Muon Spectroscopy - JRA8

Technology Development for Muon Spectroscopy

Muon spectroscopy is a powerful way of studying atomic level properties of matter, often producing complementary results to neutron scattering. Europe is fortunate in having two muon sources, ISIS in the UK and PSI in Switzerland, which each provide different facilities for muon experiments. The aim of this JRA was to develop technologies and techniques which extend the range of capabilities of the muon method available to European users at these two facilities.

Results
The JRA was split into three primary work packages, and key results from each are listed.

WP1: Detector development
o New muon detector technology: avalanche photo-diodes (APDs) were tested and found to provide an excellent way of making a compact detector array for high-field muon spectrometers. They are field-resistant, and have very good (fast) timing characteristics.
o Application: A muon beam profile monitor suitable for use in high magnetic fields was built using APDs and used to characterise muon beam behaviour in applied fields.
o A demonstration detector for a muon spectrometer was successfully built and tested based on avalanche micro-channel photo-diodes.
o Application: This new detector technology will be used to refurbish the ALC spectrometer at PSI. This will be the first muon spectrometer in the world to use APDs as opposed to conventional photomultiplier tubes.

WP2: Instrument Simulation
o A package has been developed, based on the CERN GEANT4 libraries, to simulate muon spectrometers.
o The package includes modelling of the incoming muon beam, outgoing positrons, the effects of applied fields and variable detector geometry
o The package has been tested by comparison with existing instruments
o Application: For new high-field muon spectrometers being built at ISIS and PSI, the package has proved to be invaluable for designing the instrument geometries and detector arrays.

WP3: Advanced Techniques
o Apparatus for AC-susceptibility measurements simultaneous with muon measurements has been produced and used for user experiments.
o A variety of radio-frequency (RF) µSR techniques have been developed. These include generation of circularly polarised RF (Application: measurement of shallow donor muonium states in semiconductors) and multi-pulse stimulation (Application: studies of ionic conductors)
o A high-temperature (1500 K) furnace has been equipped for RF studies using small samples. RF measurements have been extended to liquid and gaseous samples.
o Microwave µSR has been demonstrated, extending the frequency range of stimulation into the GHz region.

Partners, meetings and publications
The JRA has involved four partners: ISIS and PSI muon sources, the University of Oxford and the University of Parma. In addition to formal collaboration meetings which have occurred throughout the project, partners have had a large number of informal contacts and have worked together regularly on JRA topics. The JRA has resulted in nine publications in peer-reviewed journals, as well as a variety of technical reports.

Detectors - Work Package 1

Aims

This work package deals with the development of new detectors for µSR spectrometers. In particular:

1. Development of position-sensitive detectors and electronics readout based on

   new solid state and integrated technologies;

2. Fast timing detector system for high magnetic field and RF spectrometers;
3. Exploration of analogue detection techniques.

a. Position-sensitive detectors

A general characteristic of μSR spectrometers is the use of scintillators, light guides and photomultipliers to detect the incoming fast muons and the decay positrons. These types of detectors are found in every facility independent of whether they provide continuous or pulsed beams. These detectors are efficient, reliable, inexpensive and flexible. However, one major drawback is that they do not provide any information about the position of the muon impinging on the sample and/or the positron originating from the stopped muon. The work-package will provide position-sensitive detectors based on silicon strips or sensing pixels combined with integrated electronics such as those employed in state-of-the-art particle physics experiments, where they are successfully used to reconstruct vertices with ~ 50 μm resolution.

Position-sensitive detectors will allow coverage of a large solid angle in constrained environments (e.g. in high magnetic field spectrometers, combined with fast timing detectors – see point b. – or spectrometers for thin film studies) and reduction of background or measuring time, particularly for sophisticated samples, which are available only in small quantities or with small cross section.

b. Fast-timing detectors

The continuous muon beam at PSI offers the unique possibility of experiments with very high time resolution and thus the detection of very fast processes. In order to measure the resulting muon precession frequencies in the GHz range, the development of novel detector systems with a time resolution of less than 300 ps is required. This value is significantly better than that achievable with the current standard μSR spectrometer technology which is based on plastic scintillators connected to photomultiplier tubes (PMTs) via long light guides. The development of new multi-segment detectors based on Avalanche Photodiodes (APDs) or Silicon Photomultipliers (Si-PMs) is aimed at providing a spectrometer with the detectors located very close to the sample, within the cryostat. Accurate tests of APD and Si-PM characteristics (in particular amplification and time resolution) when used in high magnetic fields and at very low temperatures, will be performed to identify the most suitable technologies.

Such fast-timing detector technology would also have benefits for RF-μSR experiments at a pulsed source such as ISIS, where, for some samples, the pulsed source frequency limits can be overcome using RF techniques.

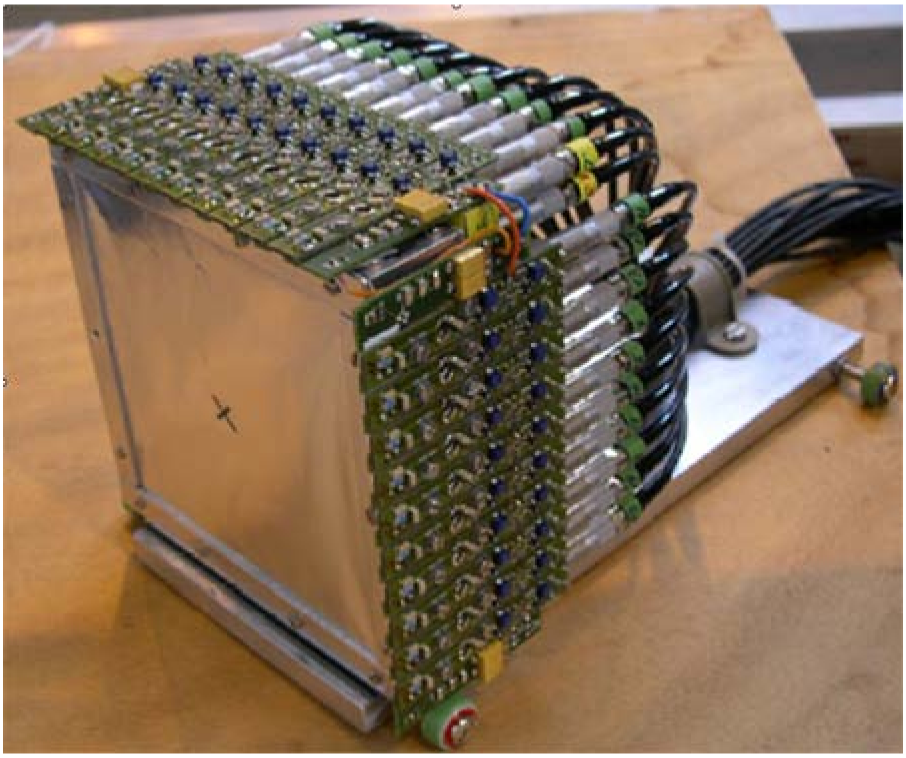
c. Analogue detection

The advantages of other detection schemes, such as analogue detection, will also be explored for high-field, high-rate muon spectroscopy.

Results

o New muon detector technology: avalanche photo-diodes (APDs) were tested and found to provide an excellent way of making a compact detector array for high-field muon spectrometers. They are field-resistant, and have very good (fast) timing characteristics.

o Application: A muon beam profile monitor suitable for use in high magnetic fields was built using APDs and used to characterise muon beam behaviour in applied fields.



Instrument Simulation - Work Package 2

Aims

There is a growing need to understand the detailed operation of muon instruments since experiments are increasingly requiring more complex sample environments, putting greater demand on the performance of individual spectrometers.

In particular, both muon facilities are engaged in designing new spectrometers which will be equipped with higher magnetic fields. However, high fields introduce complications in the operation of the instruments that need to be fully understood. In this Work Package of the muon JRA, we plan to attack this problem by developing a suite of simulation tools which will equip the facilities for the next phase of instrument development. Complete instrument simulation that will:

1. Allow a fuller of understanding of the operation of the current spectrometers; and

2. Provide a resource for spectrometer design that will be invaluable for the development

of all types of muon spectrometers, including those equipped to provide high fields.

There are various key steps in the work plan:

1. Identification of the methodology to be used, including evaluation of existing software for both beam transport and spectrometer simulation and identification of areas where specific coding will be required.

2. Initial modelling of muon and positron tracks. The magnetic field that is applied to the sample also focuses the incoming muon beam, so the fraction of the sample which is “illuminated” by muons is a function of magnetic field. A key problem to solve (work performed in close collaboration with WP1) is the injection of a surface muon beam into a 10-15 T solenoid. This strongly impacts on the design of the magnet, the size of the beam spot, and the design of detectors; this part of WP2 will be closely connected to WP1 (detectors).

3. Once these elements are in place, the aim is to move towards a full instrument design and simulation. This will include the ability to model a general µSR spectrometer, including the effects on decay positrons of degraders, sample environment equipment, etc. Specifically, part of this goal is the design of sample environment equipment suitable for use in high fields and low temperatures.

The method which will be employed is a combination of software developed "in-house" together with utilisation of existing routines and software utilities. The work is based in Oxford where feasibility tests have been performed, but will draw on the shared expertise which exists at ISIS and PSI.

Results

o A package has been developed, based on the CERN GEANT4 libraries, to simulate muon spectrometers.

o The package includes modelling of the incoming muon beam, outgoing positrons, the effects of applied fields and variable detector geometry.

o The package has been tested by comparison with existing instruments.

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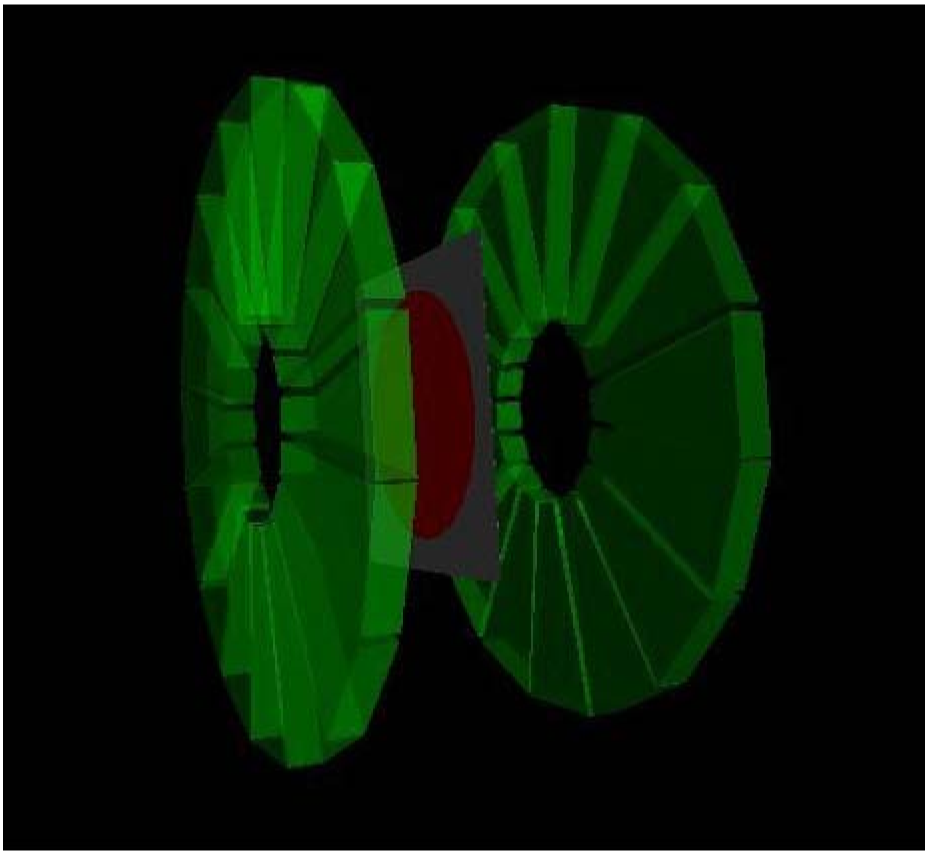
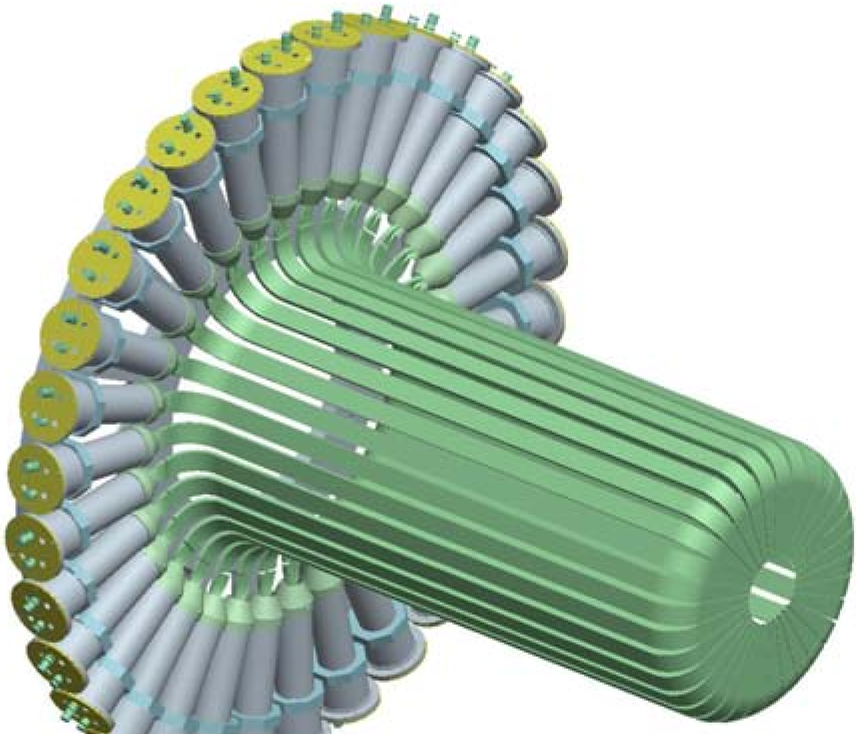




Advanced Techniques - Work Package 3

Aims

The basic muon method can be enhanced by application of external stimuli to either the implanted muons or sample atoms, and such experimental methods open up new science areas to the muon technique. These methods benefit from the synchronous application of the external stimulus with the arrival of muons in the sample, both to reduce sample heating effects and to allow dynamics studies by variation of the stimulation timing with respect to the muon pulse.

ISIS has an ongoing programme to develop the radio-frequency µSR technique; PSI also have requirements for pulsed environments in order to reduce sample heating, for example when currents are applied. This work package will provide for further development of pulsed environment methods, particularly RF-µSR, for example its extension into the microwave region, together with techniques such as acoustic muon spin resonance.

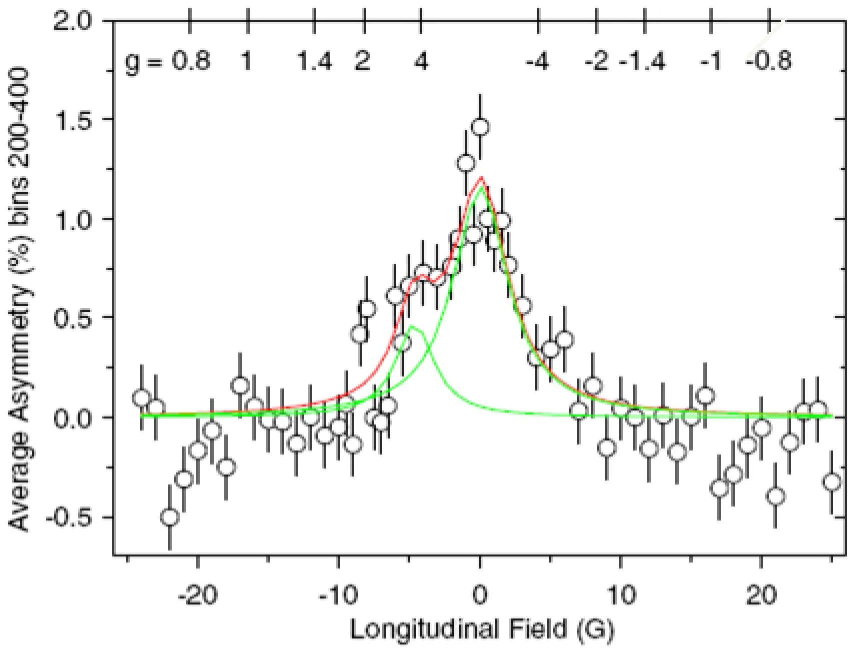
Results

o Apparatus for AC-susceptibility measurements simultaneous with muon measurements has been produced and used for user experiments.

o A variety of radio-frequency (RF) µSR techniques have been developed. These include generation of circularly polarised RF (Application: measurement of shallow donor muonium states in semiconductors) and multi-pulse stimulation (Application: studies of ionic conductors)

o A high-temperature (1500 K) furnace has been equipped for RF studies using small samples. RF measurements have been extended to liquid and gaseous samples.

o Microwave µSR has been demonstrated, extending the frequency range of stimulation into the GHz region.



Resonant repolarisation of the shallow donor muonium state in CdS. Circularly-polarised RF was required, produced from two RF coils working simultaneously:

Management, dissemination, collaboration with other JRAs

Work Package 4

Meetings of the WPs will take place every six months while JRA – Muons meetings will be convened once a year. In this occasion a yearly report will be produced. Summary reports, highlights and perspectives will be inserted into the JRA WEB-page.

Special meetings with other JRAs are envisaged around midterm to compare and exchange technical information regarding, in particular, detector and instrument simulation problem – for example, there will be interaction with JRA1 (DETNI) to look for possible synergies with Si detector development.