Optimal crossed overlap of coherent vacuum ultraviolet radiation and thermal muonium emission for \(\mu\)SR with the Ultra Slow Muon

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Abstract. For \(\mu\)SR with ultra slow muon, we are constructing U line in materials and life science facility (MLF), J-PARC at present. Generation of ultra slow muon requires thermal muonium generation and laser resonant ionization process with vacuum ultraviolet radiation (1S\(\rightarrow\)2P) and 355-nm radiation (2P\(\rightarrow\)unbound). For laser resonant ionization, the coherent radiations and the thermal muonium emission must be coincident in time and space. The radiations can be steered in a chamber for reasonable overlap in space, and they can be easily overlapped in time because they are generated from one laser source. The trigger signal of the accelerator is useful for stable overlap in time.

1. Introduction
For \(\mu\)SR experiment, a surface muon (slow muon, we called in this article) with the 4-MeV kinetic energy is usually used. \(\mu\)SR experiment with brand-new muon, ultra slow muon (USM) will be carried out at J-PARC. The USM is defined as a low energy muon generated by laser resonant ionization of thermal muonium (Mu, \(\mu^+e^-\)). Figure 1 shows a schematic diagram of generating USM and the energy level diagram of Mu. A 2100-K heated tungsten (hot W) foil plays the roles of not only degrader, but also generation target for Mu. In the W foil, muons are stopped and emitted to ultra high vacuum as thermal energy Mu (thermal Mu). The thermal Mu is ionized by coherent radiations to generate the USM. The USM beam has been developed during the quarter century at Muon Science Laboratory / KEK in Japan[2] and the RIKEN-
Figure 1. Schematic diagrams of generating ultra slow muon (left), and energy level diagram of muonium (right). The USM is a low energy muon generated by laser ionization of thermal Mu. Slow muon is injected into a hot tungsten foil, and muonium with thermal energy can escape to ultra high vacuum. Muonium is excited by 122.09-nm radiation, and ionized by 355-nm radiation. Wavelength of the second radiation is required shorter than 364 nm for taking electron away.

RAL Muon Facility / ISIS in UK [3]. However, the achieved beam intensity was not enough to conduct a $\mu$SR experiment in a practical time period.

The USM beam intensity is required to be more than 1000 /s for $\mu$SR spectroscopy in the condensed and solid-state physics. To maximize the intensity, several new ideas are proposed. The USM beam intensity is determined by two factors. One is generation of the USM, and the other is extraction and transportation efficiency of the USM [4]. The former is determined by next three factors.

1. Generation of thermal Mu [4] with the most intense pulsed slow muon beam [5]
2. High-intensity coherent radiation from solid-state source [6]
3. Crossed overlap of coherent radiation and thermal Mu emission.

In this article, we report this crossed overlap. The thermal Mu emitted in vacuum is shot by the coherent radiation to ionize and dissociate muon. The coherent radiation is introduced from a perpendicular direction to the muon beam.

2. Configuration

At our U line / MUSE [7], thermal Mu generation and laser resonant ionization process are required for generation of the USM. Coherent vacuum ultraviolet (VUV, 122.09-nm) radiation and 355-nm radiation are used for resonant ionization of the thermal Mu. All-solid-state sources were developed at RIKEN [6]. They are generated at the laser cabin and introduced to the U line [8] by a VUV steering chamber [9]. The U line is planned to be operated with more than $10^4$ times higher USM intensity than that at the RIKEN-RAL Muon facility [3, 7]. $10^4$ means $10^2$ times higher slow muon intensity and $10^2$ times higher coherent radiation intensity. All factors are important, because they act as the multiplication rather than the addition. Figure 2 shows top view of the area of USM generation (U1 shielding area), where the USM will be generated and transported to the experimental area.

3. Space overlap

Figure 3 shows schematic diagram of space overlap at the RIKEN-RAL Muon facility and J-PARC, MUSE. At Port 3 / RIKEN-RAL, the 355-nm radiation was introduced at 30° from two VUV radiations. The 355-nm radiation profile is 3 mm ($W \times H$). Each of the VUV radiation profiles is 1-2 mm ($W \times H$) in front of W foil, which size is 40 mm ($W \times 35$ mm ($H$). A volume of the overlap region of coherent radiations and thermal Mu emission
Figure 2. Top view of U1 area at U line. The USM is generated at Mu generation chamber. The area is a place where coherent radiations and thermal Mu emission are crossed overlapped.

Figure 3. Schematic diagrams of space crossed overlap at J-PARC (left), and at RIKEN-RAL (right). The most significant difference between these diagrams is an angle between coherent radiations. A small angle is realized at J-PARC, by the benefit of a VUV steering chamber.

Angular difference between these radiations is less than 0.5°. The effective crossed overlap in space will be realized at the U line by using the VUV steering chamber. The VUV steering chamber was newly designed for transportation of coherent radiation. The chamber contains four mirrors and two mirror control units (Fig. 4). VUV radiations and 355-nm radiations are steered respectively. VUV radiation is generated in krypton-argon gas mixture from fundamental radiations: 212.556-nm and 820.648-nm radiation. This process is two-photon resonance four-
Figure 4. VUV steering chamber with four mirrors (M1-M4). VUV radiation is generated by frequency mixing of 212.556-nm and 820.648-nm radiations in Kr-gas cell. The wedge plate of lithium fluoride is not only a window between the cell and the VUV steering chamber, but also a disperser of radiations. By M1 mirror, VUV radiation is separated from bright fundamental radiations, which have different incident angles to the chamber. 212.556-nm and 820.648-nm radiations are kicked out of the chamber by M2. VUV radiation is steered by M3, and injected into the Mu generation chamber. 355-nm radiation is steered by M4, and injected, too. M1 and M3 are high reflectivity (83%) mirrors for 122.09-nm radiation.

Wave mixing with phase matching gas mixture [13]. Usually, Piezo actuators with cables are applied for mirror-control in vacuum. To reduce costs and the outgassing from the cables, the brand-new mirror control units were installed. Two mirrors, M3 and M4, can be steered by these control units. In this method, the conventional mirror mounts, which can be aligned manually and can stay in vacuum, are controlled from the outside of the vacuum chamber. The adjuster screws on the mirror mounts in vacuum are rotated outside of the chamber through magnetic coupling mechanisms. Solid lubricants are applied for drive in vacuum. Then, ultra high vacuum can be achieved (∼10⁻⁶ Pa) in the VUV steering chamber. This chamber is connected to Mu generation chamber (∼10⁻⁸ Pa) with differentially pumping [10]. The profile of VUV radiation and 355-nm radiation can be controlled by setting a cylindrical lens and other optical components in the VUV steering chamber. The vertical hight of Mu emission area is estimated to be the same as the height of the W foil (70 mm (W) × 40 mm (H)) [4]. A gap between the W foil and a first electrode for extraction is 14 mm [4]. Then, a vertically long profile of high-intensity coherent radiation (∼2 mm×40 mm) is effective for ionizing Mu. The volume of the overlap region of coherent radiations and thermal Mu emission will be expected ∼5×10⁴ mm³ which is 5 times bigger than that in the RIKEN-RAL.

An absolute intensity measurements of VUV radiation will be performed by a gas cell with nitrogen monoxide [9]. The gas cell is located after the Mu generation chamber which contains the W foil. The profile of VUV radiation will be estimated by using the cell and slits for coherent radiation. A fluorescent plate with sodium salicylate is also used to align of VUV radiation and to confirm the profile easily.

4. Time overlap
To operate an accelerator and to conduct an experiment, various synchronizations are necessary in general. At J-PARC, some trigger signals are prepared for the synchronizations [11]. At D line / MLF [12] a rapid cycling synchrotron (RCS) kicker trigger, which is one of the 25-Hz
Figure 5. Schematic diagram of time overlap. MLF reference trigger is a low jitter and high stable scheduled timing. Timing of coherent radiations is depend on the signal. 355-nm radiation can be easily synchronized with VUV radiation, because they are generated from one laser source. Timing of thermal Mu emission is depend on slow muon timing with some delay. The delay, which is derived from diffusion and evaporation processes, is necessary to examine.

synchronized timings, is used for $\mu$SR. The RCS kicker trigger is generated by the rf system at RCS, and sometimes missing similarly to the real proton beam. The missing is not good for the coherent radiation source based on fiber laser technology.

At the U line, synchronizing between the coherent radiation and the thermal Mu emission is important for laser resonant ionization (Fig. 5). The slow muon beam has time structure similarity to the proton beam \cite{12}. A pulse repetition rate is 25 Hz, i.e. the pulse repetition interval is 40 ms, the double pulse interval is 600 ns, and the pulse width is 150 ns. Time structure of thermal Mu interacting with radiations depends on this slow muon beam, muon diffusion in the W-foil target, evaporation from surface and Mu diffusion in vacuum. Therefore, it is necessary to examine the details. For stable timing of coherent radiation, 2 trigger signals are used. A scheduled timing for operating J-PARC accelerator is a 12-MHz master clock \cite{11}. A scheduled timing generated at MLF via 50-Hz trigger clock from a master clock is a 25-Hz MLF reference trigger. This 25 Hz trigger has an about 2.4-$\mu$s delay after a secondary-beam injection. The master clock and the MLF reference trigger were used for operating coherent radiation sources at the U line. Low jitter ($\sim$ns) and high stability of these trigger signals are suitable for these sources. Furthermore, a control unit with an internal clock is made. Receiving some alarm signal, this unit can trigger slow shutdown system to protect the coherent radiation sources.

Compared with the RIKEN-RAL, effective overlap in time will be also realized. At the RIKEN-RAL, three coherent radiations (212.556-nm, 820.648-nm and 355-nm) are generated from four sources (Nd:YAG laser). At the U line, these coherent radiations are generated from one 1.06278-$\mu$m laser source with wavelength conversion by nonlinear optical crystals, LBO and CLBO \cite{6}. Then, 212.556-nm radiation can be easily synchronized with 820.648-nm radiation for generation of coherent VUV radiation, and 355-nm radiation can be also easily synchronized with VUV radiation for resonant ionization of thermal Mu. In particular, an optical path length
for timing adjustment can be reduced. The accuracy of the optical path length is required at least 1 cm, because the pulse widths and lengths of radiations are 2.0 ns, 60 cm, respectively.

5. Summary
The coherent radiations and the thermal Mu emission will be overlapped in time and space for laser resonant ionization. The VUV steering chamber is taken advantage of overlap in space. The scheduled timing at J-PARC is useful for stable overlap in time. Furthermore, the all-solid-state coherent radiation source takes advantage of overlap in time.

The slow muon source and coherent radiation source are improved respectively in the present work. We will be actually controlling the overlap in the autumn of 2014 when operation of J-PARC is restarted. Absolute intensities of radiations and ionization rate of the thermal Mu with changing overlap status will be monitored.

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