New μSR spectrometer at J-PARC MUSE based on *Kalliope* detectors

K M Kojima[1,2,7], T Murakami[3,7], Y Takahashi[1,7], H Lee[1,7], S Y Suzuki[4,7], A Koda[1,2,7], I Yamauchi[1], M Miyazaki[1], M Hiraishi[1], H Okabe[1], S Takeshita[1], R Kadono[1,2,7], T Ito[5], W Higemoto[5], S Kanda[3,7,6], Y Fukao[3,7], N Saito[3], M Saito[3,7], M Ikeno[3,7], T Uchida[3,7] and M M Tanaka[3,7]

[1] Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK-IMSS), and J-PARC Material and Life Science Experimental Facility (J-PARC MLF), Tsukuba and Tokai Ibaraki, 319-1195, Japan
[2] Department of Materials Structure Science, The Graduate University for Advanced Studies, Tsukuba, Ibaraki, 305-0801, Japan
[3] Institute of Particle and Nuclear Study, High Energy Accelerator Research Organization (KEK-IPNS), Tsukuba, Ibaraki, Japan
[4] Computing Research Center, High Energy Accelerator Research Organization (KEK-CRC), Tsukuba, Ibaraki 305-0801, Japan
[5] Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki, 319-1195, Japan
[6] University of Tokyo, Graduate School of Science, Hongo, 113-8654, Japan
[7] Open source consortium of instrumentation, Open-it, KEK, Tsukuba, Ibaraki, 305-0801, Japan

E-mail: `kenji.kojima@kek.jp`

Abstract. We developed a new positron detector system called Kalliope, which is based on multi-pixel avalanch photo-diode (m-APD), application specific integrated circuit (ASIC), field programmable gated array (FPGA) and ethernet-based SiTCP data transfer technology. We have manufactured a general-purpose spectrometer for muon spin relaxation (μSR) measurements, employing 40 Kalliope units (1280 channels of scintillators) installed in a 0.4 T longitudinal-field magnet. The spectrometer has been placed at D1 experimental area of J-PARC Muon Science Establishment (MUSE). Since February of 2014, the spectrometer has been used for the user programs of MUSE after a short commissioning period of one week. The data accumulation rate of the new spectrometer is 180 million positron events per hour (after taking the coincidence of two scintillators of telescopes) from a 20×20 mm sample for double-pulsed incoming muons.

1. Introduction

At pulsed muon facilities, muons come in a pulse of a time width of several 10s of nano-seconds. Time differential muon spin relaxation (μSR) measures the elapsed time between each muon's arrival and the decay positron in the mu-e decay $\mu^{\pm} \rightarrow e^{\pm} + \nu$. The requirement for the positron/electron detectors for μSR is the minimal pile-up and dead time to handle the huge event rate right after the arrival of muons. The decay muon channel (D-line) of MUSE at

Journal of Physics: Conference Series **551** (2014) 012063 doi:10.1088/1742-6596/551/1/012063

J-PARC delivers 180,000 positive muons per pulse at D1 experimental area for the 300 kW operation regularly achieved nowadays [1]. These muons decay into positrons with an average life-time of 2.2 micro-seconds, resulting to the instantaneous count-rate of $180,000/2.2\ \mu s \approx 100$ giga counts/second (Gcps) for the entire solid angle.

The most reliable method of counting high-rate events is to reduce the size of the individual counters and tile them to cover the desired solid angle. The general purpose μSR spectrometer ($D\Omega$-1) previously installed at D1 experimental area had 256 scintillators (128 telescope pairs), covering approximately 8% of the solid angle around the sample [2]. With the full beam, the instantaneous count-rate for each counter yields $100\times10^9\times0.08/128 = 60$ Mcps. This is still a too high-rate, because each counter experiences approximately 60 Mcp$\times$2.2 μs$\approx$120 counts/pulse, which corresponds to $2.2\ \mu s/120 \approx 20$ ns for the average event separation. This event separation is shorter than the typical recovery time of photo-multiplier-tubes (PMTs: $\sim$20 ns) or avalanch photo diodes (APDs: $\sim$40 ns), and we reduce the muon beam intensity to $\approx$1/10-1/20 by collimators and slits, so that the high event-rate may be handled by the existing detectors. In order to enjoy the high intensity of pulsed muons at MUSE, the segmentation of the positron counters has to be higher. Recent development of multi-pixel avalanch photo diodes (m-APD), Application Specific Integrated Circuit (ASIC) and Field Programmable Gated Arrays (FPGA) has made such spectrometer affordable. Employing these new technologies, we developed a new positron/electron detector system called Kalliope (KEK Advanced Linear and Logic-board Integrated Optical detectors for Positrons and Electrons), manufactured a 1280 channel μSR spectrometer and installed to D1 experimental area.

2. Kalliope detector system

In Fig.1, we show one unit of Kalliope detector. It is composed of three blocks: the detector block, the analogue board and the digital board. Current design of the detector block is a plastic scintillator of 10×10×12 mm cube which has a wave-length shifting (WLS) fiber of diameter 1 mm running through. At the end of the WLS fiber, a m-APD (Multi-Pixel Photon Counter (MPPC) by Hamamatsu Photonics Co. Ltd.) is equipped to detect the scintillating light. The structure is shown in Fig.2. Signals from the two cubic scintillators aligned in series are taken coincidence, in order to identify positron/electron signals from the thermal noises. The m-APD has major advantages of lower cost ($\sim$ 10 dollars/channel) and higher tolerance to the magnetic fields ($\sim$Tesla) over usual PMTs.

What distinguishes Kalliope detector system most from other APD-based positron counters is that the electronics (the discriminator, TDC and memory) are built in as the front-end circuit. The analogue board is equipped with two of 16-channel preamplifier and comparator circuits in ASIC (gold chip in Fig.1). The diagram of the VOLUME2012 ASIC [3], which is currently employed, is shown in Fig.3. It has two voltage amplifiers, each with $\times$10 gain in series, equipped with the selection switch (SW) which may bypass the second amplifier. Each amplifier is equipped with a 4-bit digital to analog converter (DAC4N in Fig.3) which controls the offset level of the amplifier to adjust the pulse shape and the response speed. After the second amplifier, a comparator is installed which outputs a digital pulse if the analog input exceeds the preset threshold level determined by a pair of DACs (ThDAC: denoted as DAC4-1 and -2 in Fig.3) and the external voltage level (vref) adjusted by a variable resister (blue box in Fig.1).

The bias voltage applied to the m-APD, which determines the detector gain, may be finely controlled by another DAC installed at the input line of the first amplifier. This BiasDAC supplies a DC current going through the termination register outside of ASIC to give a DC voltage offset from the ground level. The termination impedance is composed of a 10 kΩ register in parallel with 0.1 μF +100 Ω in series, so that the fast signal sees 100Ω, whereas DC current sees 10 kΩ as the termination.

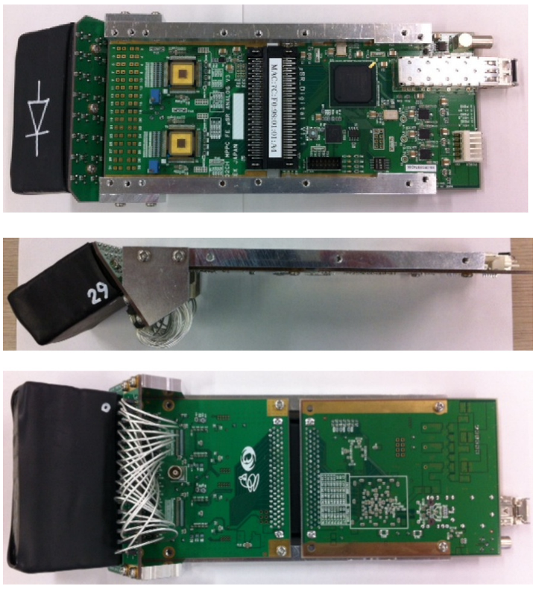

Figure 1. One unit of Kalliope detector.

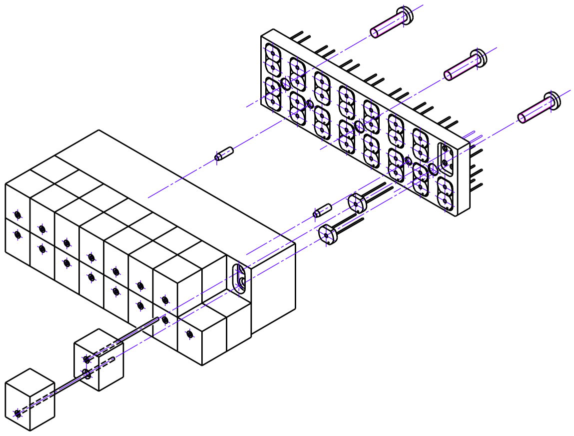

Figure 2. Structure of the detector block which appears as the black one in Fig.1. Plastic scintillators (cubes) and wave-length shifting fiber (rods) are painted by white reflective paint for light shield.

Each channel of the ASIC has a 20 bit digital control, which consists of one BiasDAC(4bit), two AmpDACs(4bit×2), one ThDAC(4bit) and four control bits. The last control bits are On/Off switchs of BiasDAC, 2nd stage amplifier, analog output and digital output. The digital control must be supplied in pulse series before the usage of ASIC.

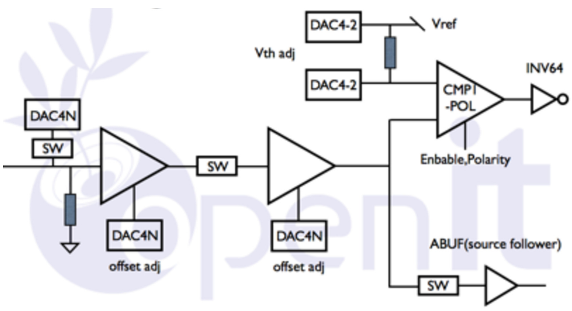

Figure 3. Diagram of VOLUME2012 ASIC used in analog-board of Kalliope.

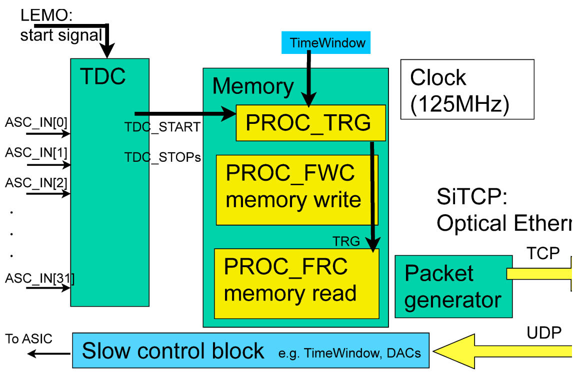

Figure 4. Diagram of digital signal processing in FPGA of digital-board of Kalliope system.

The digital outputs as well as the serial control of the ASIC is connected to the digital board of Kalliope system. The main component of the digital board is the FPGA which is the largest black chip in Fig.1. It is a programable digital chip with a pre-compiled firmware downloaded via a special cable prior to the usage. The current logic diagram running on FPGA is schematically shown in Fig.4. The time-to-digital converter (TDC) counts up the four of 250 MHz clocks which are phase shifted by 90°, and whenever the positron/electron pulse comes to the ASC_IN, which is 32 channel in parallel, the timing is recorded into the memory. The timing of the LEMO input (start) signal is independently recorded and the time difference between the start and the multiple stops are calculated with the timing resolution of 1ns. There is a preset time window of measurement (default 64 μs) which may be changed from the data acquisition (DAQ) PC, if necessary. When the time reaches after the start signal to this time-window, the stored hit events are read from the memory, formed into a series of ethernet packets and sent to DAQ-PC using SiTCP protocol [4]. The ethernet cables from each Kalliope units are combined in a commercially available ethernet hub and data are transferred to the DAQ-PC. Since the electronics are built in, Kalliope unit has only three wires connected: one optical ethernet fiber, a NIM trigger cable and a power-supply cable. Compared to the traditional PMT-based system, the reduction in the number of the cables is a great advantage of Kalliope.

3. New spectrometer at D1 experimental area

Employing 40 units of Kalliope detectors installed to a 0.4 T magnet, we have manufactured a 1280 channel (640 telescope pairs) spectrometer. The spectrometer is installed at D1 experimental area of Material and Life science experimental Facility (MLF) as shown in Fig.5. Detailed arrangements of Kalliope units inside the magnet is shown in Fig. 6.

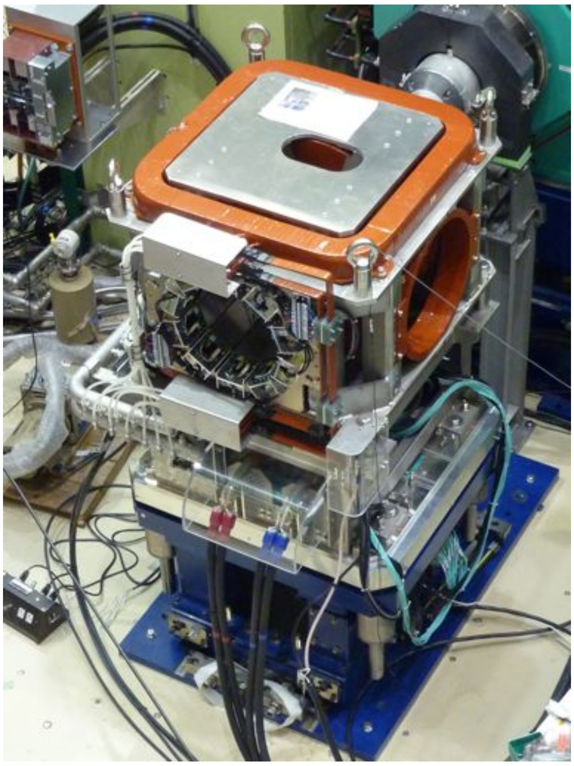

Figure 5. Full view of the new D1 spectrometer at J-PARC.

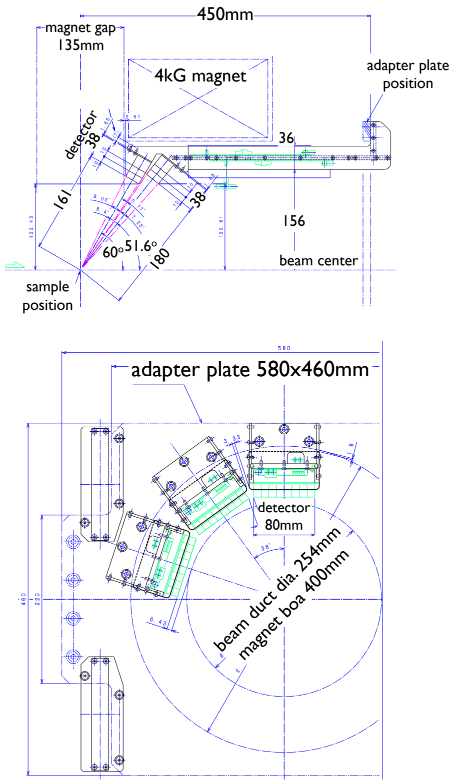

Figure 6. Diagram of the side and the tail view of the new D1 spectrometer.

The ethernet hub, the NIM start-pulse distributor as well as the power supply for Kalliope detectors are placed underneath the magnet, so that cables are confined within the spectrometer. Connections to the spectrometer are only the two cooling water lines, power cables for the 0.4 T magnet, one NIM trigger source line, one optical ethernet fiber from DAQ-PC and three 100 V power supply cables. The minimized number of the connection lines makes this spectrometer portable.

We start a commissioning of the new spectrometer on February 18th 2014. The procedure of the commissioning is (1) determination of the approprqiate bias voltage (HV) for m-APD, threshold DAC (ThDAC) and amplifier DAC (AmpDAC) of ASIC for the best performance in (2) characterization of the μSR spectra such as the full asymmetry and the spectrum distortion. The m-APD are provided with a list of minimum operation voltages which distributes within 0.2 V in our spectrometer (66.6-66.8 V). In order to perform (1), we have developed a computer program to scan the DAC values and take counts for a preset number of accelerator pulses. In Fig.7, we show an example of the efficiency curve, the signal count for the threshold DAC (ThDAC) scan. We choose the appropriate ThDAC as a few steps higher than the peak position which corresponds to the noise level.

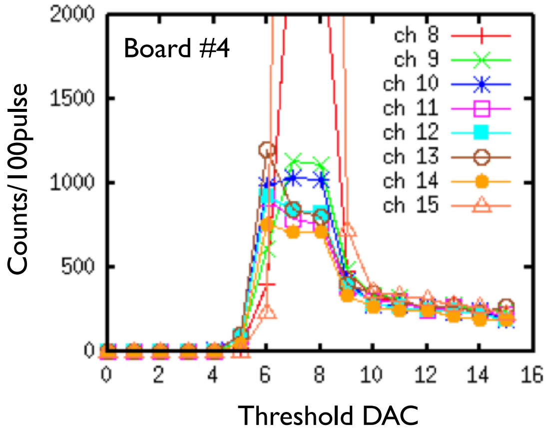

Figure 7. An example of efficiency curve, which is a count of each counters for a preset number of accelerator pulses. The condition of measurement is HV=67.92V (over-voltage of +1.1-1.3V), AmpDAC=3B. BiasDAC is not used.

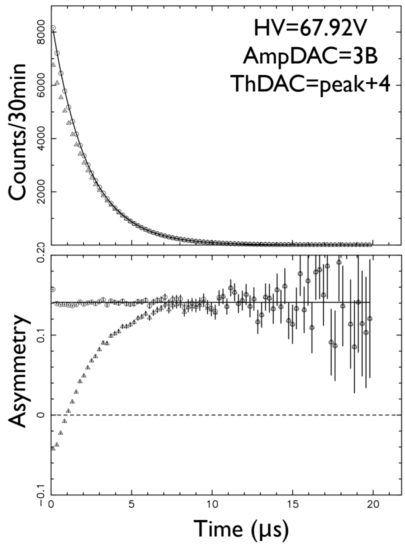

Figure 8. μe-decay spectrum (top panel) and asymmetry (bottom panel) of up-stream counter. Symbols are for before (triangle) and after (circle) the pile-up correction.

After determination of ThDAC for a set of a selective combinations of AmpDACs, we take the time spectrum of μe decay (Fig.8) and tried to find the appropriate combination of DACs and HV to give the minimum distortion. Since we receive 660k positron single hits integrated for 120 accelerator pulses, each counter receives $\sim$4 positron events (660k/120/1280=4.29) per pulse in the average. This high rate of decay positron signals result to a pile-up loss of counts in early times. We employ a theory of pile-up correction [5], and found that the simple non-extended correction scheme (eq.(2) of Ref. [5]) is practically enough to restore the μe-decay with the detector deadtime τ as an adjustable parameter. The characteristic detector deadtime is estimated to be $\tau \sim$100 ns for single counters. We phenomenologically uses the same pile-up correction scheme for coincidenced counts which results to a longer deadtime of $\tau \sim$300 ns; this is because the registered coincidence counts is reduced to $\sim$1/3 of the single counts, whereas the countloss occurs in accordance to the single hit rate. The deadtime could be improved eventually in electronics, because the recovery tail of the m-APD signal is typically $\sim$40 ns.

In table 1, we compare specification of existing spectrometers in pulsed muon facilities. The new spectrometer has a similar solid angle and longitudinal-field capability with Argus at RIKEN-RAL, but the count rate is more than 4 times higher, thanks to the high muon intensity of J-PARC MUSE.

Table 1. Specifications of general-purpose spectrometers in pulsed-muon facilities.

Spec.	$D\Omega$-1 (J-PARC)	New D1 (J-PARC)	Argus (RIKEN-RAL)
maximum longitudinal field (T)	0.15	0.4	0.4
solid angle (%)	8	23	25
counter channels (pair)	256 (128pair)	1280 (640pair)	192
data acquisition rate (Mhits/hour)*	40	180	~40

* Coincidenced counts of pair counters (if applicable) for 20x20 mm sample, double pulse.

In Fig.9, we show forward-backward asymmetry of a standard sample (silver), after adjusting HV, DACs and deadtime parameters in the new D1 spectrometer. The Full asymmetry ~0.16 is significantly smaller than that of other general-purpose μSR spectrometers (0.2-0.25), because the positron counters are placed in high-angle (51-60°: see Fig.6) relative to the beam axis, in order to maximizing the detector solid angle while accommodating various kinds of inserts. Since the muon beam intensity is high enough at MUSE, we plan to re-position the positron counters to gain a higher asymmetry.

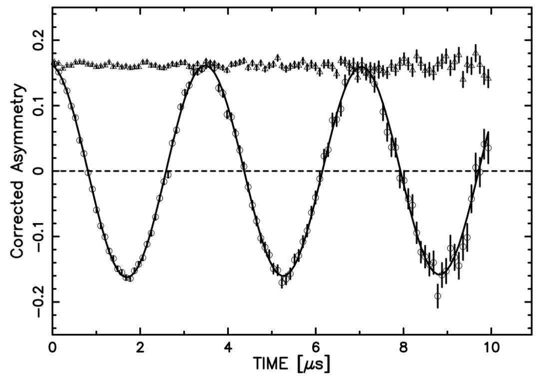

Figure 9. Forward-backward asymmetry of silver 20×20 mm sample in transverse-field of 2 mT and longitudinal-field of 10 mT. The data were taken in 10 minutes with kicker sliced single pulse operation.

4. Summary

We have developed a new positron detector called Kalliope, built and installed a general purpose μSR spectrometer at D1 experimental area of J-PARC MUSE. The spectrometer has been employed for user programs of MUSE since February of 2014. The data acquisition rate of the new spectrometer is 4 times higher than that of $D\Omega$-1 spectrometer of J-PARC and/or Argus spectrometer of RIKEN-RAL.

References

[1] Kadono R and Miyake Y 2012 *Rep. Prog. Phys.* **75** 026302
[2] Tanaka H K M *et al.* 2005 *Nucl. Inst. Meth. A* **554** 201
[3] Tanaka M *et al.* 2014 *preprint*
[4] Uchida T 2008 *IEEE Trans. on Nucl. Sci.* **55** 1631
[5] Ida T and Iwata Y 2005 *J. Appl. Cryst.* **38** 426