

# DESIGN OF A SURFACE MUON BEAM LINE FOR HIGH FIELD $\mu$ SR AT THE PSI PROTON ACCELERATOR FACILITY

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## Abstract

Starting from 2012, a High Field  $\mu$ SR (muon spin rotation/relaxation/resonance) facility will come into operation in the  $\pi$ E3 secondary beam line located at the target station E of the PSI proton accelerator. For this purpose, the last part of the beam line was redesigned in order to integrate two electrostatic spin rotator devices providing a  $90^\circ$  rotation of the muon spin. At the same time, requirements of small beam diameter ( $\sigma_{x,y} \approx 15$  mm) as well as small momentum bite ( $\Delta p/p \approx 2\%$ ) in the sample region have to be met. This work focuses on the simulation of the beam optics (27.4 MeV/c design momentum). Particular concern is given to potential transmission losses caused by the spin rotator devices. The matching of the beam line with the high magnetic field up to 9.5 T surrounding the sample region is considered as well. An overview of the spin rotator devices, specifically designed for this project, is also presented.

## INTRODUCTION

The Laboratory for Muon Spin Spectroscopy (LMU) presently operates six facilities devoted to  $\mu$ SR research [1] employing the continuous muon beam made available by the Swiss Muon Source ( $S\mu S$ ) at PSI. In  $\mu$ SR experiments polarized muons are used to probe extremely small local magnetic fields, including their spatial distribution and temporal fluctuations, in any form of matter [2]. The new High Field  $\mu$ SR facility will allow to study the dependence of material properties on external magnetic fields up to the unprecedented value of 9.5 T as well as on temperatures ranging from 0.02 to 320 K [3]. The design and construction of the new instrument was completed in 2011. In order to ensure stable operation of the new facility, the  $\pi$ E3 secondary beam line of the PSI

proton accelerator, which provides a high intensity longitudinally polarized surface muon beam, has been permanently devoted to this new installation. For this purpose, the second half of the beam line was completely redesigned with the insertion of two new so-called spin rotator devices providing a virtually fully transversely polarized beam at the location of the sample material. Simulations were performed in order to optimize the beam transmission through the spin rotator system as well as the beam spot size at the probe location and to study, at the same time, the dependence of the latter on the magnitude of the large magnetic field provided by the  $\mu$ SR instrument. Fig. 1 shows a 3D visualization of the newly designed beam line section along with the installation of the High Field  $\mu$ SR facility.

## DESIGN OF THE SPIN ROTATORS

Spin rotator (SR) devices generate crossed static magnetic and electric fields in order to rotate the beam particle spin without bending the beam trajectory. At the same time, they act as velocity filters (Wien Filter). At PSI, an extensive know-how in the operation of electrostatic elements, like SRs and separators, has been gained over years of operation of such devices. It was therefore a natural choice to carry out an in-house design of the new elements.

The High Field  $\mu$ SR facility requires a  $90^\circ$  rotation of the muon spin, which translates, for 28 MeV/c beam, to a typical rotation path of over 3 m length. Since such a distance would be too large for a single element, two SR devices, each rotating the spin by  $45^\circ$ , were conceived. In order to keep the high voltage (HV) below  $\pm 200$  kV, the electrodes gap was set to 12 cm and the effective length to 180 cm. The full spin rotation is reached by means of an effective magnetic field of  $\approx 38$  mT, corresponding to an

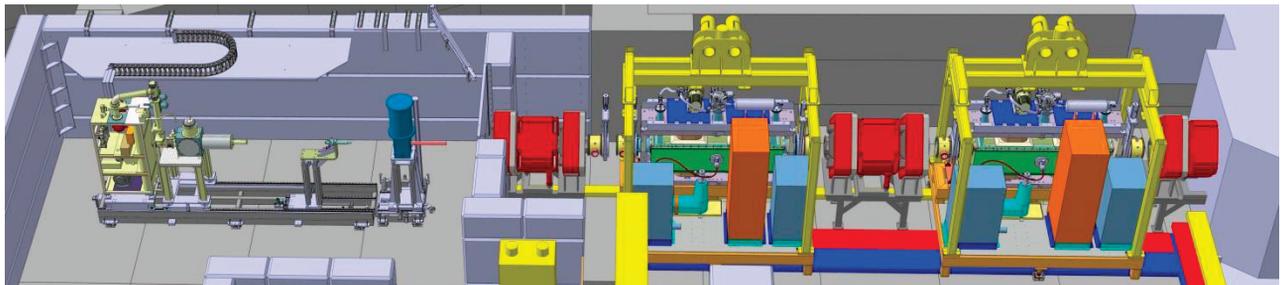


Figure 1: The section of the  $\pi$ E3 beam line redesigned for the High Field  $\mu$ SR project. The big yellow frames enclose the spin-rotators devices, while the red elements represent quadrupole magnets. On the left side the High Field  $\mu$ SR facility is visible. The muon beam comes from the right.

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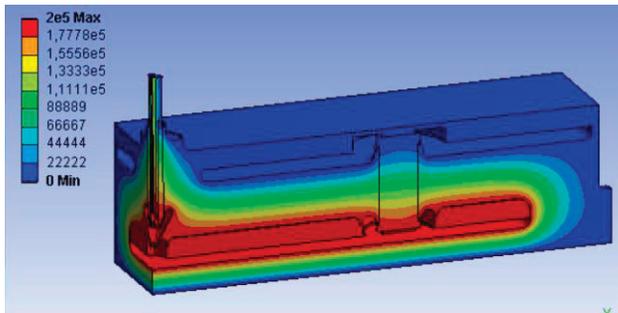


Figure 2: The simulated electric potential configuration of the optimized HV system of the spin rotator device.

operating voltage of  $\pm 175$  kV. The design of the magnetic part of the system has already been reported elsewhere [4]. Here we focus on the simulation of the electric field. In designing the HV setup, it is important to estimate and optimise the electric fields in order to avoid dielectric breakdown or flashover. The electrostatic simulation module of the ANSYS-Multiphysics [5] tool was used to optimise the component design of the HV system. The electric field configurations at critical regions were studied carefully, and the design optimisation was done in an iterative manner until the maximum electric field in vacuum is lowered to 75 kV/cm at the maximum allowed voltage of  $\pm 200$  kV. Since the electric breakdown and flashover depend on details of surface roughness, a reasonable degree of safety margin had to be taken in numerically simulated peak values. Fig. 2 shows the simulated electric potential configuration of the HV system for the 1/8 of the symmetric computational domain.

### BEAM LINE SIMULATIONS

The  $\pi E3$  beam line is an achromatic pion/muon secondary beam line starting from the target station E of the PSI proton accelerator facility. The High Field  $\mu$ SR project requires a surface muon beam with a momentum of  $\approx 28$  MeV/c. All the presented beam simulations were performed at a nominal momentum of 27.4 MeV/c.

The new beam line configuration was simulated by means of the TRANSPORT code [6]. The resulting second order beam envelope is shown in Fig. 3. The goal of the new design was to insert the two SR elements after the quadrupole magnet QSB2 while keeping a reasonable beam transmission up to the position of the material sample (SAMP). In addition to the original  $\pi E3$  beam line, the quadrupole magnet QSB3 was included in order to improve the beam focusing in the first SR. Moreover, two quadrupole triplets were placed between the two SRs and after the second SR respectively. Along with the optimization of the beam parameters, the positioning of the beam line elements had to satisfy geometrical constraints due to the limited space of the experimental area. The magnet setting calculated by TRANSPORT was then fed into a TURTLE [7] ray tracing simulation in order to compute the beam transmission through the SR system. Furthermore, since in TRANSPORT the SRs are

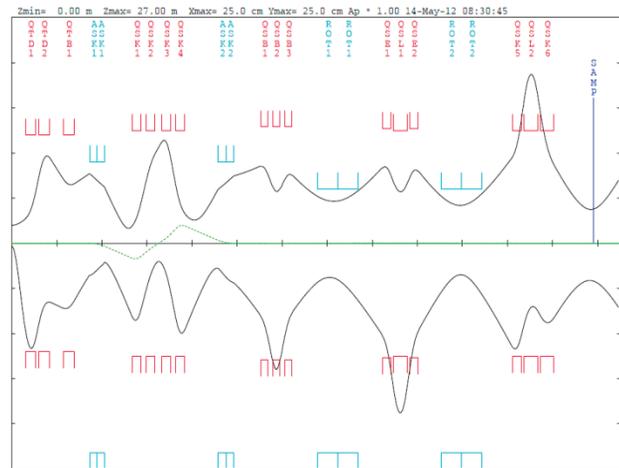


Figure 3: TRANSPORT second order beam envelope of the complete  $\pi E3$  beam line. The top and bottom plots represent the horizontal (x) and vertical (y) planes resp. The green dashes line is the dispersion trajectory.

treated as drifts, TURTLE is expected to perform a more realistic computation of the beam parameters. Indeed, in order to obtain a reasonable beam focusing at the sample location, in the TURTLE simulation the setting of the last two triplets had to be slightly changed with respect to TRANSPORT.

A more accurate beam tracking was accomplished by employing the TRACK code [8]. Contrary to TURTLE,

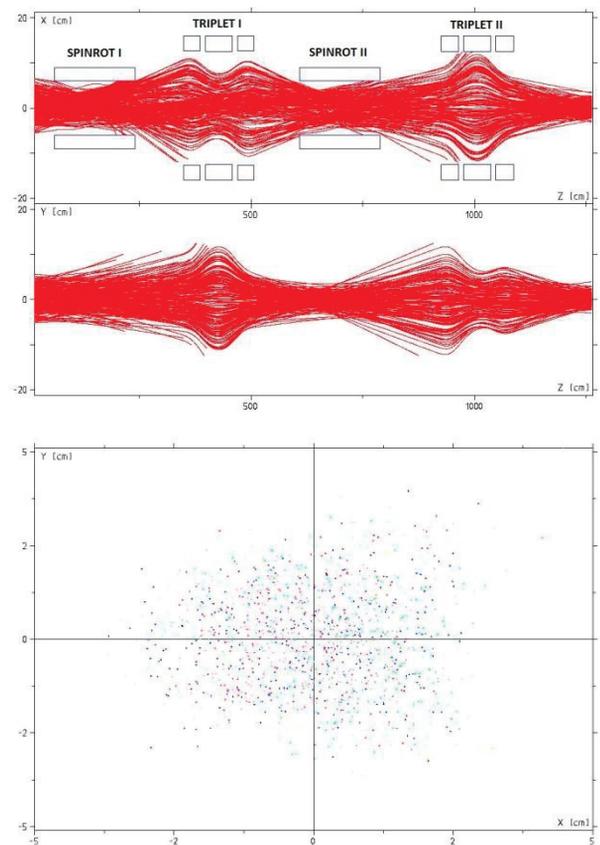


Figure 4: TRACK simulation of the muon beam through the SR system (top, 220 particles) and beam cross section at the location of the sample (bottom, 2200 particles).

Table 1: Most relevant beam parameters obtained by TURTLE and TRACK simulations

	TURTLE	TRACK
<b>Beam Transmission</b>		
SpinRot1 IN	100 %	100 %
SpinRot1 OUT	79 %	88 %
SpinRot2 IN	73 %	79 %
SpinRot2 OUT	58 %	76 %
SAMPLE	57 %	66 %
<b>Beam Size at SAMPLE</b>		
$\sigma_x$	1.71 cm	1.36 cm
$\sigma_y$	1.12 cm	1.36 cm
<b>Momentum Bite at SAMPLE</b>		
$\Delta p/p$	2.3 %	2.8 %

based on beam and transfer matrix calculation, TRACK makes use of field maps to compute the particle trajectory. The simulation starts 40 cm upstream of the first SR using the TURTLE calculated beam as input parameter. The result is shown in Fig. 4. Since the field map of the QSK type was not available, it was replaced in the second triplet by the field map of the (very similar) QSE type. As a result, the setting of the two QSKs had to be adapted w.r.t. TURTLE. A comparison between the beam parameters obtained by means of TURTLE and TRACK is given in Tab. 1.

The solenoidal magnetic field of the high field magnet has a focusing effect on the incoming muon beam [9]. To investigate this effect, a simulation based on the program Geant4 [10,11] was performed. The simulation required two input data: tabulated magnetic field of the high-field magnet, which was calculated using the design parameters provided by the magnet production company, and the initial muon beam at some position in front of the high field magnet, which was obtained from TURTLE.

The beam envelope predicted by Geant4 is shown in Fig. 5 for three different settings of the high field magnet. In the zero field case, the beam is focused by the last quadrupole triplet only. As soon as the high field magnet

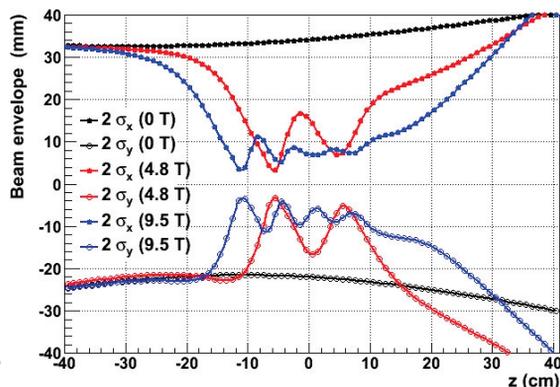


Figure 5: The effect of the high field magnet on the muon beam for three different magnetic field settings.

is switched on, the beam focusing gets significantly stronger, and the focal point shifts along the  $z$ -axis. Furthermore, several focal points appear at fields larger than  $\sim 3T$ . At 9.5 T the beam size in the centre of the high field instrument is close to a local minimum, while at 4.8 T it is close to the local maximum. The rate of muons stopped in the experimental sample therefore becomes a non-trivial function of the nominal magnetic field.

## CONCLUSION

Simulations of the redesigned  $\pi E3$  muon beam line devoted to the new PSI High Field  $\mu$ SR project as well as a short overview of the electric field computation of the two employed SR devices have been presented. The first commissioning of the facility, carried out in November 2011, showed good agreement between simulated and real beam parameters at the sample location. From May 2012 on, additional measurements should provide a deeper understanding of the quality of the simulations.

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