Generation of negative slow muon beam in J-PARC Muon Facility

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Abstract. The world strongest pulsed muon facility has been operated since 2008 in J-PARC (Japan Proton Accelerator Research Complex). This facility utilizes 3-GeV proton to produce muon beam, and thus the negative pion and also negative muon yields are superior to the other meson factories in the world. We try to slow down these negative muons. Negative slow muon beam is desired to check the standard model and search a new physical rule, as well as various applications in material science.

1. Introduction

The intensity of proton accelerator has attained to the order to mega-watt, and several MW-class proton accelerators start to operate in the world. A high intensity proton accelerator (Japan Proton Accelerator Research Complex, J-PARC) project was proposed jointly by Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK) [1]. The new facility consists of a 400-MeV linac, 3-GeV and 50-GeV synchrotron rings, which provide an intense proton beam to generate a variety of secondary beams, i.e. muon beam, neutron beam, meson beam and neutrino beam for the purpose of particle physics, nuclear physics, material science, life science and nuclear technology. The muon facility established in order to provide the pulsed muon beam for various experimental programs.

The J-PARC Muon Facility succeeded to transport the first muon beam to the experimental area in September 2008 [2]. Although the proton beam power is still one fourth of its design value of 1 MW (3GeV, 333µA), the beam power increases step by step and is almost comparable to ISIS Facility (800MeV, 200µA) in the UK at the present. In comparison with ISIS beam energy of 800 MeV, in J-PARC, 3 GeV is about four times higher. The negative pion production cross section increases steeply above 1GeV, while positive one does not show a big change [7]. Thus, the negative pion yield in J-PARC Muon Facility is higher than the value simply scaled up by the beam current. Therefore, the negative muon characterizes J-PARC Muon Facility.

The other characteristic point in J-PARC Muon Facility is ultra slow muon beam by laser resonant-ionization (LRI) method [3, 4], by which positive muons almost at rest are dissociated from thermal muoniums emitted from hot tungsten surface. LRI method has been developed at KEK-MSL [3, 4] and the RIKEN-RAL Muon Facility. Based upon their developments, in J-PARC Muon Facility, the design work of ultra slow beamline by LRI is in progress for practical use. The key technique of this method is the intense laser synchronized with the muon pulse. In
in general, the time resolution of signals form pulse muon beam is inferior to that from continuous muon beam due to the finite width of the muon-beam pulse. However, the time width of ultra slow muon beam by LRI is determined by the width and spot size of laser, and thus is able to be quite narrow. Furthermore, the beam emittance by LRI is also able to be quite small. The LRI method provides not only low energy positive muons but also high quality beam with low emittance and low time and momentum dispersion.

This superior LRI method is available only to a positive muon and not to a negative muon, because a positive muon forms a muonium which is dissociated by laser, while a negative muon forms a muonic atom. A negative muon has 200-times higher binding energy than a normal atom, in which a negative muon waits for the decay to an electron and two neutrinos or a competitive process of nuclear capture. In the case of a heavier nucleus, the nuclear-capture process becomes dominant, and the effective lifetime of muon becomes much shorter than the free-decay lifetime of 2.2 $\mu$s. Therefore the behavior of negative muon in matter is much different from positive one, and LRI method is not applicable.

An approach to negative slow muon beam was performed by applying Ramsauer-Townsend effect in solid hydrogen [5]. Namely, a muon stopped in solid hydrogen with 1000-ppm deuterium forms a muonic deuterium, and its mean free path reaches 1 mm due to Ramsauer-Townsend effect. From a 1-mm film of solid hydrogen, a muonic deuterium can be extracted. Although a high energy laser like a free electron laser is required to dissolve a muonic deuterium with a a-few-keV binding energy, the muon is able to be released by leading a muonic deuterium to solid deuterium, where a muon catalyzed fusion phenomenon is expected to occur and a 10-keV muon is released. The efficiency of slowing down by this method is quite small, and is not suitable for applying a practical beamline, although it is a novel idea.

In order to generate slow negative muon beam, i.e. low energy and low emittance beam, from the world-intense negative muon beam in J-PARC, we start a fundamental study.

![Figure 1. A schematic figure of negative slow muon setup in J-PARC Muon Facility](image-url)
2. Negative muon slowing down

Technically, slowing down of a negative muon is much difficult in comparison with positive one. We cannot use any cooling method applied to positive muons like the degrader method established at PSI [6] nor LRI method. Furthermore, muon has a 2.2-µs life time, which is too short to apply any cooling methods for any other particles with infinite life time. Slowing down have to be complete enough earlier than the muon life time to free-decay loss. About 10% of incident muon is lost by free-decay every 200 ns.

For the first step of negative slow muon production at J-PARC Muon Facility, we will use a cyclotron to trap a few MeV muons from pion decay. Simons et al. succeeded to trap cloud muons, 4MeV µ−, and slowed them down to the range of around 10 keV [8]. Negative muons are injected toward the outer side of the weak-focusing cyclotron field and are bound into the orbit where they lose the energies through moderators placed at the mid-plane of cyclotron. According to the energy loss, the orbit gets smaller and smaller, and the low energy, up to a few tens of keV, muons are accumulated around the center of the cyclotron. By a pulse kicker device, the accumulated muons are extracted to the axis direction of cyclotron and are injected into a frictional cooling chamber. As reported by Mühlbauer et al. [9], the frictional cooling method, moderation in matter and acceleration in an electric field, is well match with connecting to the cyclotron trap. The balanced energy is typically a few keV, and could be around 1 keV.

![Diagram of the setup for test experiment](image)

**Figure 2.** A schematic figure of the setup for test experiment

Simons developed a cyclotron trap [8], by which about 0.3% of 4-MeV muons were converted to 5-25 keV. Frictional cooling method becomes efficient below about 100 keV, and the conversion efficiency to a few keV was estimated to be about 30% [9]. Assuming a negligible transmission loss between a cyclotron trap and a frictional cooling chamber, 0.1% of conversion efficiency are expected. Practically, both cyclotron trap and frictional cooling chamber are axial focusing
elements, and thus low-loss extraction and injection require well-studied magnetic field design. A pulse extraction kicker in the cyclotron trap is one of the key devices. Making the transmission efficiency higher, the cyclotron and the frictional cooling chamber is planned to be placed just beside (Fig. 1).

In J-PARC Muon Facility, 30-MeV/c $\mu^-$ rate is expected to be above $10^5$/s for 1-MW proton beam, and this yields $10^2$ keV-muons per second. The yield above 100 MeV/c is two orders of magnitude higher than that of 30 MeV/c, and thus low-loss slowing down from 100-MeV/c $\mu^-$ is important to increase the keV-muon rate. By slowing down from higher momentum, the beam becomes more dispersive and more difficult to be trapped in the cyclotron. The optimization of the moderator and cyclotron field is important in the design work. The setup for the test experiment starts to construct in J-PARC, as shown in Fig. 2. The first step is to check the effect of moderators placed in the magnetic field. For this purpose, a dipole magnet will be used, and several moderators to be placed in the cyclotron containing rare-gases solids will be examined.

3. Conclusions and Discussion
The most challenging and attractive usage of the world strongest negative muon in J-PARC is slowing them down. Connecting an intense positron source with the present setup, creation of anti-muoniums, i.e. $(\mu^- e^+)$, is one of the goal for checking the CPT theory and search a new physical rule beyond the standard model. Not only particle physics but also material science requires a high quality beam with low emittance and low energy. As the ultra slow positive muon beam pioneers a new application of muon use, slow negative muon also opens new muon science. Tomography by muonic X-ray is one of possible application by using high quality negative slow muon beam of which stopping position is easily controllable with high precision.

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