS in UK [2]. But, enough yield of beam, for the study in material science, was not obtained. Now, there are four secondary beam lines (D, U, S, and H-line) at MUSE / J-PARC [3]. Muons are produced via pions ( $\pi^+$  or  $\pi^-$ ) decay by the nuclear reactions between the 3 GeV proton beam and the muon target which made of 20-mm thick graphite [4]. And the muons are extracted from secondary beam line. D-line has been operational for fast muons (decay muons: up to 120 MeV/c,  $\mu^+$  or  $\mu^-$ ) or slow muons (surface muons: 30 MeV/c, 4 MeV,  $\mu^+$ ). And U-line, for Ultra Slow Muon microscope for material science, is planned to be operational with more than  $10^4$  times higher USM intensity than that at RIKEN-RAL [5]. At U-line, magnetic or electric properties will be investigated for surface or subsurface of condensed or soft matter.

## 2. Muon U-line

Muon U-line consists of Superomega beam line [6] and Ultra Slow Muon beam line [7]. And USM beam line consists of muonium production chamber and transportation line. (U-line is sometimes



called as Superomega beam line, in a narrow sense) Fig. 1 shows a schematic diagram and a photo of U-line.

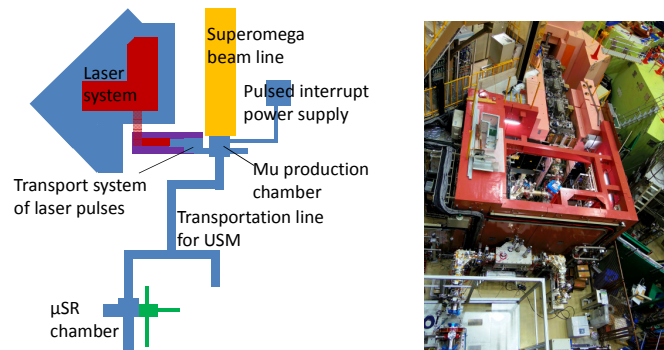


Fig. 1: Schematic diagram and photo of muon U-line

### 2.1. Superomega beam line

Superomega beam line, the slow muon source for the USM beam, was already installed. It consists of the capture solenoid, the curved transport solenoid, and the axial focusing solenoid [6]. And, the positron separators with DC high voltage power supplies were added on the beam line chambers of the axial focusing solenoid [8]. In Nov. 2012, the intensity of slow muons has been achieved 100 times higher than that at RIKEN-RAL [9].

### 2.2. Muonium Production chamber and Transportation line for Ultra Slow Muon

At Mu production chamber, the surface muon beam from Superomega beam line is injected into a hot tungsten (W) foil, which is heated up to 2100-2300 K, and the Mu can escape to the vacuum with thermal velocity ( $E \sim 0.2-0.3$  eV). At this chamber, ultrahigh vacuum (UHV,  $10^{-7}$  Pa $\sim 10^{-8}$  Pa; required for the thermal Mu production) has been achieved with a tandem unit of turbo molecular pumps and a cryopump. The W foil has been heated by a pulsed interrupt power supply [10]. And highly pure W foil (6N, 99.9999%;  $50 \mu\text{m} \times 54 \text{ mm} \times 70 \text{ mm}$ ) has been developed with mechanical polishing, without hot rolling technics [11], because the purity of W foil affects Mu emission[1,2]. Recently, the surface of this W foil has been observed by laser scanning microscope (LSM), and it has been showed that there are many gaps ( $1\text{-}\mu\text{m}$  depth $\times 2\text{-}10\text{-}\mu\text{m}$  wide) (Fig.2) [12]. And it has been also showed with wavelength dispersive X-ray fluorescence spectrometer (WDX) that the surface is covered with tungsten oxide in the same way as a 3N-W foil [13]. At Mu production chamber, it is expected that oxygen and carbon at the tungsten surface is removed by hydrogen and oxygen treatment, respectively.

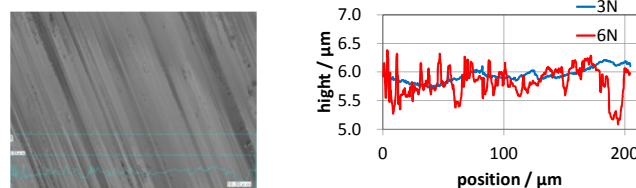


Fig. 2: Surface of the 6N-W foil (left), comparison of 6N-W and 3N-W with hot rolling (right)

The thermal Mu is ionized by laser pulses (cf. § 3), and the USM is produced. After extraction by SOA lens [7, 10], the USM beam is transported to  $\mu\text{SR}$  chamber [14]. The beam optics parameters have been optimized by off line beam tuning with  $\text{Li}^+$  [10].

## 3. Laser system

The USM beam is produced by laser resonant ionization of thermal Mu. In this laser resonant ionization process, thermal Mu is excited ( $1\text{S} \rightarrow 2\text{P}$ ) by coherent vacuum ultraviolet wave (VUV, 122.09 nm, Lyman- $\alpha$ ) and ionized by 355-nm wave (required: shorter than 366 nm, UVA). This coherent VUV wave, a pulsed (25 Hz) resonance radiation, is generated in a krypton (Kr) gas cell by sum-difference frequency mixing of 212.55-nm wave ( $\omega_1$ ; UVC, two photon resonant

excitation) and tunable difference wave ( $\omega_2$ , near infrared, NIR, 820.65 nm for Mu). These coherent radiation sources based on a diode-pumped fiber laser and solid-state laser technologies are developed at RIKEN [15], and it will be installed in a laser cabin [16].

The Omega 1 system is an all-solid-state coherent light source, which consists of a distributed feedback laser ( $\omega_1$  seeder), three fiber amplifiers, a regenerative amplifier (regen.), an intermediate amplifier system, a power amplifier (final amp.) system, and a nonlinear frequency converter [17]. The laser pulses are planned to be amplified up to an output energy of 1 J at 1062.75 nm by use of the power amplifier. The 1062.75 nm wave is converted to the fifth harmonic wave (212.55 nm), through second harmonic generation in a LBO, fourth harmonic generation in a CLBO, and fifth harmonic generation in a CLBO in the nonlinear frequency converter.

The Omega 2 system is a tunable coherent light source, which consists of a broadband spectrum diode laser ( $\omega_2$  seeder) and a  $\omega_2$  amplifier system [18, 19]. The  $\omega_2$  amplifier contains an optical parametric oscillator (OPO) and an optical parametric amplifier (OPA) using KTP crystals as a nonlinear optical crystal.

For generation of muonium Lyman- $\alpha$  resonance radiation, we use a Kr cell in which argon gas is mixed to krypton to satisfy phase matching (Kr and Ar exhibit negative and positive dispersion, respectively.) [17, 20, 21] Pulsed coherent Lyman- $\alpha$  resonance radiation is generated in two-photon resonance four-wave mixing (sum-difference frequency mixing) using the Omega 1 and 2 according to the process as shown in Fig. 3. At present, a new way of focusing in Kr gas is extensively studied in RIKEN to adapt high intense laser pulses with the effect of plasma development and dephasing.

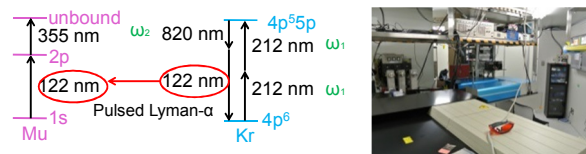


Fig. 3: Simplified energy level diagram (left), laser system in a laser cabin at J-PARC (right)

#### 4. Transport system of laser pulses

Transport system of laser pulses [22] introduces laser pulses to the Mu production chamber (Fig. 4). The vacuum chambers for the transport system (manufactured by AVC Co., LTD. [23]) consist of a VUV steering vacuum chamber and a nitrogen monoxide (NO) gas cell. The VUV pulse generated in the Kr cell goes through the VUV steering chamber, the Mu production chamber, and the NO gas cell, sequentially.

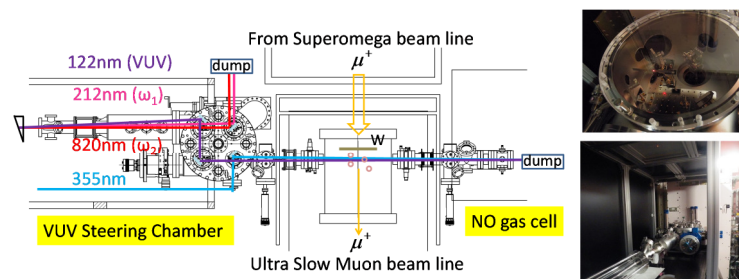


Fig. 4: Transport system of laser pulses

In the VUV steering chamber, two bright fundamental waves ( $\omega_1$ ,  $\omega_2$ ) can be separated from VUV wave. The 355-nm wave has a nearly same incident angle to the Mu production chamber as that of VUV wave. UHV ( $<10^{-6}$  Pa) can be achieved in the VUV steering chamber. That is because mirrors are steered from outside of the chamber by control units with magnetic coupling mechanism, without other drive mechanisms in the chamber. Because mirror control units were prepared for each VUV pulse and 355-nm pulse, respectively, we can easily control the distance between these pulses and the W foil. By monitoring ionization rate of thermal Mu with changing this distance, it will be revealed that the velocity of thermal Mu follows a Boltzmann distribution or not. Radiation profiles and the separation of laser pulses were calculated by a ray tracing, *Optica* [22]. Although a wavelength

dispersion of the refractive index at a cylindrical lens of magnesium fluoride ( $\text{MgF}_2$ ) was used for pulse separation at RIKEN-RAL muon facility [2], that at a wedge plate of lithium fluoride (LiF) is planned to use for suitable horizontal pulse separation. The vertically long profile of VUV pulse is suitable for effective ionization of Mu. A cylindrical lens of LiF is used for making vertical profile. At the NO gas cell, there are parallel plates that accumulate nitrogen monoxide molecules ion for measuring intensity of the VUV pulse [24].

## 5. Summary

The Ultra Slow Muon Beam is supported by Muon U-line, the laser system, and the transport system of laser pulses. They are almost ready for next beam time, giving us a quarter-century waited *new* muon science, while some detailed and improved studies are performed in this shutdown term. You will investigate magnetic or electric properties of surface or subsurface of condensed or soft matter, with this new probe.

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