PAUL SCHERRER INSTITUT

Condensed Matter Research with Neutrons and Muons

High Magnetic Field μSR Instrument
Project Description

Motivation for a High Magnetic Field Instrument at the Swiss Muon Source

Positive muons are very sensitive probes which have a large variety of applications in condensed matter research and chemistry. With a magnetic moment larger than any nuclear moment, the muons are used to probe extremely small local magnetic fields, their spatial distribution, and their temporal fluctuations, in any form of matter. The positive muon carries an elementary electric charge and can therefore be considered as a light proton, which makes it particularly useful for studying electronic quantum effects in matter. All these studies are performed with the µSR (muon spin rotation/relaxation/resonance) technique which utilizes the parity-violating decay of muons from a highly spin-polarized beam.

The number and diversity of phenomena studied by µSR has seen a remarkable growth over the last two decades. In Europe, the perfect complementarity between the ISIS Pulsed Muon Facility (Rutherford Appleton Laboratory, UK) and the continuous muon beam at the Swiss Muon Source (SµS) at PSI ushered in a new era of growth in techniques and applications of µSR.

At present, the Laboratory for Muon Spin Spectroscopy (LMU) at PSI operates 5 spectrometers for bulk µSR studies, listed in Table 1.

	GPS	LTF	GPD	Dolly	ALC
H_{max}[T]	0.6	3	0.5	0.5	5 (LF)
T_{min}[K] T_{max}[K]	1.8 900	0.02 4.2	0.3 500	1.8 900	4.2 500
δt [FWHM, ps]	800	1000	800	800	- (TI)

Table 1: Characteristics of the present µSR spectrometers at the SµS. The presently highest available field (5 T) can be used in time-integral mode in longitudinal fields only.

At PSI, the µSR user community has established itself as one of the principal user communities. In 2005, about 80 research proposals of groups from PSI, Swiss universities, and from abroad are active, using roughly 50% of the total beam time allocated to approved experiments at the target M and E beam lines. About 240 scientists from institutions in 22 countries are involved in the µSR proposals.

In the period 1995-2005, more than 600 articles, based on µSR work performed at PSI, have been published in internationally recognized journals, of which 54 articles appeared in prestigious journals like Physical Review Letters, Science, Nature, and J. American Chemical Society.

Since the year 2002, SµS takes part in the Framework Programs of the European Commission (current activity area: Integrating activities combined with transnational access and research projects). Within this program, the LMU proposal has received 'top ranking' by the EC experts who recognized the unique position of SµS within the Condensed Matter and Chemistry Communities.
To maintain its leadership in the field and to closely follow the internal and external user demands, the LMU is permanently enhancing the level of its µSR Facilities. Two aspects can be considered:

- improvements of the muon beam lines.
- improvements and developments of the µSR instruments.

Concerning the developments of the µSR instruments, much effort has been put recently on technical aspects like the improvement of the signal/background ratio, improved electronics, automatisation and user-friendliness. To cope with the increasing demand of the users, the sample environment has recently been widely extended (see Table 1). In addition, high-pressure cells suitable for µSR experiments at GPD have been developed, so that external pressures up to 24'000 bar can be applied to the samples.

However, and partly due to the specificity of the μSR technique, the increasing demand on high magnetic fields (i.e., >> 1 Tesla), which has been observed among the μSR users at PSI, could not be fulfilled due to the lack of a dedicated facility. This fact has triggered the high-field μSR project at PSI.

A detailed scientific case (see High Magnetic Field μSR Instrument, PSI Bericht Nr. 05-11 (ISSN 1019-0643) summarizes the outcome of a workshop held in January 2002 with 50 participants from 15 countries. Taking into account technical restrictions and wishes expressed by the users led to the design specifications of the instrument shown in Table 2.

Maximum magnetic field	$H_{max} \approx$ 10 T (horizontal, parallel to muon beam)
Field homogeneity / stability	$\Delta H/H \leqslant$ 10 ppm (over sample volume 10×10×2 mm^3 for > 4hrs.)
Geometry	horizontal magnet, warm bore, minimised length
Bore diameter	$\approx$ 100 mm
Temperature range	first version with flow or bath cryostat (2 K), later option: DR
Time resolution	FWHM < 300 ps (transverse field, time differential mode)

Table 2: Design specifications for the PSI High Magnetic Field μSR Spectrometer.

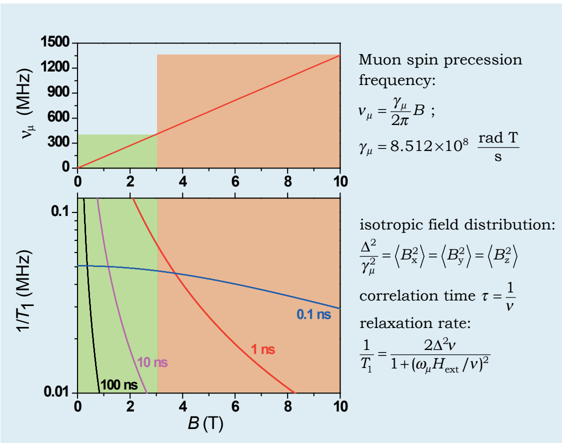

Figure 1: The orange shaded area visualizes the extension of the time window for muon spin precession in transverse fields (top) and observable correlation times τ (bottom), assuming an isotropic field distribution of 1.1 kG.

The extension of the available field range in line with improved time resolution will open the window for the observation of precession frequencies of 1.4 GHz and of correlation times of field fluctuations of less than 3 ns as illustrated in Figure 1.

Complementary to the project at the continuous muon beam at the SμS a high-magnetic field project at the ISIS pulsed muon source focuses on the application of longitudinal fields (where only moderate time resolution is required, due to the pulse width of the muon beam). But only continuous muon beams will allow to perform transverse field muon spin rotation experiments in high magnetic fields up to 10 T.

Technical Challenges

In order to fulfill the requirements for the desired time resolution a new detector system has to be developed. According to the simulations of the light output of the system, which have been performed in collaboration with the Joint Institute of Nuclear Research (JINR) in Dubna (Russia), it is essential to provide the highest quality of fast plastic scintillators and light guides. The small spiraling radius of the relativistic decay positrons (e.g., 1 cm for a 30 MeV positron in a field of 10 T) requires that the scintillators are placed close to the sample and cover the full solid angle. To enhance the time resolution the length of the light guides has to be minimized, which makes it necessary that the photon detectors are capable to operate in high magnetic fields. Recent progress in the development of avalanche photodiodes (APDs) make them the first choice, but new, fast multichannel electronics where the diodes are mounted on-board, and stable high-voltage power supplies have to be developed. As commmercially available APDs have several disadvantages (such as magnetic components or bulky housings) a collaboration between PSI and JINR aims towards the development of an advanced microchannel photodiode (sensitive to blue light) operating in Geiger mode with improved gain and time resolution. This task of developing fast-timing detectors for high magnetic field μSR is adressed in a work package within the Joint Research Activity of the Neutron and Muon Integrated Infrastructure Initiative under the European Framework Program 6 (FP6/NMI3-JRA8), joined by PSI, ISIS (UK), the University of Oxford (UK), and the University of Parma (Italy).

The even more challenging specifications of the magnet cannot be met by any commercially available system. A tolerable value of the homogeneity over the sample volume of 10 ppm will already lead to a Gaussian damping of 80 kHz at 10 T. The

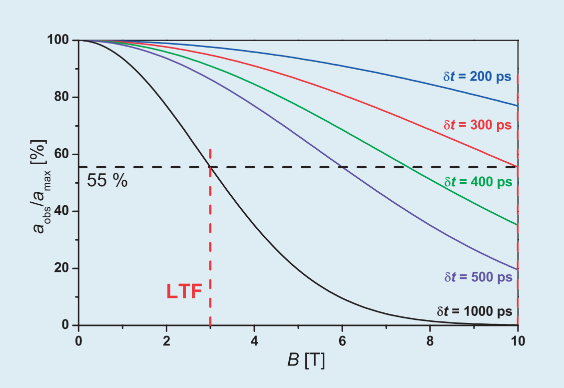

Figure 2: Field dependence of the fraction of observable asymmetry (calculated from E. Holzschuh , PRB 27 (1983) 102) for different time-resolutions of the detector system. At 10 T a time resolution of 300 ps (FWHM) is needed to obtain a suitable μSR signal.

distribution of the field integrals along the muon trajectories and the finite momentum bite of the muon beam will cause a loss of transverse spin polarization before the muons hit the sample. In order to decide on a suitable magnet design, GEANT4 simulations of the evolution of the muon spin polarization and of the measured asymmetry (with a certain detector geometry) are performed within a second work package of the NMI3-JRA.

Furthermore, a dedicated new surface muon beamline providing a highly parallel beam with small diameter and small momentum bite (≈1%) and 90° spin rotation (i.e., two consecutive spin rotator devices with high transmission) is necessary to ensure optimum performance of the new instrument.

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