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Optimising a muon spectrometer for measurements at the ISIS pulsed muon source

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ABSTRACT

This work describes the development of a state-of-the-art muon spectrometer for the ISIS pulsed muon source. Conceived as a major upgrade of the highly successful EMU instrument, emphasis has been placed on making effective use of the enhanced flux now available at the ISIS source. This has been achieved both through the development of a highly segmented detector array and enhanced data acquisition electronics. The pulsed nature of the ISIS beam is particularly suited to the development of novel experiments involving external stimuli, and therefore the ability to sequence external equipment has been added to the acquisition system. Finally, the opportunity has also been taken to improve both the magnetic field and temperature range provided by the spectrometer, to better equip the instrument for running the future ISIS user programme.

1. Introduction

The muon spin relaxation (μSR) technique involves the implantation of intrinsically 100% spin polarised positively charged muons (μ^+) to probe condensed matter systems. Owing to its spin ($I=1/2$), the muon couples to and provides information about the local magnetic environment, while the mass ($m_\mu \approx m_p/9$) enables the muon to mimic a very light hydrogen isotope. In certain materials muonium may be formed as a tightly bound μ^+e^- species (analogous to the hydrogen atom) to provide a powerful chemical probe. These unique properties have led to numerous and diverse applications of the μSR technique [1–3] including the study of magnetism and associated spin dynamics, superconductivity, the hydrogen environment and diffusion, and the chemistry associated with radical states. The scope of the technique, however, presents a challenge to the facility scientist, who is required to develop instrumentation that is capable of satisfying the often contradictory demands of these various user communities studying all three phases of matter. For example, the spectrometer is expected to be easily configurable to run from 20 mK to 1400 K, and then within a few hours be adapted to run a gas cell with a triggered radio frequency (RF) excitation.

The EMU μSR spectrometer was commissioned in 1993 as part of a major upgrade of the European Muon Facility to deliver single muon pulses simultaneously to three experimental areas [4] through the use of a fast electric field (EF) kicker. At ISIS, beams of ~ 4 MeV/c surface muons are produced in ~ 80 ns full width half maximum (FWHM) pulses with a repetition rate of 40 Hz, with each muon pulse defined as one ISIS frame. Thus, muons are produced every 20 ms (excepting one pulse in five, where the proton beam is diverted to the ISIS second target station) with data acquisition continuing for 32 μs following the muon arrival. Muons are guided to the spectrometer by a series of dipole and quadrupole magnets, forming an uncollimated muon spot of $\sim 25 \times 10$ mm^2 at the sample position. Muons have a lifetime of ~ 2.2 μs and are typically detected by measurement of their decay products. The instrument detector array consists of rings of symmetric scintillation counters positioned upstream (forward) and downstream (backward) relative to the sample position to follow the time evolution of the decay positron distribution. The original EMU array was segmented into 32 elements to permit measurement without distortion caused by the high instantaneous rates that are inherent to a pulsed source following muon implantation. The number of elements chosen was well matched to then typical ISIS beam currents, with each muon pulse containing ~ 300 muons, corresponding to an average of less than five hits per ISIS frame per detector over the entire array. Finally, the solid angle of the array was designed to compensate for the 50% reduction in muon flux arising from the spatial splitting of the beam by the kicker. The instrument incorporated a vacuum

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chamber to minimise the number of beam windows and the associated scatter when using a cryogenic sample environment, while enabling the use of suspended samples for small sample measurements [5,6]. Resistive coils provided 0.4 T and 0.01 T fields parallel and perpendicular to the incident muon beam respectively, while three orthogonal low field ($\sim$0.2 mT) air-cooled coil pairs were incorporated to enable environmental fields to be nulled to create a true zero field condition at the sample position.

The spectrometer operated as part of the muon facility at ISIS for about 17 years or approximately 3000 beam days, delivering over 600 separate user experiments over its lifetime. Over this period, however, both the development of the ISIS source and an increase in the thickness of the muon production target combined to increase muon production by a factor of approximately six. To make effective use of this enhanced flux the design of both the detector array and the counting electronics needed to be reconsidered, with this providing a valuable opportunity to revisit other aspects of the instrument performance. Recently there has been a significant growth in the number of groups seeking to carry out experiments that involve external stimuli and exploit the pulsed nature of the ISIS beam. In this type of experiment excitations of either the muon or the sample, depending on the specific measurement, are synchronised with muon implantation. This includes the development of RF and EF techniques, together with novel applications of pump–probe laser excitation. To facilitate this work, the opportunity was taken to provide the acquisition system with a flexible method of sequencing the switching of multiple pieces of external equipment, collecting data for each separate experimental state.

2. Designing a state-of-the-art spectrometer

2.1. Instrument detector array

A number of factors needed to be considered when designing the array for the upgraded instrument:

(i) Increased detector segmentation is clearly essential for measuring high data rates without the distortion associated with signal pile-up (when one or more positrons strike the same scintillating element within the deadtime of the first). However, increasing the number of scintillation counters carries both a financial and engineering cost, with the latter relating to the difficulty of mounting multiple photomultiplier tubes and light guides and the problem of the scintillator wrapping reducing the available active area. While the application of a multichannel detector [7] or the development of a Geiger-mode avalanche photodiode based detector array [8] may eventually overcome these difficulties, it was preferred that the new array be based on established technologies to facilitate rapid development. The final segmentation for the detector array was derived by considering the typical sample size ($\sim$24 mm diameter) and the appropriate setting of the collimator slits incorporated in the beamline ($\sim$15 mm), chosen to avoid an excessive signal from around the sample. From a calibration of beam intensity, for efficient use of available beam it was concluded that an array capable of handling data rates of up to $\sim$500 detected events per ISIS frame was required. With a typical deadtime for each segment of $\sim$10 ns, an average detection rate of less than five hits per ISIS frame per detector element was required to avoid measurable distortion for typical run statistics, and therefore a detector segmentation of $\sim$100 elements was appropriate for the design. In fact, a configuration using 96 elements was selected after considering engineering constraints, with novel data acquisition electronics being developed to permit higher counting rates through effective deadtime correction.

(ii) While there was a desire to maximise the solid angle coverage of the new detector array, its design was constrained by the overall configuration of the instrument including the beam path and the need to ensure enough space was left to mount the sample environment in the spectrometer (Fig. 1a). In practice the solid angle coverage for the new detector array is similar to that used on the original instrument ($\sim 2.2\pi$ sr).

(iii) A growing number of experiments measure small samples (<10 mm diameter) where the signal from around the sample would dominate given conventional mounting on a large silver plate. To overcome this problem the technique of suspending the sample in the beam is typically employed [6], where muons not implanted in the sample continue in an evacuated flight tube and are removed from the sample position and no longer contribute to the measured signal. Unfortunately, because data rates from the sample are low, the signals measured using this technique are particularly susceptible to distortion from counts originating outside the sample. The origin of these stray counts is currently unknown, although previous work [6] suggests they originate from muons scattered by the beamline window into the walls of the cryostat and instrument vacuum vessel. To minimise their effect on the data both the forward and backward detector banks were subdivided into three stepped rings, each ring containing 16 scintillating elements. The total solid angle of the new detector array is identical to the old array; however, the addition of a third ring offers greater flexibility for removing contaminated detectors from the data analysis while maintaining the maximum possible count rate. A cross-section through the array showing the general arrangement of the scintillating elements is shown in Fig. 1b. During tests, this geometry appeared to maximise the possible data rates as two of the three rings were generally found to be completely unaffected by distortion in the data – presumably the individual rings make a different solid angle to the source of the stray counts. The design therefore gives great flexibility for selecting detector rings to provide clean data during analysis.

(iv) Robust construction of the detector elements was essential, and to this end comparatively short light guides ($\sim$1 m) were designed with the corresponding stepped elements formed into a single unit by encapsulating the guides in resin. The final units, shown in Fig. 1c, could then be easily located on the spectrometer to build up the full detector array. Magnetic field tolerant photomultiplier tubes (PMT) made by Hamamatsu [9] (R5505, running with positive polarity) were used owing to their proximity to the centre of the 0.5 T magnet. The tubes were mounted unscreened with their axes approximately perpendicular to the 0.05 T stray field. In this configuration, measurements of the PMT pulse amplitudes confirmed their gain was invariant with magnetic field, essential to avoid artefacts occurring in the data during magnetic field sweeps.

2.2. Data acquisition elements

Analogue signals from the photomultiplier tubes are conditioned using CAEN [10] V895B leading edge discriminator modules, the units have been modified by the manufacturer for improved input frequency (250 MHz) and pulse pair resolution (4 ns). PMT voltages were optimised with reference to the pulse height spectrum, and set such that a discriminator threshold value of 75 mV clearly separated the signal peak associated with