Proposal for an experiment to demonstrate the radiography with a multi-GeV muon beam

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Executive Summary

We propose a test experiment aiming at practical use of high-momentum muons. In the T106 experiment conducted in January 2025, we demonstrated that high-momentum high-purity muons could be provided at B-Line, so called the high-momentum beam line. The purpose of the experiment is to show performance of the high-momentum muon beams in imaging balk matter. For this we prepare a concrete block with four steel bars embedded in the center as a sample object. By irradiating high-momentum muons onto the sample, we obtain scattering-angle distributions of muons for several sets of a certain incident position (s) and certain incident angles (ϕ), and determine the standard deviation of a distribution, $\theta_{rms}(s, \phi)$, to extract the average radiation length, $\bar{X}_0(s, \phi)$, corresponding to the effective amount of high-Z materials at a line specified by s and ϕ. From a set of $\bar{X}_0(s, \phi)$s, it is expected that the X_0 distribution within the sample object is obtained by tomography. We request 78 hours in total for the present purpose.

Below are the summary of request.

Beam line:	B-Line (Lambertson magnet off), secondary beams
Beam polarity:	Positive is assumed for the beam time estimation
Beam momentum:	3 (5), 4.8 (8), and 6 (10) GeV/c for muons (pions)
Beam time:	78 hours in total
	1.5 hours for Q2e/Q2f tuning
	52 hours at 3 GeV/c, 14.5 hours at 4.8 and 6 GeV/c

1 Muon radiography

High-momentum muons with multi-GeV/c are useful for measurement of the thickness of the materials crossed by the muons, so-called the muon radiography. According to the multiple Coulomb scattering theory, the standard deiviation (θ_{rms}) of the projected angular dsitribution is described as,

$$\theta_{rms} = \frac{13.6MeV}{\beta cp}\sqrt{\frac{L}{X_0}}\left[1 + 0.038\ln\left(\frac{L}{X_0\beta^2}\right)\right], \tag{1}$$

for muons passing through a material with a charge number of ±1. The length L of the material measures in the unit of radition length (X_0). Since the velosity of a muon with a momentum higher than $\sim$1 GeV/c is almost β=1, θ_{rms} is inversely propotional to the muon momentum (p), and the factor depends on X_0, the quantity intrisic to the material. Figure 1 plots θ_{rms} estimated for various materials of 50-cm length as a function of the incident muon momentum. One can estimate the effective thickness of the material from θ_{rms} measurement. In a simulation, we considered that muons of 1, 2, and 3 GeV/c are incident on a concrete cubic block of 50×50×50 cm^3 with a pair of iron square bars of 50 cm length, each of which measures 2×2 cm^2 in cross section, embeded in the center of the block with an interval of 10 cm, as illustrated in Fig. 2. Figure 3 shows expected θ_{rms} plotted as a function of the muon incident position. A large θ_{rms} is obtained at the location of an iron bar. It is found that deduced $\bar{X}_0$s are independent of the incident momentum (Fig. 3(b)). This means that $\theta_{rms}p$ is sensitive to the averaged radiation length $\bar{X}_0$ defined as $\bar{X_0}^{-1} = \int dZ/X_0(Z)/L$, where Z is the coodinate along the muon beam and L is the path length of the muon in the material.

Employing the back projection method of the tomography, distribution of the radiation length in the object material, $X_0(x,z)$ can be reproduced from a measured set of $\bar{X}_0(s,\phi)$ as follows.

$$X_0^{-1}(x,z) = \frac{1}{4\pi^2}\int_0^\infty\int_0^{2\pi}\tilde{Y}(r,\phi)\exp\left(ir(x\cos\phi - y\sin\phi)\right)rdrd\phi, \tag{2}$$

$$\tilde{Y}(r,\phi) = \int_{-\infty}^{\infty}\bar{X_0}^{-1}(s,\phi)L(s,\phi)\exp\left(isr\right)ds. \tag{3}$$

Here, x and z are the coordinates fixed in the object material, and s is the coordinate perpendicular to the incident muon beam and ϕ is the angle between the s and x axes. See Fig. 8 also.

This is a part of the project to develop a portable muon four-momentum measuring system and a high-momentum muon source supported by the JST K Program [3]. We recently carried out a test experiment T106 and successfully measured secondary particles and tertiary muons with a positive charge at the B-Line in the J-PARC Hadron Experimental Facility [2]. Owing to this grant, we will introduce polarity changing devices for the B-line magnet power suppliers. After introducing the polarity changing devices, we will study negative secondary particles, for which an another test experiment will be proposed separately [4]. Demonstrating a muon radiography, a new application platform utilizing high-momentum muon beams will be open at J-PARC.

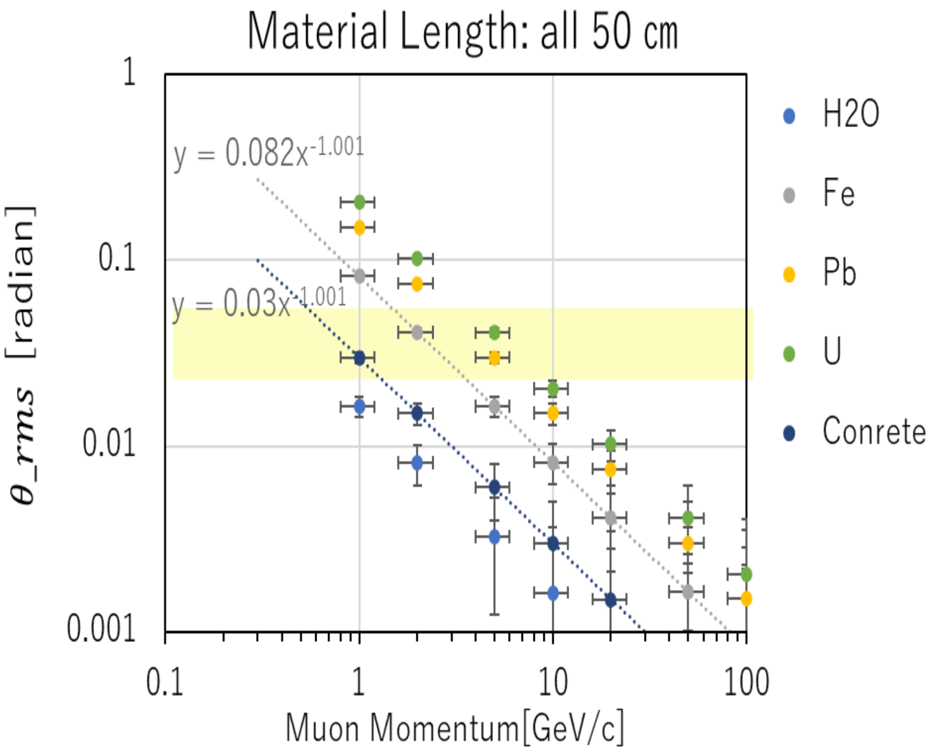

Figure 1: Standard deviation of the projected angular distribution in Coulomb multiple scattering, θ_{rms}, estimated for muons passing through water, concrete, standard rock, iron, lead, uranium of 50 cm lngth as a function of muon momentum.

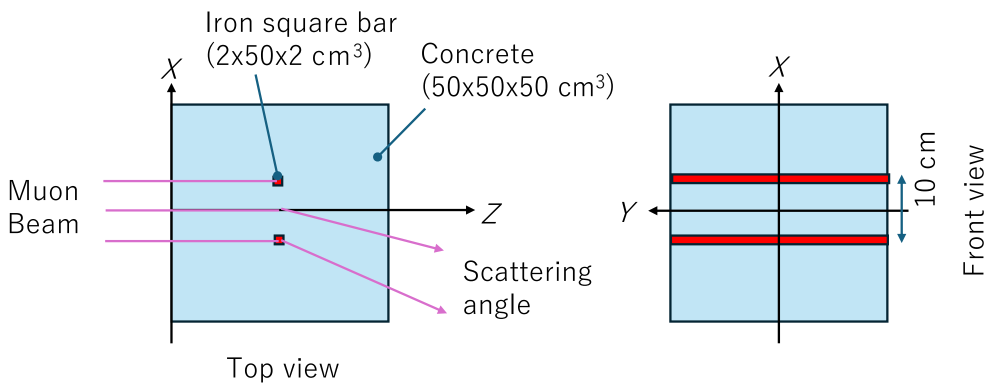

Figure 2: Concrete block with a volume of $50 \times 50 \times 50$ cm^3 considered as a scatterer by muons in the simulation. A pair of iron square bars of 50 cm length, each of which has a cross section of 2 cm by 2 cm, are embeded in the center of the block with an interval of 10 cm.

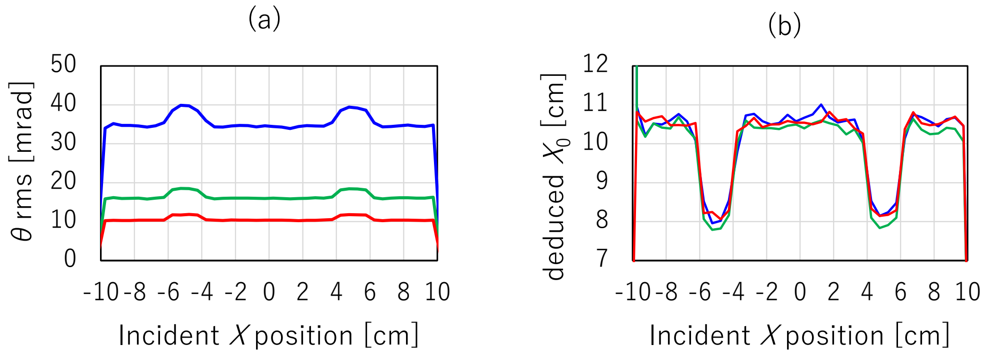

Figure 3: (a) θ_{rms} distribution as a function of the incident position (X). (b) deduced $\bar{X}_0$ distriutions, showing that they are independent of the incident momentum.

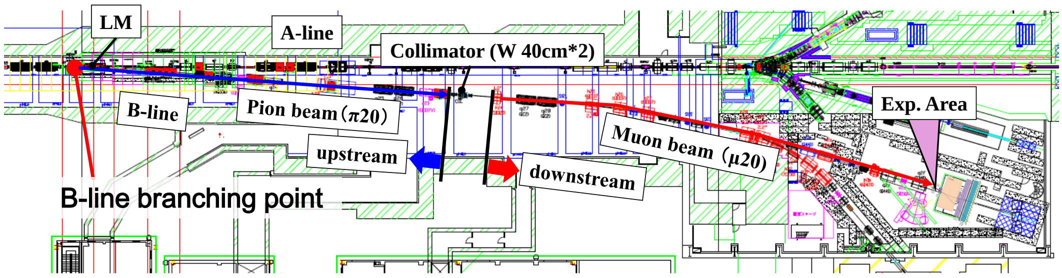

Figure 4: Current layout of the B-line. It is branched from the A-line at so-called the Lambertson magnet. A small fracion of the primary protons are splitted by the Lambertson magnet into the B-line. The B-line can be operated to collect and transfer secondary particles produced at the Lambertson magnet without any special treatment.

2 Experimental Plan

2.1 High-momentum muon beam line

The B-line in the J-PARC hadron experimenal facility is in operation to deliver a small fraction of the primary protons of 30 GeV for the E16 experiment [1]. The plan view of the B-line is shown in Fig. 4. Since a beam loss of a few hundred watts is expected at the beam-splitting magnet in operation of the B-line and secondary particles are naturally produced there, we expect to transfer secondary pions. Here, we call this operation mode $\pi 20$.

A pion decays into a muon and a muon neutrino in 26 nano seconds at rest. As illustrated in Fig. 5, a muon decaying backward in the rest frame of a beam pion is emitted forward in the laboratory frame. The backward-decaying muon has a momentum $p_\mu = m_\mu^2/m_\pi^2 p_\pi \approx 0.57 p_\pi$ in the relativistic limit. This relation is practically applicable even at $p_\pi \sim 1$ GeV/c. Thanks to this nature, we could find an optial design to separate the backward-decaying muons from the beam pions completely. We call this new operation mode of the beam line as $\mu 20$. A concept

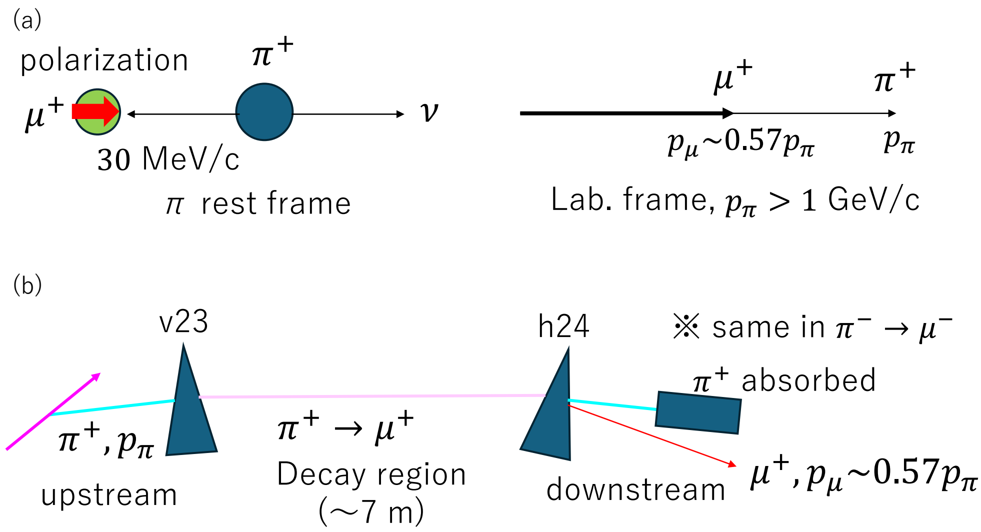

Figure 5: (a) Graphical illustrations of a pion decay into a muon and a neutrino in the pion rest frame and the laboratory frame. In the pion rest frame, the muon is emitted in the opposite (backward) direction to the pion travelling direction. In this case the muon momentum is 57% of the pion momentum in the laboratory frame. (b) Concept of the μ20 mode. A part of pions passing though the upstream part of the beam line decay into muons (and neutrinos) in the drift space between the v23 vertical and the h24 horizontal bending magnets. Since the downstream part of the beam line is operated at 60% of the momentum of the pion beam, only the backward-decaying muons are accepted to and tranferred through the downstream part of the beam line.

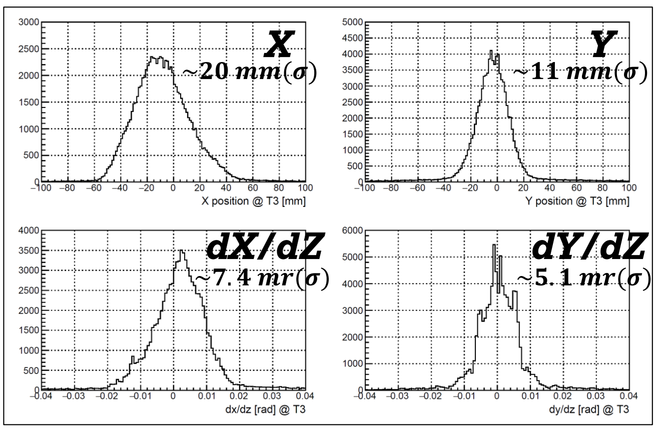

Figure 6: Muon profile measured at 3 GeV/c in the T106 test experiment.

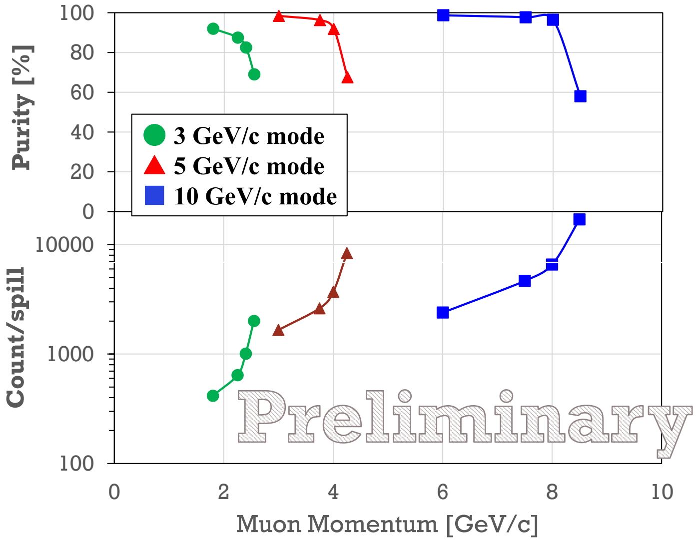

Figure 7: Muon intensities and purities obtained in the T106 experiment.

of the μ20 mode is illustrated in Fig. 5(b).

A test experiment, T106 [2], was carried out in January, 2026 and successfully measured secondary particles and tertiary muons. Fig. 6 and 7 show muon profiles measured at 3 GeV/c and measured muon intensities and purities as a function of the muon momentum. A curve connecting a several points means muons measured with different momentum settings at a same parent pion momentum. The purities of muons at 3 GeV/c and 6 GeV/c were found to be as high as 98% and 99%, respectively. They are 60% of the momentum setting for parent pions at 5 GeV/c and 10 GeV/c, respectively.

2.2 Beam Time Request for Muon Radiography

To demonstrate muon radiography, we prepare a sample object as shown in Fig. 8 (different from the sample shown in Fig. 2). As describe below, the sample object has 4-fold rotational symmetry to save beam time. We will measure θ_{rms} to extract $\bar{X}_0$ as a function of the incident position. Fig. 9 shows simulated θ_{rms} and $\bar{X}_0$ at the irradiation angle of $\phi = 0$ degree at 3 GeV/c. In order to obtain a sharp image, it is necessary to collect approximately 5 mega events for each. We need to obtain $\bar{X}_0$ at different muon incident angles for tomography. As the sample object is 4-fold rotational symmetric, the range of ϕ from 0 to 45 degrees is enough to measure. We will take data at 12 different angles in this angular range. Based on the beam intensity obtained in T106, we estimate necessary beam time of 52 hours for this measurement at 3 GeV/c For reference, we will measure θ_{rms}s at $\phi = 0$ and 45 degrees at 4.8 and 6 GeV/c. For this, we need another 14.5 hours including time consumption of 30 minutes for momentum changes. In the present measurement, a parallel beam optics is preferable. We need 1.5 hours for tuing of the last quadrupole doublet, Q2e and Q2f. Expected parallel beam optics is calcualted by the TRANSPORT code [5], as shown in Fig. 10(upper panel). Employing the simulation code, Decay

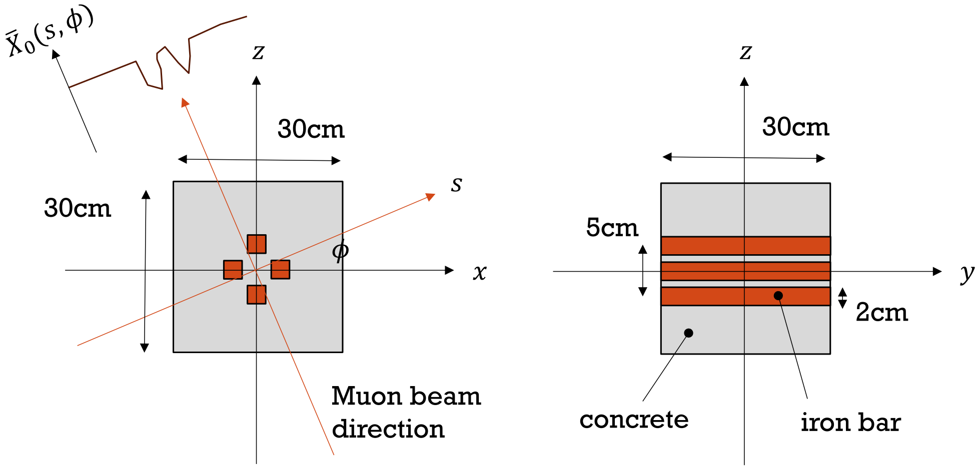

Figure 8: Concrete block with a volume of 30×30×30 cm^3 to be prepared for muon radiography. Four iron square bars of 30 cm length each of which has a cross section of 2 cm by 2 cm, are embeded in the center of the block with a diagonal distance of 5 cm.

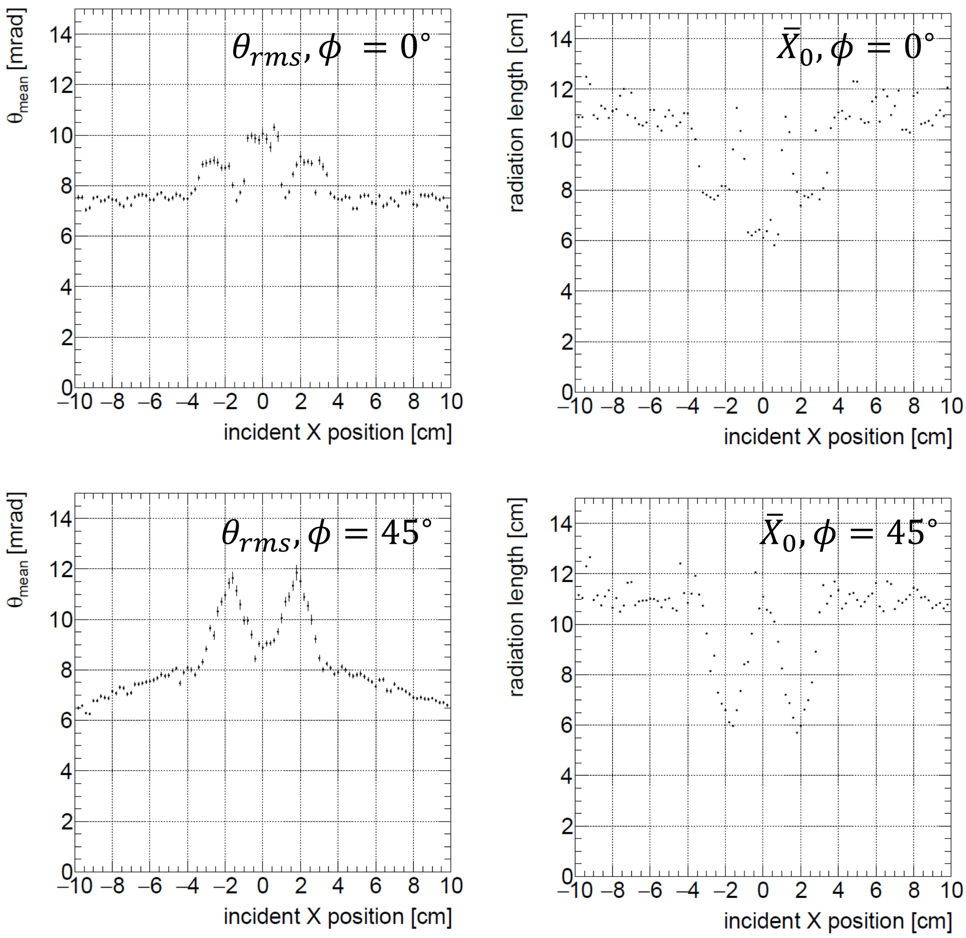

Figure 9: Standard deviation of the scattering angle (θ_{rms}) and extracted radiation length ($\bar{X}_0$) at 3GeV$/c$ in the simulation. The θ_{rms} and ($\bar{X}_0$ distributions as a function of incident position at the muon incident angle of $\phi = 0°$ (upper panels) and 45° (lower panels) are shown.

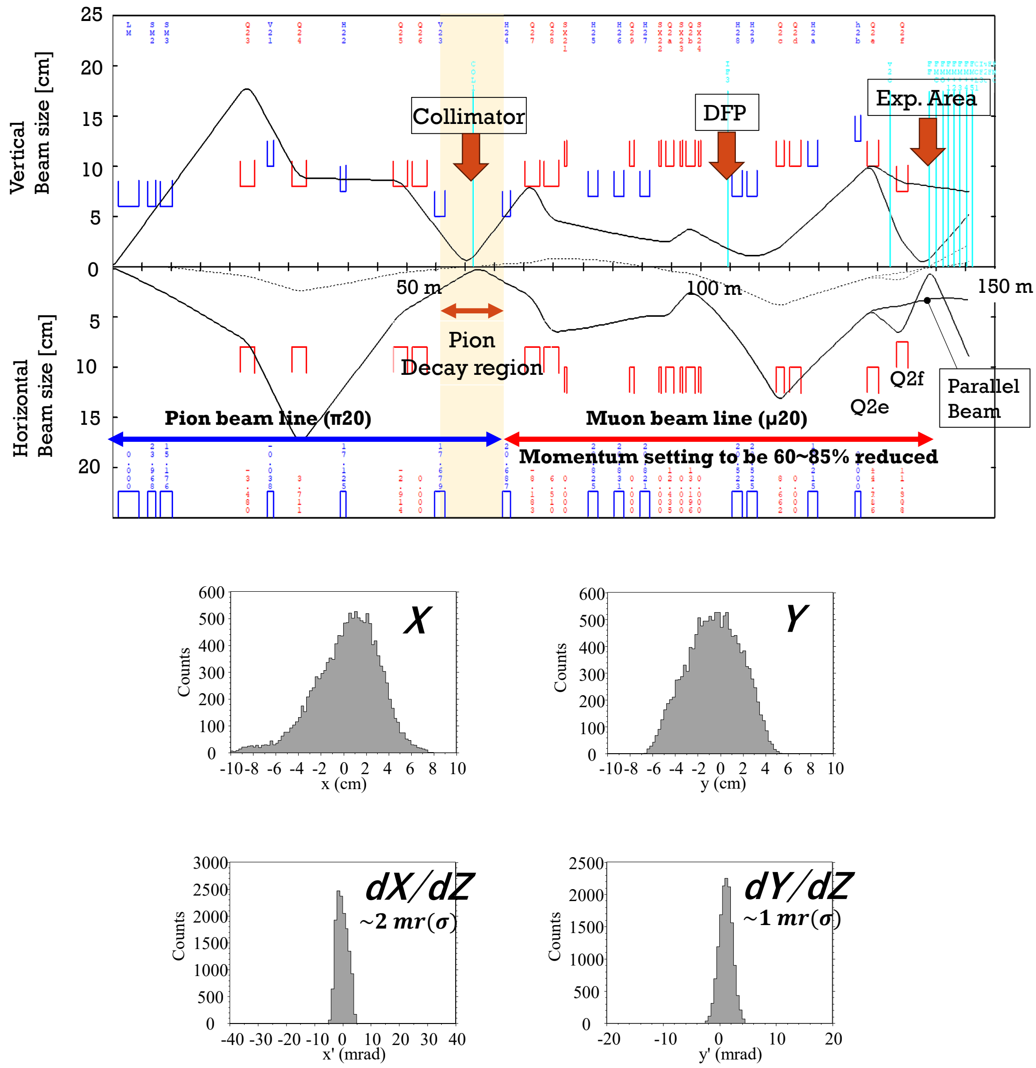

Figure 10: (upper panel) The first order calclation of the beam envelope for the $\pi 20/\mu 20$ beam line. Adjusting the last quadrupole magnets, Q2e and Q2f, a parallel beam optics is realized for the muon radiography. (lower panel) Parallel beam optics for muons at the experiment area simulated by the Decay TURTLE code.

TURTLE [6], we expect that the beam divergences as small as 2 mrad ($sigma$) and 1 mrad (σ) are realized in the horizontal and vertical direction, respectively (Fig. 10(lower panel)). Although the beam divergences make the measured θ_{rms} defuse, it can be deconvoluted.

Below is shown a summary of beam time request:

1.5 hours for Q2e/Q2f tuning

52 hours for data taking at 3 GeV/c

14.5 hours for data taking at 4.8 and 6 GeV/c

78 hours in total

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3 Setup

The detector system for the muon tomography is placed after the last quadrupole magnet, Q2f of the B-line. The layout of the system is shown in Fig. 11. A sample object will be located at the center of the setup. It is put on a turn table to irradiate it at any muon incident angle remotely. A set of scintilating fiber trackers, BFT1 and BFT2, are set in front of the sample object in order to measure the incident angle and position of the muon. Another set of scintillating fiber trackers, SFT1 and SFT2, are placed behind the sample object to measure the scattering angle of the muon.

References

[1] S. Yokkaichi *et al.*, J-PARC Proposal E16, "Measurements of spectral charge of vector mesons in nuclei" (2006).

[2] K. Shirotori *et al.*, J-PARC Proposal T106, "Proposal for the first stage of the P93 experiment (Evaluation of the performance of the secondary beam at the high-momentum beam line)" (2024).

[3] H. Noumi *et al.*, JST K Program Grant No. JPMJKP24J3, "Developement of a Portable Muon Four-Momentum Measuring System and a High-momentum Muon Source" (2024).

[4] K. Shirotori *et al.*, J-PARC Proposal, "Proposal for the second stage of the P93 experiment (Evaluation of the properties of the secondary particles delivered at the high-momentum beam line)" to be submitted.

[5] K. L. Brown, Advances in Particle Physics, 1, pp71-134(1967);
See also `http://aea.web.psi.ch/Urs_Rohrer/MyWeb/trans.htm`.

[6] K. L. Braown, D. C. Carey, Ch. Iselin, and F. Rothacker, CERN 80-04 (1980), SLAC Report No. 91, NAL 91;
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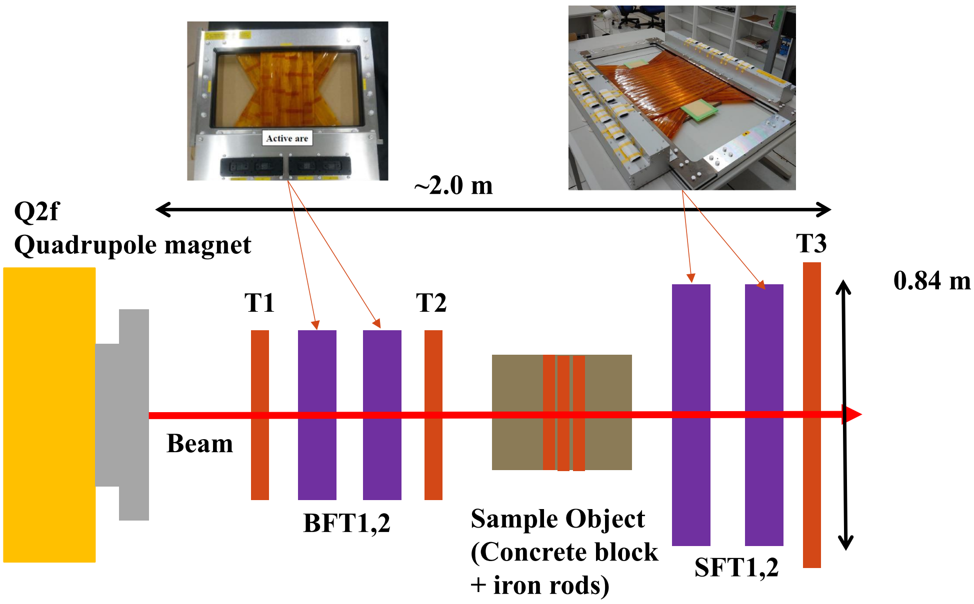

Figure 11: Schematic layout of the detector system. T1 and T2: plastic scintillators, the size of each scintillaor is a cross section of 20×20 cm^2 and 1 cm thick, BFT1 and 2: scinttilating fiber trackers, X(0°)U(30°V(-30°) configuration, with ϕ0.5-mm fibers are used. SFT1 and 2: scintillating fiber trackers, X(0°)U(30°V(-30°) configuration, with ϕ0.5-mm fibers are used. T3: plastic scintillator wall, the wall covers an 80 cm×60 cm sensitive area of SFTs.