Design of the First μSR Spectrometer at China Spallation Neutron Source

Qiang Li[1, 3, †], Ziwen Pan[2, †], Yu Bao[1, 3, *], Tianyi Yang[2], Hui Cheng[1, 3], Yang Li[1, 3], Haitao Hu[1, 3], Hao Liang[2], Bangjiao Ye[2]

[1]Spallation Neutron Source Science Center, Dongguan 523803, China.
[2]State Key Laboratory of Particle Detection and Electronics，University of Science and Technology of China, Hefei 230026, China.
[3]Institute of High Energy Physics, Chinese Academy of Sciences (CAS), Beijing 100049, China.

[†]Co-first authors.
*E-mail address: yubao@ihep.ac.cn

Abstract. The Phase II upgrade project of the China Spallation Neutron Source (CSNS) includes the construction of a surface muon beam line and a muon spin rotation/relaxation/resonance (μSR) spectrometer, which will be the first μSR spectrometer built in China. Here, we report the conceptual design of the spectrometer, including the detector arrangement, magnets, sample environment (SE) and sample chamber. Based on the design parameters of the muon beam (1 Hz, 10^5 μ^+/pulse), the spectrometer possesses over 2500 detector units to maximize the counting rate. Three different types of magnets can generate a zero field (ZF), a longitudinal field (LF) within 5000 G, and a transverse field within 400 G. The SE consists of a cryostat and a closed-cycle refrigerator (CCR) to provide temperatures lower than 2 K in the current stage. It has potentials to be updated to 300 mK. The sample chamber is designed with a fly past structure to reduce the background for experiments with small-sized samples.

1. Introduction

The muon spin rotation/relaxation/resonance (μSR) techniques use the high sensitivity of polarized muon spins to magnetic fields to study the microscopic magnetic structure and dynamics of condensed matter[1][2]. These techniques rely on muon sources with high polarization and high intensity. To date, there are five international muon facilities, including PSI/SμS [3], TRIUMF/CMMS [4], RAL/ISIS [5], J-PARC/MUSE [6] and RCNP/MuSIC [7]. Apart from these existing muon sources, several new proposals are under design or construction, such as RAON in RISP [7], Muon station for sciEnce technoLOgy and inDustrY (MELODY) at China Spallation Neutron Source (CSNS) (progresses of the design and technique development of MELODY are presented in other proceedings of the 15th International Conference on Muon Spin Rotation, Relaxation and Resonance), and SEEMS at SNS [8].

The Phase II upgrade project of CSNS will construct a new muon source, MELODY, which includes a surface muon beam line and a corresponding μSR spectrometer. MELODY will start with 1 Hz of proton pulses (1.6 GeV, 20 kW) to make muons by the bombardment of protons on a carbon target. The beam line collects surface muons and transports them to the sample position with a polarization greater than 95% and an intensity higher than 1×10^5 μ^+/s.

More than 90% of muons can be stopped by samples with a diameter of 30 mm. To make use of the intensive muon pulse, a large number of detectors are required for the design of the spectrometer to take full advantage of the positron events per muon pulse.

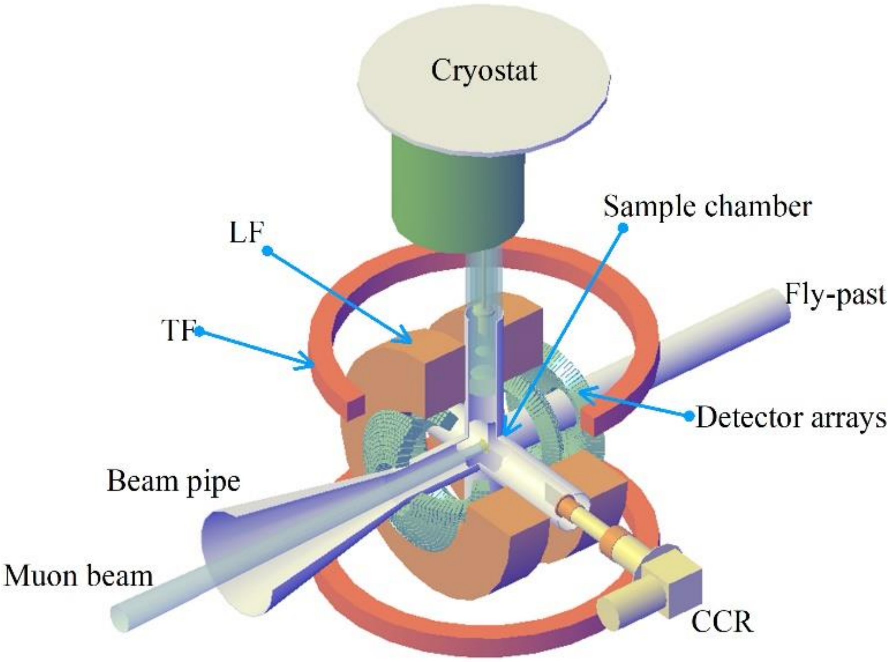

Figure 1. Spectrometer layout

2. Spectrometer layout

The μSR spectrometer mainly consists of cryogenic devices, magnets, a detector system and a sample chamber. The spectrometer layout is shown in Figure 1. Cryogenic devices include a cryostat and a Close-Cycle Refrigerator (CCR) to cover the temperature range of 2 K-600 K. The sample chamber is designed as a cruciform structure connected with a long tail to provide vacuum for the CCR. The long tail known as the fly past lets stray muons decay far away from the sample. The three-layered tail of the cryostat plugs into the cruciform vertically through the top branch tube, and the tail of the CCR plugs into the cruciform horizontally through the side branch tube. The magnets provide three types of field environments: a longitudinal field (LF), a transverse field (TF) and a zero field (ZF). The detector system includes the detector arrangement, electronics and data acquisition software. The detector array is symmetrically arranged along the μ beam line, covering the space solid angle between the sample chamber and the inner diameter of the LF magnet. Considering the space limitation and the requirement of high granularity, the detector unit adopts a small-sized plastic scintillator and a silicon photomultiplier (SiPM). Over 2500 detector units are arranged in the spectrometer, with each detector pointing to the sample position.

Journal of Physics: Conference Series **2462** (2023) 012022 doi:10.1088/1742-6596/2462/1/012022

3. Sample environment & chamber

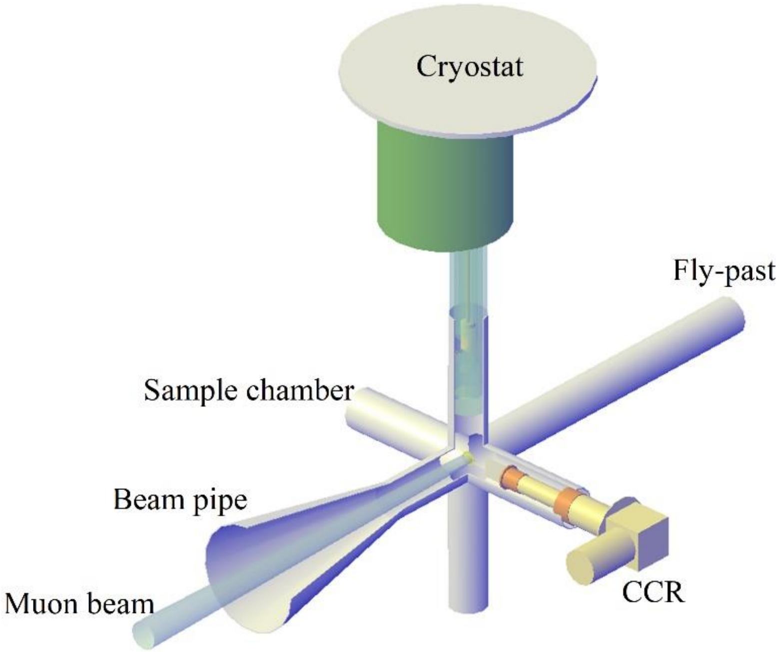

Figure 2. The sample environment and chamber layout

A very wide temperature range of the sample environment is always required to characterize the magnetic properties of various materials in μSR spectroscopy. For example, superconducting and quantum magnetic materials require the temperature to cover the region below a few Kelvin or even tens of millikelvin [9]. Magnetic functional materials (dilute magnetic, multiferroic, etc.) mostly require variable temperature conditions from a few Kelvin to several hundreds of Kelvin [1]. General battery materials require the temperature to cover more than several hundreds of Kelvin [10]. Therefore, we designed the sample environment with a temperature covering 2 K – 600 K. The cryostat can provide the temperature range of 2 K – 300 K and generally has an interface matching the extremely low temperature fridge insert which can hold sample and insert into the cryostat to extend the low temperature environment of the sample to below 300 mK. This design retained the potential of updating to extremely low temperature to ensure the applicability of the spectrometer. The tail of the cryostat is a three-layer structure. The two inner layers are for heat shielding and low-temperature setup, while the outermost layer is removable to reduce muon scattering events. The diameter of the beam window on the tail is designed to be 50 mm to ensure that over 99% muons can penetrate the beam window into the sample for a Φ30-mm (in FWHM) beam spot. The materials of the beam window are aluminized Mylar films or titanium films with a thickness of tens of microns. The length of the tail can be customized according to the actual situation. The CCR can generally cover the temperature range of 10 K – 600 K. The SE design allows the cryostat and the CCR to be operated alternately. The sample chamber can be sealed during experiments to provide a vacuum for the CCR.

More than 90% of the muons decay in the sample with a diameter of 30 mm to obtain μSR spectra with low background. In practical experiments, there may be cases where small-sized samples cause more muons to decay outside the sample. Therefore, the sample chamber is designed as a cruciform connected with a fly past structure shown as a long tail in Figure 2. The fly past lets stray muons outside the sample decay far away from the sample. Such a design allows the measurements of small samples [11].

4. Magnetic field

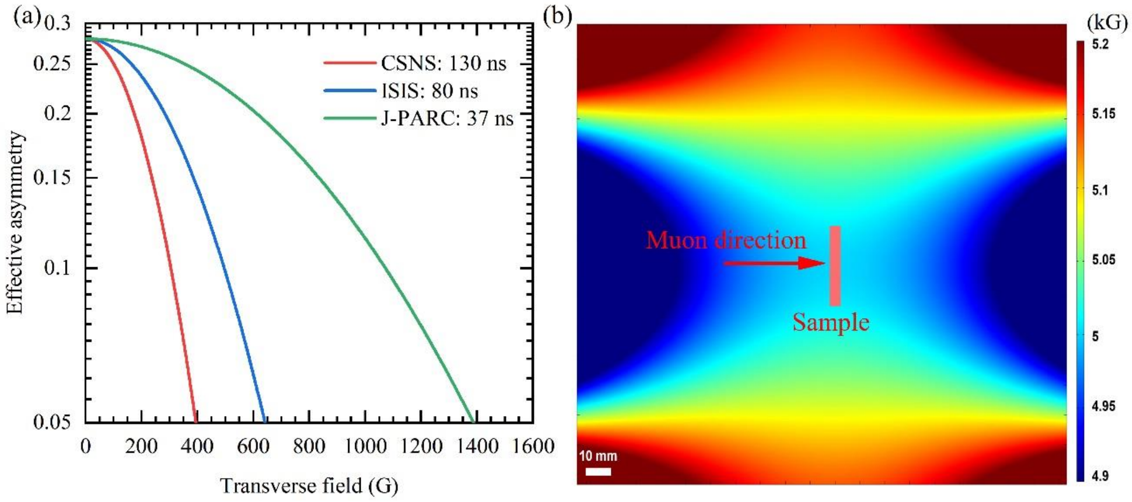

Figure 3. (a) The effective asymmetry under different pulse widths as a function of the TF strength, (b) the field homogeneity of the LF and TF in the sample position. Herein, the pulse width is the FWHM of a Gaussian distribution.

External LF and TF are basic requirements in μSR experiments. The placement of magnets is shown in Figure 1.

LF experiments generally require a high magnetic field strength. For example, muonium repolarization measurements require LF to reach about 0.5 T [12]. Therefore, the LF is designed to have a working field range of 0 ~ 0.5 T, which basically reaches the current limit of water-cooled Helmholtz coils. In the case of a TF experiment, the spin of each muon injected into the sample undergoes Larmor precession. The mathematical form of the Larmor precession is a cosine or sine function. The intrinsic asymmetry, A_0, of a spectrometer is the amplitude of the cosine function. As the injection time of each muon is different, the initial phase of every cosine function is also different which is correlated with the time distribution of muon pulses. The time spectra of muons in a pulse are the superposition of multiple cosine functions with the same frequency but different initial phases. Similar to the superposition of waves, the overall amplitude (or the effective asymmetry, A_0') after superposition is in variation with the distribution of initial phases. In pulsed μSR experiments, assuming the time of muons is in the form of a Gaussian distribution function, the effective asymmetry of the spectrometer in the TF condition follows the expression

$$A_0' = A_0 e^{-\frac{(2\pi f)^2}{2}\cdot\sigma_{\mathrm{beam}}^2}$$

where f is the Larmor precession frequency of the muons, and σ_{beam} is the standard deviation of the muon pulse width . The correlation between the precession frequency f and the TF can be expressed as

$$2\pi f = \gamma_\mu B$$

where γ_μ is the muon gyromagnetic ratio (135.5 MHz/T), and B is the TF strength. The effective asymmetry in TF reduces as a function of the field strength. According to the above equations, the effective asymmetry factors under different pulse widths and TF strengths are obtained, as shown in Figure 3(a). Therefore, the TF of the spectrometer is designed in the applicable range of 0 – 400 G to fit the pulse width of MELODY muons. The magnet design of LF and TF (especially the LF magnet) takes into account the sufficient space for the detector arrangement. Moreover, the field homogeneity is better than 100 ppm inside a volume of 40×40×10 mm^3 in the sample position, as shown in figure 3(b).

In addition, compensating magnets are required to be placed in the X, Y, and Z directions to offset the geomagnetic and ambient fields to obtain a zero-field environment. The adjustment accuracy of the compensation field is preferably better than 1 mG since the magnetic properties of the experimental samples are generally very weak.

5. Detectors and electronics

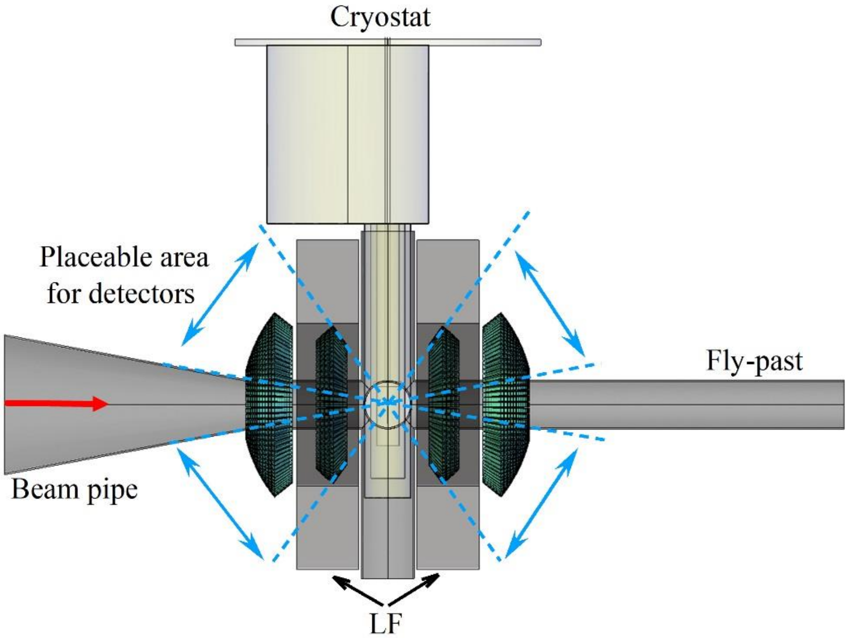

Figure 4. The spatial layout of detector arrays

The spatial layout of the detector arrays is shown in Figure 4. Under the spatial constraints of the sample environment, the sample chamber and the magnets, the spatial angle range of detector arrays covers 11.5° to 64°, as indicated by the blue arrows in Figure 4. This spatial layout takes into account the actual size of the detector units after optical and mechanical packaging (about $12\times12\times52$ mm^3). The detector area covers 54% of the solid angle of the full space, and the corresponding full positron detection efficiency is about 0.42. The MELODY design uses fast output SiPMs to reduce signal pile up in the detection system. A SiPM matched to a plastic scintillator with a size of $10\times10\times50$ mm^3 can achieve a single-channel count rate of about 8 e^+/ch/pulse. In the above constrained space, four detector arrays containing ~2800 detector units are designed and arranged to cover all feasible solid angles. These detector units are spherically arranged and point to the center of the sample to effectively suppress multiple counts from scattering or spiral motion of positrons in strong fields. Figure 5(a) shows the connection of the detector and electronics, including front-end electrons (FEE) and Time-to-Digital Converters (TDC). Multi-channel TDC based on Field Programmable Gate Array (FPGA) are used to process signals into the recordable digital information. To maintain the fast timing ability of 8 signals in a detector channel in every muon pulse, these signals will be shortened by a pole-zero cancellation (PZC) circuit and then discriminated by a leading-edge discriminator (LED) with fast comparators, as shown in Figure 5(b)[13]. Based on a beam intensity of about 1×10^5 μ^+/pulse, the event rate of the MELODY is calculated to be about 80 MEvents/h. The measurement time of each μSR spectrum can be achieved within about 15 minutes. By removing low-energy positrons with a suitable degrader, the intrinsic asymmetry of the spectrometer can reach above 0.28.

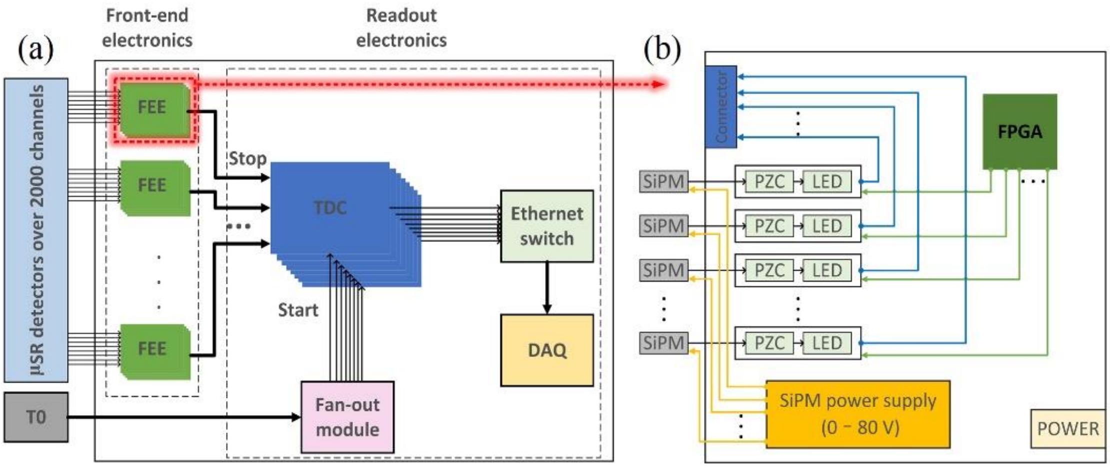

Figure 5. (a) Diagram of the connection of the detector and electronics, including FEEs and TDCs, (b) diagram of an FEE.

6. Conclusion

The MELODY spectrometer is currently undergoing physical simulation and structural design based on the beam parameters. It is expected to be completed and open to users in 2029. The MELODY spectrometer has very high flux intensity per pulse and designed the largest granularity of detector array in the current world to adapt to the high intensity, which allows the spectrometer to make more efforts to meet the user's personalized requirements such as smaller beam spot, higher asymmetry, weak relaxation measurement, etc. while maintaining sufficient counting rate (~80MEvent/h). Moreover, the maximum possible 5Hz beam supply frequency of CSNS makes the spectrometer have the potential to increase the counting rate to ~400MEvent/h, which will make it reach the relatively high experimental efficiency. Together with other µSR facilities in the world, it will provide support for scientific research such as superconductivity, magnetism, and new energy materials.

Acknowledgment

The authors would like to thank all those who have contributed to this work, particularly Peter J. Baker, Stephen P. Cottrell, James S. Lord and the ISIS muon group for helpful discussions and useful comments.

References

[1] De Reotier P D and Yaouanc A 1997 Muon spin rotation and relaxation in magnetic materials *J. Phys. Condens. Matter* **9** 9113
[2] Hillier A D, Blundell S J, McKenzie I, Umegaki I, Shu L, Wright J A, Prokscha T, Bert F, Shimomura K, Berlie A, Alberto H and Watanabe I 2022 Muon spin spectroscopy *Nat. Rev. Methods Prim.* 2 4
[3] Abela R, Baines C, Donath X, Herlach D, Maden D, Reid I D, Renker D, Solt G and Zimmermann U 1994 The µSR facilities at PSI *Hyperfine Interact.* 87 1105–10
[4] Beveridge J L, Doornbos J and Garner D M 1986 Muon facilities at TRIUMF *Hyperfine Interact.* 32 907–12
[5] Eaton G H, Carne A, Cox S F J, Davies J D, De Renzi R, Hartmann O, Kratzer A, Ristori C, Scott C A and Stirling G C 1988 Commissioning of the Rutherford Appleton Laboratory pulsed muon facility *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* 269 483–91

[6] Miyake Y, Nishiyama K, Kawamura N, Strasser P, Makimura S, Koda A, Shimomura K, Fujimori H, Nakahara K and Kadono R 2009 J-PARC muon source, MUSE *Nucl. Instrum. Meth. A* 600 22–4

[7] Yamamoto A, Hatanaka K, Cook S, Yoshida M Y, Sakamoto H, Tran N H, D'Arcy R T P, Hino Y, Kuno Y and Truong N M 2011 MuSIC, the World's Highest Intensity DC Muon Beam using a Pion Capture System *Conf. Proc.* 110904 820–2

[8] Williams T J and MacDougall P G J 2017 *Future muon source possibilities at the SNS* (Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).)

[9] Amato A 1997 Heavy-fermion systems studied by μSR technique *Rev. Mod. Phys.* 69 1119.

[10] McClelland I, Johnston B, Baker P J, Amores M, Cussen E J and Corr S A 2020 Muon Spectroscopy for Investigating Diffusion in Energy Storage Materials *Annu. Rev. Mater. Res.* 50 371–93

[11] Lynch M C, Cottrell S P, King P J C and Eaton G H 2003 Measuring small samples at the ISIS muon source *Phys. B Condens. Matter* 326 270–4

[12] Nuccio L, Schulz L and Drew A J 2014 Muon spin spectroscopy: magnetism, soft matter and the bridge between the two *J. Phys. D. Appl. Phys.* 47 473001

[13] Deng F S, Liang H, Zhuang M Q, Zhang Y G, Fu E Q, Ni X J, Pan Z W, Ye B J, Tang J Y, Cottrell S P and Pooley D E 2019 Development of a data acquisition system for the μSR spectrometer prototype at the China spallation neutron source *J. Instrum.* 14 P10024–P10024