Beam transport calculation and beamline design for μSR facility in RAON

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1. Introduction

Rare Isotope Science Project (RISP) has been constructing a heavy-ion accelerator complex RAON (Rare isotope Accelerator complex for ON-line experiments) since 2011. RAON will include various experimental facilities for nuclear physics, nuclear astrophysics and applied science [1]. RAON will have a μSR facility for studying matter science that will be installed in high energy experimental hall II. It is expected that RAON will be the fourth in the world to have continuous wave (CW) μSR facility by 2021. μSR uses surface muons which are nearly 100% spin-polarized and can be a sensitive microscopic probe of magnetism when it is implanted in matter. The surface muons arise from pions decaying at rest in the surface layer of production target made of low Z material such as graphite or beryllium. The pions are generated from the interaction between high energy proton (>300 MeV) and the target. The maximum production yield of pion appears when proton energy is ~600 MeV. The surface muon beams generated from the target should be delivered to an experimental sample through beamline consists of various electromagnetic components such as dipole and quadrupole. In this paper, the configuration of the muon beamline and the specification of the electromagnetic components were described with the beam transport calculations using ray-tracing technique. The calculations were performed by using G4beamline code [2]. The trajectories and transmission rate to the sample of the muon beam were estimated taking into account the fringe field effect of all components.

2. Methods and Results

2.1 Properties of the surface muon from the target

An initial proton beam of RAON will be generated from a ECR-IS (electron cyclotron resonance ion source) and then accelerated up to an energy and an intensity of 600 MeV and 660 μA, respectively, through the superconducting driver LINAC (SCL3-SCL2). The accelerated proton beam will be transmitted to the μSR facility after passing through the proton beamline in high energy experimental hall II and produce pions which decay into muons by interacting with the production target. Finally, the proton beam will be absorbed by the beam dump that is located downstream from the target. Fig. 1 presents the layout of RAON and the location of μSR facility.
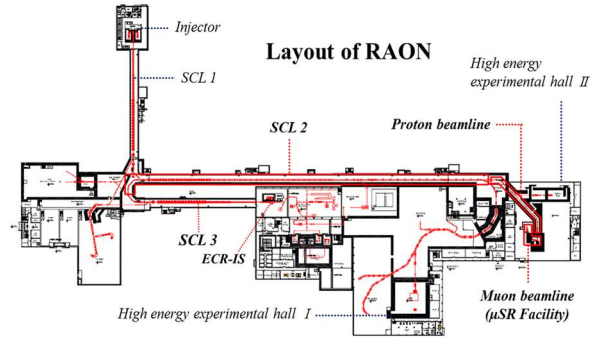

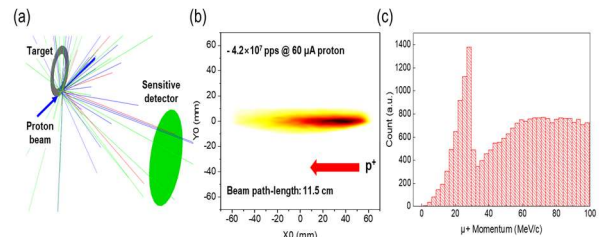Fig. 1. Layout of RAON accelerator complex and location of μSR facility

Fig. 2. (a) schematic of the muon production target (b) initial position distribution of muons at target (c) initial momentum distribution of muon

Fig. 2 shows the muon production target and initial distribution of position and momentum calculated using Geant4 toolkit. The muon production target is a rotating wheel shape with a radius of 21 cm. The 600 MeV proton beam will be injected 1 cm from the bottom of the target. Proton beam path-length in the target is 11.5 cm and beam size is 1.2 mm (horiz.) × 2.9 mm (verti). The design momentum of the beamline was determined to be 28.5 MeV/c in order to maximize transmission efficiency of the beamline. The momentum acceptance of beamline was ±3% (27.5~29.5 MeV/c). The flux of muons entering the first component (solenoid) in the momentum range was estimated to be 4.2×10^7 μ+/s at a proton current of 60 μA, which is about 10% of maximum current.

2.2 Beamline elements

The designed beamline consisted of 2 solenoids for collecting muons, 2 dipoles for bending the trajectories with a deflection angle of 70°, 9 quadrupoles for muon beam focusing and a Wien filter (spin rotator) for rotating muon spin angle and removing contamination. The total length of beamline is about 18 m. The layout of the beamline is shown in Fig. 3.
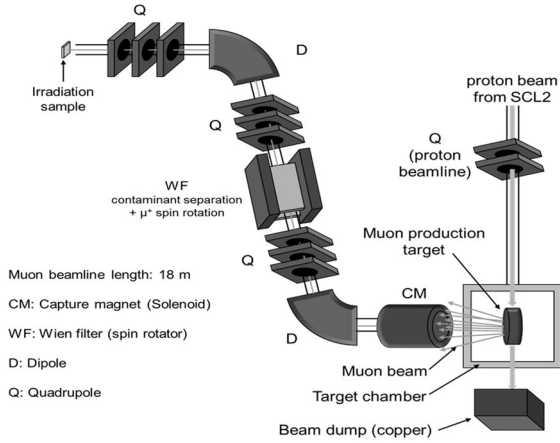
Fig. 3. Layout of surface muon beamline

The muons generated from the target will be collected by a pair of normal conducting solenoids that will be placed 1 m from the target. The aperture radii and effective lengths are 25 cm and 85 cm for both, respectively. The solid angle acceptance is ~107 msr. When charged particles enter the solenoid, they undergo a helical motion so that this results in phase space rotation. The rotation angle of phase space is given by

$$\theta_{PS} = \frac{B \cdot l_{eff}}{2B\rho}$$

where B is magnetic field, l_{eff} is effective length, $B\rho$ is the magnetic rigidity. The phase space mixing in horizontal and vertical direction at the beginning of the beamline can dramatically increase in beam size and momentum dispersion at the end of the beamline. However, when $\theta_{PS} = 90°$, the disadvantages of phase-space mixing can be reduced [3]. Finally, θ_{PS} of the solenoids was determined to be about 83° considering transmission efficiency to the dipole which is placed 1.4 m after the solenoids. Therefore, the maximum magnetic fields were found to be 0.22, 0.11 T.

After the solenoids, two dipoles with deflection angles of ±70° will be installed 7.6 m apart from each other. The distance was determined considering the shape of the shielding concrete wall, which was designed due to a radiation safety issue. The deflection radius and the maximum magnetic field were determined as 1.3 m and 0.074 T, respectively. 6 quadrupoles and a Wien filter will be placed between the dipoles, and a mirror symmetry structure is formed to minimize aberrations of the beam. A quadrupole triplet after the first dipole focuses the beam in the middle of the Wien filter. The other triplet delivers the beam to the second dipole, and the beam shape is symmetrical to that coming out of the first dipole. The field gradient of quadrupoles ranges within 0.3 ~ 0.5 T/m.

The Wien filter is used to rotate spin angle and separate charged particles by velocity. The device consists of electrodes and magnetic poles, and passes only particles with a desired velocity using perpendicular electric and magnetic fields. The Wien filter in the beamline was designed to rotate muon spin as 45° and separate other particles excluding muons that have different velocities (for example, positrons which have the same momentum with surface muons.) According to the velocity of 28.5 MeV/c surface muon, $v = E/B = 0.26c$, the electric field and the magnetic field were determined to be ±1.47 kV/mm and 37.6 mT. The effective length is 1.96 m.

After the second dipole, the beam is focused to the sample position by the last quadrupole triplet. The sample is of size 1.5×1.5 cm^2 and 1 m apart from the last quadrupole.

2.3 Surface muon beam transport calculation

Beam transport calculation was carried out using G4beamline to estimate the transmission rate and the trajectories of the muon beam. In the calculation, QGSP-INCLXX was used as the physics model because the distribution of angular divergences is well agreed with previous target study carried out in PSI [4]. The distributions of position, angular divergences and momentum derived from Geant4 calculation were applied. The fringe field effect is included for every component. The field information was adopted from the electromagnets designed by using OPERA-3D code [5]. Fig. 4 shows the field distribution along the z-axis (beam direction) of the electromagnetic components.
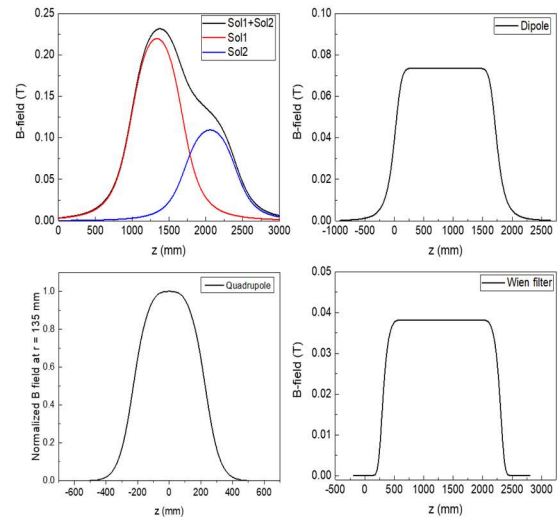

Fig. 4. Field distribution of electromagnet components including fringe field.

In the simulation, 11 virtual detectors were placed before and after the components to record the particles passing through them. The sizes of the virtual detectors vary according to the aperture size and the size of the last one is the same as the sample size. The trajectories and transmission rate of particles through the beamline are presented in Fig. 5. Every particle excluding surface muon was eliminated after the Wien filter. The

transmission rate of muon beam was about 1.23%. According to the muon production yield from the target, 4.2×10^7 μ⁺/s, muon flux at the sample was estimated to be 5.2×10^5 μ⁺/s at a proton current of 60 μA. In case of using a larger sample (3×3 cm^2) such as those used in PSI μE4 line or J-PARC D-line, the flux can be increased as 1×10^6 μ⁺/s. The beam profile of surface muons and momentum distribution at the sample are shown in Fig. 6.

3. Conclusions

The surface muon beamline of μSR facility of RAON was designed by determining the positions and the specifications of electromagnetic components. The beamline was composed of 2 solenoids, 2 dipoles, 9 quadrupoles and a Wien filter. The beamline has a symmetry structure between dipoles and the total length is about 18 m. Beam transport calculation was performed
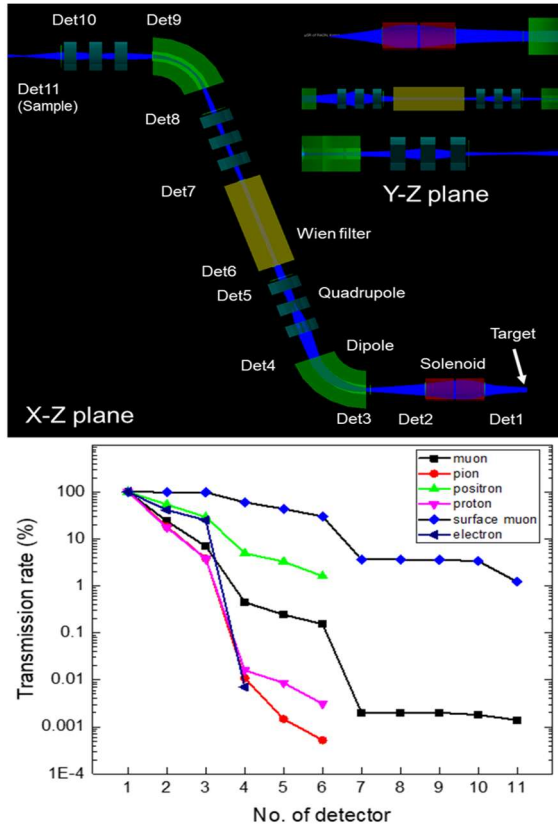

Fig. 5. (Top) Trajectories of muon beam through the beamline (Bottom) Transmission rate by particles
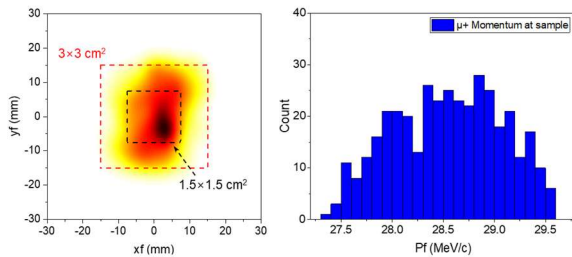

Fig. 6. (Left) Beam profile of surface muons at the experimental sample (Right) Momentum distribution at the sample

to estimate transmission efficiency and trajectories of the beam. Other particles except for surface muon were separated by the Wien filter. Muon flux injected to the 1.5×1.5 cm^2 sample was estimated to be 5.2×10^5 μ⁺/s at a proton current of 60 μA. The transmission rate of muon beam was about 1.23%. Since the muon flux required for the general purpose μSR experiment is known as $10^4\sim10^5$ μ⁺/s-cm^2 at sample [6], it is sufficient to perform the experiment. μSR facility of RAON is being manufactured with some components with the goal of completion in 2021.

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