# Progress in development of new $\mu$SR spectrometer at RIKEN-RAL

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**Abstract.** A new $\mu$SR spectrometer has been developed at the RIKEN-RAL Muon Facility, UK. The spectrometer comprises two significantly advantageous devices of accurate magnets and multi-channel counter system for efficient use of the highly intense muon beam. A commissioning test to commence operation is in progress toward new $\mu$SR experiments under various conditions.

## 1. Introduction

A new research project to explore various matters under multiple extreme conditions, such as high pressure, low temperature, laser irradiation as an additional parameter combined with $\mu$SR technique, has recently been launched using the high intensity beam [1] at the RIKEN-RAL muon facility, UK [2]. In order to promote the project more intensively, a high performance and multi-channel spectrometer is newly designed in the Port-4 area. The new spectrometer has two significantly advantageous devices: one is precise Helmholtz magnets which can apply magnetic field to a sample with good homogeneity. They have a wide gap in which many kinds of apparatuses for making various conditions can flexibly be fabricated. The other is a new high-performance counting system for $\mu$-e decay positrons/electrons. Since the intensity of primary proton beam becomes higher owing to upgrade of the ISIS proton synchrotron at the Rutherford Appleton Laboratory (RAL), an instantaneous muon beam rate reaches approximately $3 \times 10^6$ muons/sec. However, distortion of the time spectrum becomes severe due to pile-up of signals. The larger number of segments of the counter system than existing spectrometers can reduce the pile-up and then, the systematic error can be suppressed even in the high intense beam. In addition, $\mu$-e decays from the sample can be observed selectively. This "direction-sensitive method" is employed to observe the long-time relaxation by reducing background particles.

This article concentrates on the design of these two devices and a current status of the development using the muon beam.

## 2. Spectrometer Design

### 2.1. Main Frame

Figure 1 shows a vertical cross section of the spectrometer comprising five pairs of Helmholtz magnets and electron/positron counters. A pair of large longitudinal field coils coaxially along with the muon beam, transverse field coils on top and bottom, and three pairs of zero

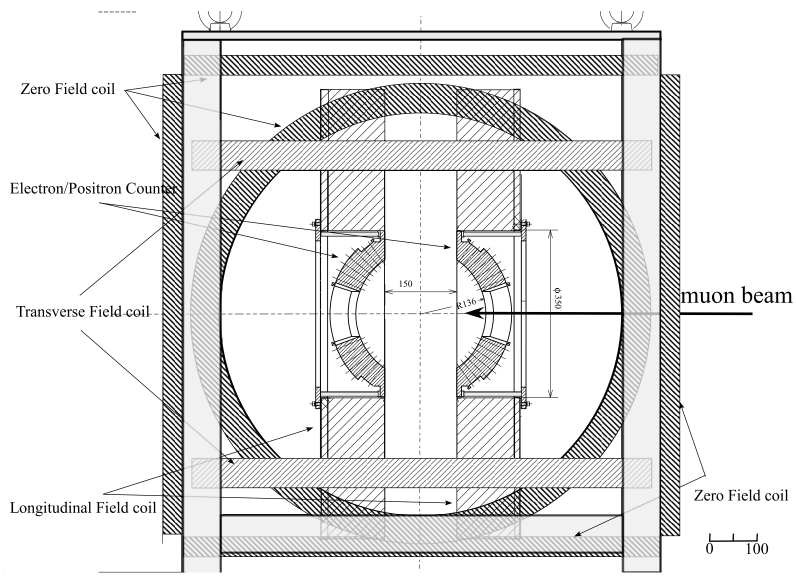


**Figure 1.** Schematic figure of the magnets and counter system in the spectrometer.

field coils around the sample were mounted in a square aluminum frame. Highly segmented electron/positron counters were mounted coaxially inside of the bore of the longitudinal field magnet. There was an option to rotate the frame of the magnets and counters at an angle of 90 degrees to the muon beam axis, enabling us to cancel the spin asymmetry of both sides of the counters. It was also available for a general purpose of $\mu$-e decay detection.

### *2.2. Magnets*

The longitudinal field coils could apply the external magnetic field up to 0.4 Tesla to the sample space of 150 mm gap in the muon spin direction. The transverse field coils could apply it up to 0.015 Tesla in order to rotate polarized muon spins on a horizontal plane. The other three pair of magnets were installed to cancel the magnetic field around the sample for precise zero field $\mu$SR measurements. The spatial homogeneity of the magnetic field is less than $10^{-4}$ at their maximal field around the sample volume from -15 mm to 15 mm of $x, y$ and $z$ coordinates.

### *2.3. Counter System*

The spin direction of muons which were stopped in the sample was determined by two counter assemblies located at the core of longitudinal coils, which were very limited spaces upstream and downstream to the muon beam direction. A special counter system was newly designed to fit the longitudinal coils. Our requirements were a compact read-out to mount the narrow spaces of the core, a multi-channel counters with less pile-up under highly intense pulsed muon beam and no magnetic field effect for the photon detection from the scintillator, in particular, for photomultiplier tubes (PMT). For this purpose, we employed a spindle scintillator, wavelength shifting fibers, clear fibers and multi-anode photomultiplier tubes (MAPMTs) and then, optimized their size to maximize their performance of $\mu$SR spectrometers.

Figure 2 shows the counter system including spindle scintillators and optical fibers. The wavelength shifting fiber of 1.5 mm diameter (Kuraray Y-11(400)MS) was buried at the center of a spindle plastic scintillator (10×10×40 or 50 mm$^3$) coated with $TiO_2$ and tightly connected the clear fiber of 2.5 m length (Kuraray) as a light guide. The 16 clear fibers were bundled and connected to the 16ch MAPMT (H6568-10-200mod). The spindle counter is mounted to point to the center of the sample position. Our recent feasibility test of the prototype counters [3]

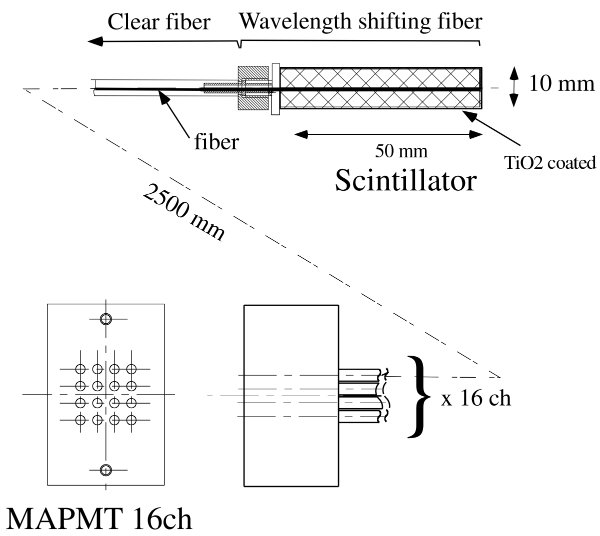


**Figure 2.** Schematic figure of the counter system composed of spindle scintillator, wavelength shifting fiber, clear optical fiber and MAPMT connection.

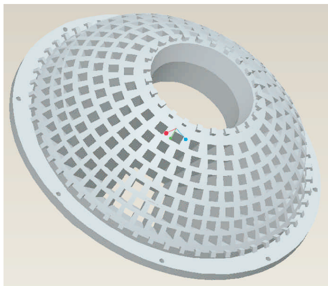

**Figure 3.** A special mold to house 303 counters which was attached to the longitudinal magnet.

showed that we can selectively observe positrons within 7 degrees from the sample by setting an appropriate threshold level of an analog output. It was determined in the commissioning test using muon beam for each counter.

The seven layers of counter were mounted coaxially along with the beam axis and in total 303 scintillator segmented the detection areas upstream and downstream, respectively. Figure 3 shows a special mold made of ABS to house counters, which mounted at the bore of the longitudinal magnet with aluminum supports. It is also noted that this large number of segments can reduce count-loss due to pile-up of positrons hitting the counter sequentially, resulting in suppressing deviation, at least, in less than 1% of the time spectrum at the time zero just after the muon beam arrival, which is calculated by a present positron hit rate per counter.

Moreover, the wavelength shifting fiber and the optical fiber could guide photons from the scintillator to the MAPMT which was remote from the magnetic field below the magnets. The MAPMT detected approximately 70 photons in average including efficiencies of scintillator variability, photon collection efficiency of WLS fiber, its transmission, fiber connection and MAPMT photocathod. It was covered by double-layered magnetic field shield made of iron and permalloy. It could suppress the magnetic field in less than 0.01 Tesla at the maximal field of the longitudinal magnet of 0.4 Tesla and the remaining magnetic field coming from the magnetized iron layer could be canceled by the permalloy layer in a zero field measurement.

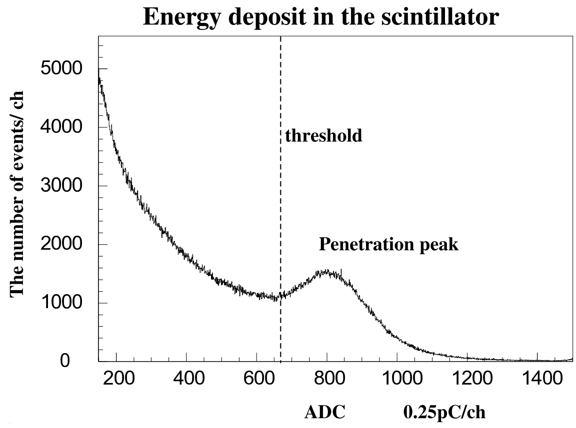


**Figure 4.** A typical spectrum of energy deposit in a scintillator in a prototype detector.

### *2.4. Data Acquisition*
A new data acquisition to dedicate the multi-channel counter system was built to accumulate large amount of data from the counters. The VME-based 128ch multi-hit TDC (Kaen V1190A) was operated with Linux software. The front end software (MACS/Windows [4]) controlled overall of the data acquisition system and slow control system for temperature and magnet control modules. A detail of the DAQ system is reported in Reference [5].

## 3. Counter Commissioning
A counter commissioning test using muon beam is being performed with an ADC module built into the new data acquisition system. Firstly, an energy deposit of decay positron for each counter was measured. Since analog pulse outputs from counters had distinctive variations, a threshold level of the discriminator was individually determined by observing an energy deposit spectrum. As shown in the prototype test [3], the counter system could be work as a direction sensitive counter if the threshold level is set at the 70 % of this peak height. Figure 4 shows a spectrum of a prototype counter for the new spectrometer. It shows that a peak on the decreasing component is made by the positrons which penetrates through scintillator in a spindle direction. These positrons are particularly chosen by setting the appropriate threshold level. It enables us to discriminate the signals from a background component in the muon decay time spectrum, called "direction-sensitive method". At present, this study for all counters of new spectrometer is underway.

## 4. Summary
The new spectrometer was designed and commissioning test is now performed at Port-4, RIKEN-RAL. At present, commissioning of the spectrometer and preparation of apparatus such as cryogenic system are in progress. A various remote control system is now being improved to commence operation toward various new $\mu$SR experiments.

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