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Concept Study of a Muon Micro-Beam

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The goal of the present study was to investigate the feasibility and the research potential of a so-called muon micro-beam. The overall motivation is the observed trend that sub-millimetric samples are increasingly used to reach a high level of metallurgical quality often necessary to study the interplay between different ground states as for example in strongly correlated electron systems. In this vein, micro-beams are mandatory as they can precisely control the dosage and the lateral position on a sample. Micro-beams of photons, electrons and protons are well established in various fields of science. For instance, instruments and techniques based on collimated beams of ionizing radiations play an important role in biology and medicine.

Since muons are obtained from the isotropic decay of pions, muon beams have much worse phase space properties as compared to electron and proton beams. Moreover intensities are also lower making the generation of a muon micro-beam far more challenging.

A muon microscope by re-accelerating ultra-slow muons previously generated by laser resonant ionization of thermal muonium in vacuum has been proposed at J-PARC and is under development since several years. Such a scheme needs intense R&D and relies on an efficient generation of thermal muons. Apart from the technical complexity, it has the drawback to generate muons with only 50% polarization, as the ultra-slow muons produced by such methods are only 50% spin polarized by the contribution of the triplet muonium. In addition, the use of UV lasers limits the possible use to pulsed muons facilities as J-PARC and ISIS.

In this study work, we investigated the possibility of generating a micro-beam by modifying an existing beam line of an intense surface muon beam of 100% polarized particles. Besides the polarization, the advantage of such a scheme is that it could be quickly implemented at an existing facility with modest financial investment.

Positive 100% polarized muons are very sensitive microprobes of matter. As such they find use in various fields ranging from condensed matter physics, material science, soft matter and chemistry with some applications in biology as well. The method of study is called μSR (muon spin rotation/relaxation/resonance)[1].

Energy of the muon beam and size of the beam spot define the typical size and thickness of a sample. Whereas a large variety of muon beam energy is available, their beam spot dimension is to date rather limited and large. Presently, typical beam sizes range between 20 mm^2 and 300 mm^2. No lateral resolution is available. Low energy muons[2], i.e. muons with an

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[1] For a recent review see: A. Yaouanc, P. Dalmas de Réotier, MUON SPIN ROTATION, RELAXATION and RESONANCE (Oxford University Press, 2011)

[2] P. Bakule, E. Morenzoni, GENERATION AND APPLICATIONN OF SLOW POLARIZED MUONS,

energy of the order of the keV created by moderating so-called surface-muons, possess a depth resolution in the nanometer range, but the lateral size of the beam is typically more than 100 mm^2. All this limits the range of application of the μSR technique.

In this study we have investigated the possibility to generate a "micro-surface muon beam" of transverse size of ±100 μm. A much smaller beam spot is not realistic, because even with a perfect pencil surface beam, our simulation shows that the lateral scattering is about 50 μm in the two transverse coordinates. The beam spot considered in our study represents an increase of more than a factor 10^3 with respect to the present capabilities, this as far as sample area as well as weight are concerned. Only 40 μg of material would suffice to stop the muons; the present lower limit of necessary sample quantity is 30 mg, which can be achieved only at very few instruments with special detectors arrangement to take into account muons missing the sample.

A muon micro-beam provides many new features:

i) μSR-experiments of samples of a few ~100 μm dimensions (lateral and thickness) are made possible. This is a key feature, since novel materials can be generally synthetized and grown in good and crystalline quality only in tiny quantities and cannot be analyzed by μSR.

ii) On larger samples by scanning the sample, inhomogeneities can be investigated and intrinsic from extrinsic effects can be discerned (a question still affecting many studies of unconventional superconductors) and micro-phases detected.

iii) Multiple sample measurements are possible, thus sizably reducing the setup time, accelerating the data acquisition and reducing the systematic errors. In such a scheme several micro samples are mounted on a holder and the beam is switched from one to the other by steering elements.

iv) Additionally, a very small beam spot has a series of positive side effects, which allow important extensions of the experimental capabilities and of the physical parameters. To name a few, a small beam spot makes shielding problems of thermal loads to the sample less severe or effective volumes where homogeneity conditions (e.g. of magnetic field) must be fulfilled easier to be fulfilled so that lower temperatures (in mK range) and higher field homogeneities can achieved. Another important physical parameter in experiment is the pressure. Presently pressure cells for μSR experiments can reach about 2.5 GPa. Essentially piston technology has to be used, requiring rather large bulky cells, due to the large beam spot. A microbeam of energetic muons would allow the use of anvil cell systems, which require much less sample material and can reach higher pressures, so that an extension of the pressure range to ~ 10 GPa can be envisaged.

As a feasibility study for a muon microbeam we considered the existing πE3 beamline at the Paul Scherrer Institute, which extracts muons from the thick graphite target E under a 90-

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degree angle[3]. The πE3 beamline has a vertical bending plane and provides high intensity longitudinally polarized surface muons delivering in its present configuration up to $5\cdot10^7$ μ^+/sec at a momentum of 28 MeV/c and 7% momentum bite (full-width-at-half-maximum, FWHM), on a beam spot of size 3 cm in x and 2 cm in y (FWHM). It consists of two bending magnets, quadrupole and sextupole magnets with mid-plane symmetry. In order to make the beam spot smaller and to achieve a high intensity of muons in a micro-sized area of $200\times200\ \mu m^2$, we investigated a potential modification of the beam optics and beam elements in the last part between the second bending magnet and the target position (i.e. the elements located downstream from the ASK72 bending magnet). A constraint was the possibility to install a separator device to reduce the positron contamination in the muon beam.
The beam-focusing ability of the quadrupoles and the separation performance of the separator of the last part have been taken into considerations for the final micro beam spot.

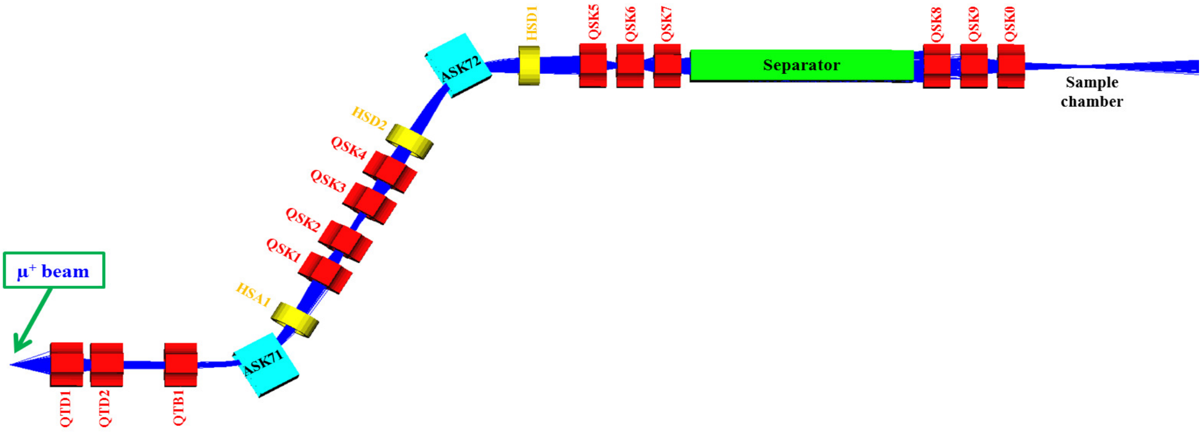

Fig. 1. Layout of the piE3 beamline at the Paul Scherrer Institute. Up to the second bending magnet, the layout corresponds to the present situation. The positions and characteristics of the elements located downstream from ASK72 were determined in the present study. A surface muon beam ($p \approx 30$ MeV/c) is transported and focused to the instrument by quadrupolar and dipolar elements. The separator consisting of E x B fields acts as mass separator to eliminate the positron contamination in the beam line.

We performed several series of systematic simulations using TRANSPORT[4], TURTLE (ray-tracing Monte-Carlo code: **T**race **U**nlimited **R**ays **T**hrough **L**umped **E**lements)[5] and GEANT4 (Geant4Beamline)[6]. TRANSPORT has a unique advantage that it can fit the parameters of elements to obtain required beam properties at a certain location of the beam

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[3] https://www.psi.ch/smus/pie3

[4] http://aea.web.psi.ch/Urs_Rohrer/MyWeb/trans.htm

[5] http://aea.web.psi.ch/Urs_Rohrer/MyWeb/turtle.htm

[6] https://geant4.web.cern.ch/geant4/ and http://www.muonsinternal.com/muons3/G4beamline

line. It can give the information of beam envelopes and emittances, but it is unable to provide the transmission efficiency. Muon transmission efficiencies and envelopes of different momentum spreads, beam divergences and different incoming beam spot sizes were calculated.

By performing several systematic iterations, we optimized the parameters of the magnetic elements and their optimal positions by TRANSPORT's fitting, and then determined the transmission efficiencies by making use of TURTLE. In addition, we systematically checked that the envelopes calculated in second order by TRANSPORT agree well with the envelopes calculated by ray-tracing code of GEANT4 (G4beamline).

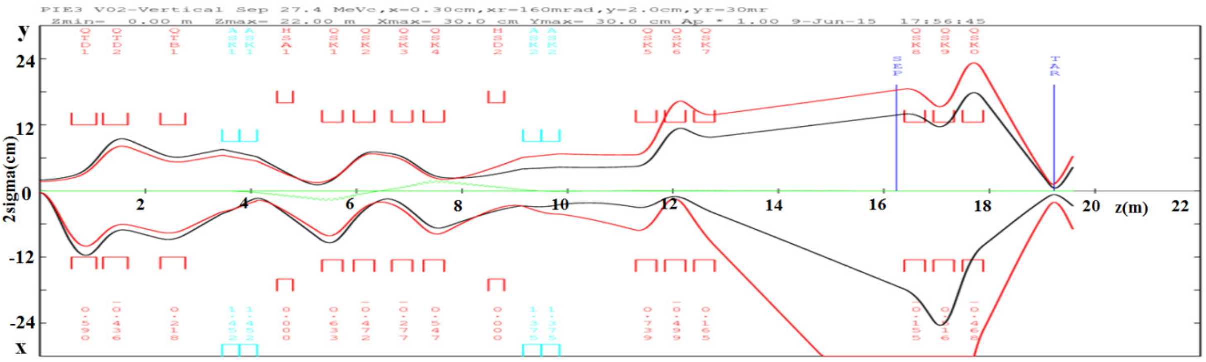

Fig. 2 Beam envelopes of the πE3 beam line calculated by TRANSPORT and G4beamline (GEANT4) giving a good agreement between the two simulations.

Using realistic initial beam parameters, source size and divergence (at the PSI Target E): $2\sigma_x = 0.3cm, 2\sigma_{x'} = 160\,mrad,\ 2\sigma_y = 2.0cm, 2\sigma_{y'} = 30mrad,$ $P = 27.4\frac{MeV}{c}$, Momentum spread $\delta = 0.03$ the simulations show that muons can be transported from the production target on a micro spot of (200 μm)^2 with an overall efficiency of ~2 10^{-4}. This corresponds to an intensity of ~10^4 muons/sec at the sample position, which is comparable to the usable rate at existing continuous muon instruments. This result on its own is already promising and indicates that a muon micro beam of sufficient intensity could be realized by relatively modest modifications of an existing beam line. More intense surface muon beam lines available at PSI (e.g. μE4, πE5) promise even higher intensities. Greater improvement (transport efficiency, background suppression) is expected with more sophisticated focusing and slit systems, as those used in electron microscopy.