Developments at the ISIS muon source and the concomitant benefit to the user community

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Abstract. For the last 27 years, muon experiments at ISIS have been making a significant contribution to a number of scientific fields. However, as a community of researchers, we are always aiming to improve and extend the instruments’ capabilities. In this paper we will review the current significant developments at the ISIS muon facility, namely the primary beamline upgrade, proton pulse compression and the MANTID muon analysis package.

1. Introduction
The ISIS Muon Facility has been operating a science program for the past 27 years which has resulted in a significant contribution to a number of scientific fields. Over this time, the facility has been developed, upgraded and enhanced from one beamline to three and a new facility, namely RIKEN-RAL. Recently the ISIS muon facility has undergone significant instrument upgrades: the new instrument HiFi [1] and the new EMu spectrometer [2] and now the installation of an high-power laser on HiFi [3]. Along with instrument upgrades, smaller developments with data acquisition electronics have enabled data rates in excess of 120 Mev/h. In this paper we describe the latest developments and the benefits to the user community.

2. Primary Beamline Upgrade
2.1. Current Beamline
The ISIS muon beamline was constructed in the mid-1980s and first muons were delivered on 23rd March 1987 [4, 5] into the original MuSR area. Later, with EU funding, the beamline was split into three independent instruments: DEVa (subsequently replaced by HiFi), EMu and MuSR (see Fig. 1a) [6]. The beamline was constructed using components from previous accelerators and experiments of various types which might not have been optimal. Next to the muon target there are two quadrupoles which focus the beam into two bending magnets with a quadrupole triplet and momentum slits between them. After this there is a separator and two more quadrupole doublets. Finally, this leads into the electrostatic kicker which ‘kicks’ the first of two closely spaced pulses from the accelerator into the two side instruments (EMU and HiFi via a septum and three more quadrupoles) and the second goes through into MuSR.
2.2. Possible Beamline Configurations

The primary beamline has remained largely untouched and is starting to show signs of ageing. Given the age and location of these components, we started a project to upgrade the primary beamline with purpose-designed components, with a planned phased installation between 2014 and 2016. This new beamline has to fit into the existing space and deliver muons to the present instrument locations. The current design was simulated using TRANSPORT [7] and TURTLE [8]. These results (see Fig. 2a) reproduce those reported by Eaton et al [6] and the observed performance of the current suite of instruments. Therefore, we explored the following options: 1) Keeping same optics but with standard types of quadrupoles and 2) upgrade to use quadrupole triplets instead of doublets.

Now considering option 1) the standard quadrupoles proposed are the M9 type as on MuSR and larger, radiation-hard, quadrupoles used for Q1 and Q2 (the first two quadrupoles of the primary beamline), and also for Q4 where the beam envelope is larger. The opportunity has been taken to have Q1 and Q2 centred nearer the muon target in order to increase the acceptance angle, since they will be shorter than the current ones. This setup gives a slightly lower flux for the same spot sizes. The second option is to use quadrupole triplets everywhere, which gives a more circular beam envelope. Here we could replace Q1 and Q2 with a triplet of radiation-hard quadrupoles (see Fig. 2b). Similarly the Q6-Q7 and Q8-Q9 groups become triplets of M9s. The beam still has to be focused through the kicker and septum magnet apertures. Triplets at the end of each beamline give some opportunity to vary spot height versus width while keeping a focus.
Figure 2. The upper graph (a) gives the TRANSPORT envelope for the current ISIS beamline and the lower graph (b) gives the TRANSPORT envelope for the new beamline. The red blocks represent quadrupoles and blue blocks bending magnets. Their positions represent the aperture. The black lines through the figure are the beam envelope for vertical (upper half) and horizontal (lower half).

at the sample, and adjusting the X collimation slits, in front of the final focusing components, will allow both the spot height and width to be tailored to suit an experiment.

2.3. Instrument Performance
The triplet configuration gives an increase in acceptance to the sample position. Therefore, we simulated the instrumental performance by considering the spot size and rate using TURTLE. The simulations used a standard flux of muons from the target and gives a relative performance for each design, not absolute figures (which depend on target thickness and ISIS beam current). The plot (see Fig. 3) shows spot size (rms radius) and rate at the MuSR instrument, with slit setting as an implicit parameter. The minimum spot size achievable is similar for both designs.
A rate increase around a factor of 2 should be obtained by going to a triplet-based beamline. Therefore, the triplet based design has been chosen for installation (see Fig. 1b).

3. Proton Pulse Compression

The ISIS muon facility is a pulsed source and operates with a repetition rate of 40 frames per second, with each frame containing two proton pulses with a width of \(\approx 60\) ns (FWHM) each, separated by 330 ns. The frequency response of the muon instruments at ISIS is determined, primarily, by the width of the proton pulse, but also by the pion decay process. One method of improving the frequency limit, currently around 10 MHz, is to shorten the extracted proton pulse length. An experimental trial to compress the proton pulse was carried out at ISIS and its effect on the muon instruments frequency response measured.

Pulse compression, shortening the length of an accelerated particle beam, has become a common technique in accelerator physics. Several methods can be used, but many involve variation of the synchrotron RF cavity parameters [9] to induce a rotation in the longitudinal phase space. The technique used in this experiment involved an adiabatic reduction of the cavity voltages over 2.75 ms to increase the bunch length whilst also reducing the spread of particle momenta. These voltages were then abruptly increased over 0.25 ms to induce rotation in phase space where the reduction in particle momenta rotated to deliver a shorter bunch length. The bunch was then extracted from the synchrotron at its shortest length and transported toward the targets. As seen in figure 4 the bunch length was visibly reduced by an average of 20.75 %
The left graph gives pulse charge density in time and the right graph gives the frequency response of the MuSR instrument. The frequency response was determined by measuring the asymmetry of the transverse field precession of a Ag sample at room temperature. (FWHM) from 58.8 ns to 45.8 ns. The frequency response of the MuSR spectrometer was measured with and without pulse compression (see Fig. 4). From these results it is clear that the measurable frequency response for MuSR was increased by 20-25 % with the shorter pulse. Future studies are planned to reduce the bunch length further including making full use of the ISIS second harmonic RF system.

4. MANTID Analysis Software
The MANTID project provides a framework that supports high-performance computing and visualisation of scientific data[10, 11]. MANTID has been created to manipulate and analyse neutron scattering and muon spectroscopy data, but could easily be applied to many other techniques. This framework is open source and supported on multiple target platforms (Windows, Linux and Mac). The development of codes running under the MANTID framework for the analysis of muon data continues. An interface focused on time domain analysis is now included as part of the MANTID distribution, is available on all the ISIS instruments and was successfully used on the recent muon training school. Currently, in the time domain analysis, the spectra can be reduced, fitted (with any model the user cares to fit) and the results from the fits easily obtained, along with the relevant logging information. Using this, models can be fitted to the results. Recently, Fourier/maximum entropy has been added for analysis of both transverse and longitudinal spectra. Developments are planned to augment the capabilities of this interface over the coming months, such as simultaneous fitting of multiple groups and runs with shared parameters. Improvements to simplify data analysis of Radio Frequency and Avoided Level Crossing experiments are to be included as part of the work of the Muon JRA, with existing algorithms being developed into a single interface guiding users through the process of reduction and analysis of these datasets. Moreover, developments with simulation codes are leading to greater exploitation of data. It seems clear that establishing links to codes modelling both sample phenomena and instrument characteristics should bring an additional degree of sophistication to the analysis and interpretation of muon data. This development will be fed into MANTID.
5. Conclusion
In conclusion, the primary beam upgrade, the proton pulse compression and the software development will clearly lead to an improvement to the muon facility at ISIS, enabling the next 27 years of muon production. For our user community, these developments will give improved data rates, increased frequency response and the software tools to exploit these enhancements.

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