Super-MuSR

The next generation of muon spectroscopy instrument with a transformational increase in counting rate and time resolution.

Estimated cost

Total of £5.93M including VAT, contingency and staff costs.

Summary of physical changes

The MuSR beamline will be extended by 6m to add a switchable electrostatic pulse slicer to increase the time resolution of the instrument (10x) and electromagnetic spin rotators to enable higher transverse field measurements (10x). A new highly segmented detector array will increase the counting rate (20x).

Science justification

Super-MuSR will provide significant increases in counting rate and time resolution. Figure 1 shows the current MuSR capability (black line) which is limited by both the detector array and the muon pulse width, and how the upgraded instrument (red, green, and blue lines) will enormously increase the capability of ISIS muon measurements across a wide range of science areas.

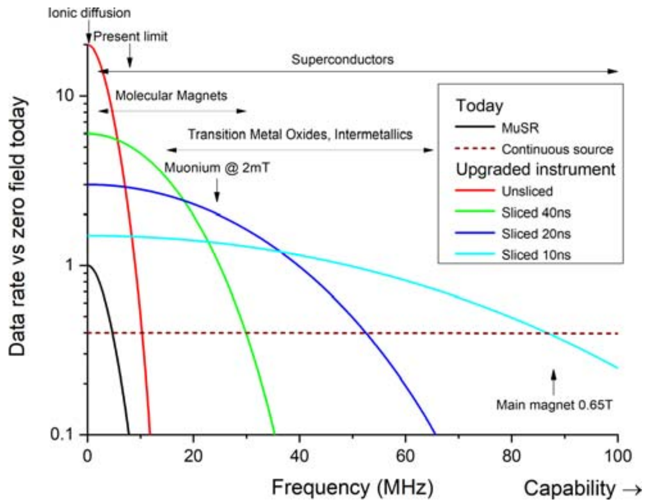

Figure 1: Performance of Super-MuSR compared to today's instrument. The x-axis describes the instrument's capability in frequency/magnetic field and the logarithmic y-axis describes the rate at which data of a given quality can be collected.

The red line shows the improved counting rate without pulse slicing. This significantly improves studies requiring high statistics or short collection times such as in-operando studies of battery materials, recently started within Faraday Institution projects; studies of quantum coherence in muon-fluorine bound states complemented by DFT+μ computational work (already supported by grants from EPSRC, Horizon 2020, and STFC); investigations of time-reversal symmetry breaking in exotic superconductors (where machine learning is now being applied to data interpretation); and probing the exotic states of frustrated magnets, which has previously led to many of MuSR's highest impact publications.

The blue and green lines show the increase in capability provided by the pulse slicer. The large superconductivity and magnetism user communities immediately benefit as the ISIS measurement range is extended to a far wider range of materials, with higher data rates than currently available elsewhere. Other areas that will be greatly improved will be studies of muonium states in semiconductors and molecular systems, where muonium is a lighter analogue of hydrogen, probing areas such as liquid crystal dynamics, the antioxidant capacity of vitamins, and developing fundamental understanding of reaction kinetics.

Spin rotation of muons in flight allows studies of superconductors over the full magnetic field range provided by the instrument magnet without beam deviation in a field perpendicular to the beam.

Business case

MuSR is consistently among the most requested ISIS instruments (>2.5x). Comparable continuous muon source instruments already providing increased time resolution (albeit at low data rate) are similarly over-subscribed (>2x). The increased capacity and capability of Super-MuSR improves the speed and quality of existing MuSR experiments, means experiments needing higher time resolution could be performed at ISIS with the benefit of longer measurement time windows, and studies needing both pulsed and continuous muon sources can be completed in a single measurement. The MuSR user base originally came from the condensed matter physics community in the UK and Europe, focussing on superconductivity and magnetism studies, but it has broadened to include solid state chemists and work on energy materials.

Over the range of fields needed for most studies of magnets and superconductors Super-MuSR will have greater performance than a continuous muon source. Super-MuSR's medium rate, medium resolution mode surpasses the capability of continuous muon sources for many experiments, while its high rate, low resolution mode surpasses the capability of other pulsed muon sources. Super-MuSR will be a unique instrument in the world and a benchmark for what can be achieved at future pulsed muon sources like those planned at CSNS, SNS, and Fermilab.

The counting rate improvement would provide a performance that far exceeds that of continuous muon sources and exceeds the highest performing instrument built at J-PARC.

Summary of current status

Summary from engineering on status of design, costing, and schedule:

The increased time resolution is provided by the pulse slicer, and the basic design is complete. Areas of uncertainty, such as the power supply design, have been de-risked by commissioning two separate feasibility studies, and initial reports suggest that the timing is achievable. Expected design, manufacture and testing time is around 2 years and a cost of £1 million.

Spin rotation of the muons will be delivered by two spin rotators, and similar designs are used in several other facilities. All basic design has been undertaken within ISIS, but PSI have been successfully approached with the possibility of collaboration to help accelerate the design. Expected design, manufacture and testing time is around 2 years and cost of £0.57million.

Simulation has shown that distortion-less measurement of the full muon flux requires a detector array segmented 20-fold more than the existing instrument. Mechanical design (ongoing) has confirmed that an array size of approximately 600 channels is optimum, which will meet the user requirement provided a factor of two count-rate improvement can be achieved per-channel. This enhancement can be realised with digital signal processing (DSP) methods. While digitiser technology is available commercially it will require significant development to interface with the current ISIS DAE systems and data processing.

The detector array itself will utilise silicon-PMs, a technology used on J-PARC and PSI muon instruments. The technical risk pertains to the development of the ‘front-end’ electronics, expected to take two years, with a further two years for manufacture, testing and delivery. The full cost of the detector array will be just below £1.9 million.

The total project time is 4 years for the full upgrade but a phased approach to delivery could be achieved to allow for the detectors to be developed fully with the shorter time frame items, the pulse slicer, spin rotators and new quadrupoles being installed earlier. The ISIS design section has a high confidence in designing and delivering Super-MuSR, as all the technology is used at existing facilities throughout the world, coupled with experience in successfully delivering similar projects and very experienced MuSR instrument scientists.