Proposal for the first stage of the P93 experiment (Evaluation of the performance of the secondary beam at the high-momentum beam line)

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Executive Summary

We propose a test experiment to evaluate the performance of the delivered high-momentum secondary beam in terms of intensity, profile, and abundance of secondary particles at the high-momentum beam line. We aim to confirm the designed beam optics and to obtain operational information for the construction of the $\pi 20$ beam line from the actual beam extraction to evaluate the performance of the high-momentum secondary beam. This test experiment is the first step in the construction of the $\pi 20$ beam line for the realization of the E50 experiment.

This proposal describes the first stage of the P93 experiment, including the study of beam loss at the A-B branching point, scanning of the current setting of the most upstream beam-line magnets, and evaluation of optics and properties of positively charged beams. Beam loss, linearity of the beam-loss monitor response, scanning of the upstream beam-line magnets and reproducibility check are performed during the beam-line commissioning by the hadron experimental facility group (HDBL commissioning) using the shot-beam operation. The beam-loss stability check, evaluation of optics and properties of secondary beam are conducted simultaneously when the A-line is operated under the continuous beam. We request a total of 33 hours of beam time, including 9 hours for HDBL commissioning, 8 hours for detector commissioning and 16 hours for performance evaluation.

Beam line:	High-momentum beam line in the secondary beam mode
Beam polarity:	Positive
Beam momentum:	3, 5 and 10 GeV/c
Beam time:	33 hours in total, 9 hour for the HDBL commissioning, 8 hours for detector commissioning(5 GeV/c), and 16 hours for performance evaluation(3 and 10 GeV/c)

In addition, we propose a test experiment to measure muon beams after completing the P93 study at the B-line. We would like to show that muons produced from pions are delivered from the B-line by dedicating the upstream and downstream of the transport line to deliver pions and muons, respectively. For this, we will reduce the magnet currents in the downstream part of the B-Line to 60% or 85% of those in the upstream part in order to collect and seperate the decaying muons from undecayed pions. The beam pions will be absorbed by the downstream magnets in the switchyard. We request additional beam time of 1.5 hours in total for the confirmation of muon delivery.

Beam line:	High-momentum beam line in the secondary beam mode
Beam polarity:	Positive, as P93 expects to use.
Beam momentum:	3(1.8, 2.6), 5(3, 4.3), and 10(6, 8.5) GeV/c for pions (muons), as P93 expects to use
Beam time:	1.5 hours (15 minutes for each muon momentum)

1 First stage of the P93 experiment

According to the original P93 proposal [1], the following tests will be carried out in the first-stage P93 experiment;

1. study of beam loss at the A-B branching point,
2. scanning of the current setting of the small (SM2) and large (SM3) septum magnets, and
3. evaluation of optics and beam-line performance such as intensity, profile, and abundance of secondary particles using positively charged beams.

1.1 Beam-loss study at the A-B branching point

The SM collimator of the Lambertson magnet is utilized to produce secondary beam. The narrow roof of the SM collimator is irradiated with the primary proton beam so that the beam loss is below the limit for producing a secondary beam of sufficient intensity. Thus it is necessary to estimate the absolute value of the beam loss at the SM collimator, including information on the accuracy of the beam-loss measurement. We use the tail of the primary proton beam to produce the secondary beam and the amount of beam loss can be estimated from the beam power and the shape of the beam hitting the SM collimator. Although the beam shape can be measured with a profile monitor, the tail cannot be accurately estimated due to its low intensity. To accurately estimate the amount of beam loss, we irradiate the SM collimator as close to the center of the beam as possible, where a Gaussian approximation can be applied. With the amount of beam loss estimated by the above method, the loss monitor can be calibrated by comparing the amount of beam loss and can be used to estimate the production rate of the secondary beam.

A profile monitor is installed in front of the Lambertson magnet to measure the horizontal and vertical positions of the primary proton beam delivered to the production source point in the SM collimeter location. To obtain an accurate beam loss, we use the primary proton beam with a low intensity of about 5 kW and study the beam loss closer to the center of the primary proton beam which can be fitted by the Gaussian distribution at the shape of the irradiation spot of the SM collimator as shown in Fig. 1. When the proton beam positions at 2.5σ and 1.6σ from the center are used at the 5-kW beam, the corresponding beam losses are 125 W and 250 W by calculating from the proportions of the Gaussian distribution, respectively. Then these beam-loss values can be used to calibrate the beam-loss monitors around the A-B branching point as shown in Fig. 2. The accuracy can be estimated from the profile monitor and the fluctuations between the beam spots symmetrically irradiated from the center of the SM collimator. Accuracy information can also be obtained from the linear response of the beam loss from different irradiation points of the SM collimeter such as 2.5σ and 1.6σ from the beam center. This measurement determines the absolute value of the beam loss, including the accuracy, for the first time. The result of the study allows us to determine the beam-loss conditions with a safety margin for further studies.

We perform the beam-loss study under the shot-beam operation during the

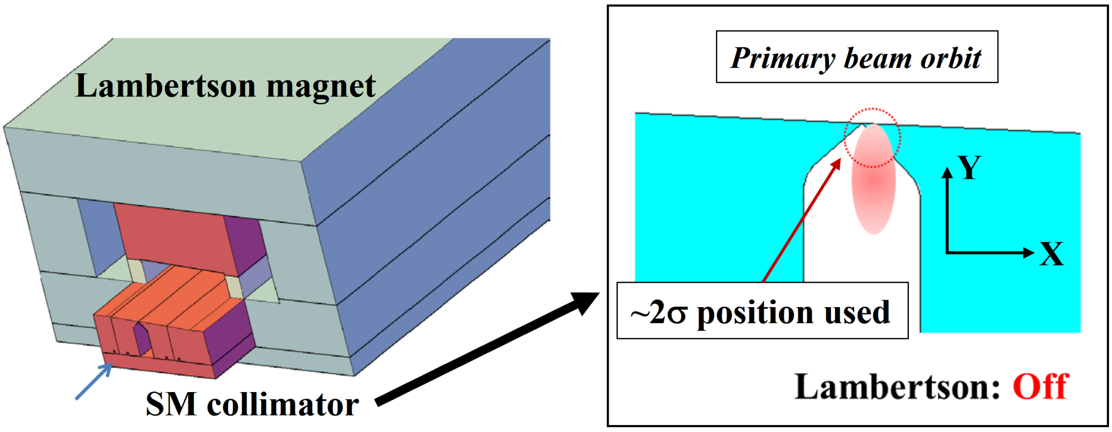

Figure 1: Study of the beam loss closer to the center of the primary proton beam at the SM collimator.

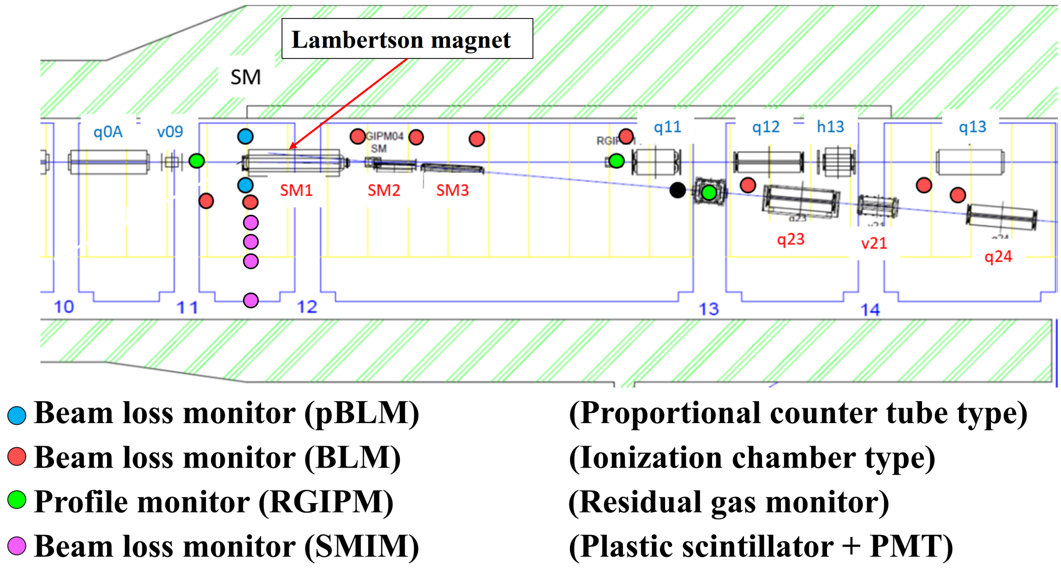

Figure 2: Positions of the loss monitors.

beam-line commissioning by the hadron experimental facility group (HDBL commissioning). The estimated beam time for the shot-beam operation is 2 hours, including the adjustment of the primary beam trajectory and the verification of the beam profiles and conditions. It is essential to study with safety precautions such as checking the radiation monitor values for each shot. We also study the linearity of the beam-loss monitor response with different primary beam power conditions. We use about 0.5 hours for study (once or twice) during the HDBL commissioning.

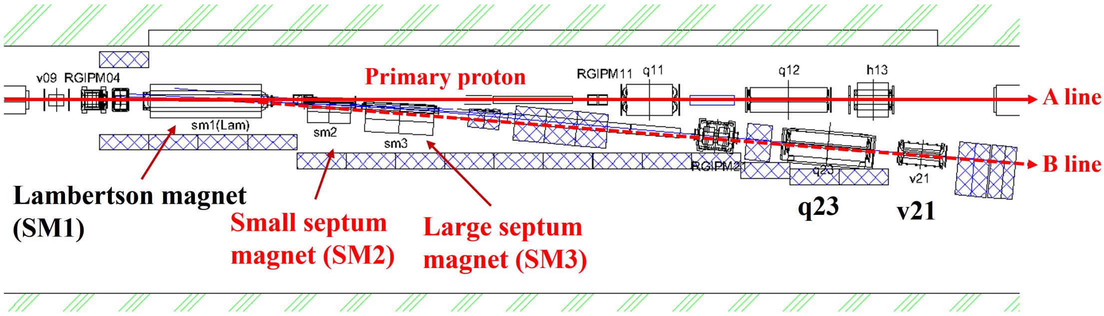

Figure 3: Pair of septum magnets called the small septum (SM2) and large septum (SM3) located downstream of the Lambertson magnet.

1.2 Scanning of the current setting values of the SM2 and SM3 magnets

A pair of septum magnets following the Lambertson magnet are called the small septum (SM2) and the large septum (SM3) as shown in Fig. 3. The Lambertson magnets are not used in the secondary beam mode, but it is necessary to adjust the current setting values of SM2 and SM3 to obtain the correct orbit for collecting the secondary beam from the loss point. The study of SM2 and SM3 involves scanning the magnet current setting value while checking the intensity of the delivered secondary beam from the counting rate measured by the timing counters. The beam-loss condition for scanning the SM2 and SM3 currents are determined by the beam-loss study at the A-B branching point described in Sec. 1.1.

Starting with the calculated magnet currents, the setting values of SM2 and SM3 are scanned by measuring the intensity of the delivered secondary beam depending on the set of the SM currents. The current setting at which the secondary beam intensity is maximum is found by scanning, and those value are used as of SM2 and SM3. Since the beam center position is adjusted by the downstream dipole and steering magnets, only the current settings with the maximum beam intensity are determined by this study.

This study was originally proposed as a tuning of the beam-line magnets during the continuous beam operation. However, it is performed under the shot-beam operation during the HDBL commissioning because the magnetic fields of SM2 and SM3 affect the trajectory of the primary proton beam in the A-line. We perform the scanning of SM2 and SM3 currents at the 5-GeV/c beam-line magnet setting. We need about 45 minutes for the 5-point measurement, including a beam condition confirmation shot and a 10-shot beam operation, according to the background study for the E16 experiment in the previous beam time [1]. We estimate the total beam time to be 4 hours, including both scans of the SM2 and SM3 currents with a re-tuning process.

1.3 Evaluation of optics and beam-line performance using positively charged beams

We perform the evaluation of the properties of positively charged beams by using the beam-loss condition and the current setting values of SM2 and SM3 determined from the studies described in Sec. 1.1 and 1.2, respectively. We perform the detector commissioning at the beginning of this study. The beam momentum of 5 GeV/c in the previous study is used to keep the same conditions for the detectors. The beam-line tuning involves scanning the magnet current setting value while checking the intensity and profile of the delivered secondary beam. We will scan the magnet current setting values as

1. dipole magnets for tuning the central orbit of the horizontal direction,
2. vertical steering magnets for tuning the orbit of the vertical direction, and
3. quadrople magnets for focusing the beam at the collimeter and the final-focus point (FF).

In Scanning 1 and 2, the current setting values of the dipole and vertical steering magnets are adjusted to center the delivered secondary beam orbit. The current setting values are verified by checking the centered position of the horizontal and vertical profiles on the FF. Before proceeding to Scanning 3, we repeat Scanning 1 and 2 to ensure that the secondary beam profile is centered. Scanning 3 mainly checks the focus of the beam at the collimator and at the FF. Focusing at the collimator will also be checked by the profile at the FF against the collimator aperture. At the collimator, the response of the profile at the FF is checked for proper focus. Since these scanning processes are correlated, the processes must be repeated to obtain the optimum magnet current setting.

We conduct the evaluation of beam optics and beam-line performance after fixing the primary proton beam power of $\sim$80 kW. Before the evaluation, the reproducibility of the beam loss and conditions of SM2 and SM3 for all beam momenta used in evaluation tests is to be confirmed under the shot-beam operation for 1 hour. We also conduct the stability check study under the continuous beam using the determined beam-loss condition and current setting of SM2 and SM3. It is estimated for 1 hour of the continuous beam operation. We use the secondary beam momenta of 5 GeV/c for the detector commissioning, and 3 and 10 GeV/c for the performance evaluation. The evaluation of the optics and properties of delivered secondary beam is conducted simultaneously during the A-line operation under the continuous beam. We request a beam time of 24 hours, including 8 hours for detector commissioning and 16 hours for performance evaluation.

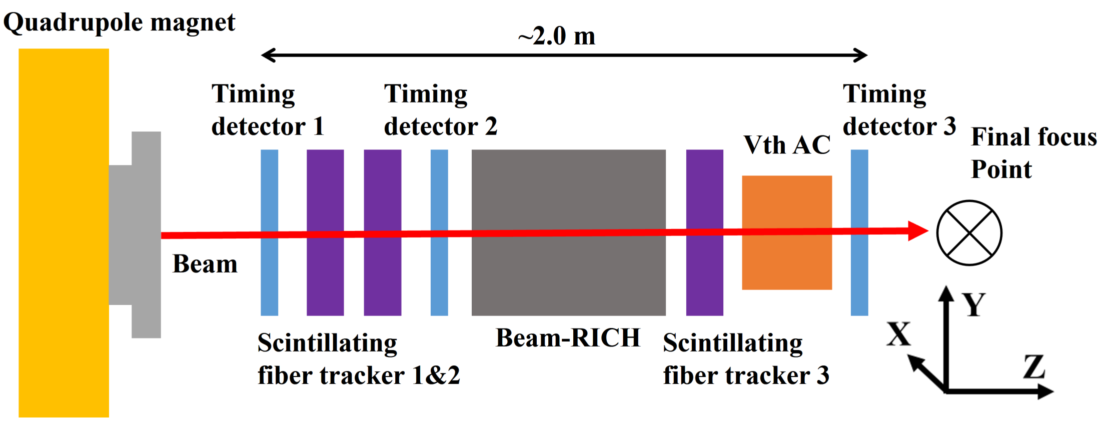

Figure 4: Schematic view of the experimental setup. Plastic scintillator timing detectors, scintillating fiber trackers, a RICH detector(Beam-RICH) and a threshold-type aerogel Cherenkov detector(Vth AC) are used. All detectors are installed on the beam direction (z-axis) downstream of the most downstream quadrupole magnet. The flight distance is ∼2.0 m between the upstream and downstream timing detectors.

1.4 Experimental setup

Beam intensity, profile, and secondary beam particle abundance are investigated. Beam intensity is measured as the counting rate of the beam timing detector. Beam profile is measured by the tracking detector as the horizontal (x) and vertical (y) position and incident angle distributions of the beam at the final focal point associated with the beam optics. The secondary beam particle abundance is studied by the particle identification detector.

The detectors used for studying properties of the delivered secondary beam are located downstream of the last quadrupole magnet to the final focusing point. All detectors are located in the beam direction (z-axis) as shown in Fig. 5 and study the intensity, profile, and secondary beam particle abundance with a plastic scintillator timing detector, a scintillating fiber tracker, and a particle identification detector, respectively. We use a RICH detector [4] and a threshold-type aerogel Cherenkov detector [5] for particle identification. All detectors have an effective area of more than 100 mm(x)×100 mm(y), which is sufficient to cover the secondary beam passage for the simulated beam profile. We use a trigger-less data-streaming type DAQ system. Details of the detectors and DAQ are referred to the original P93 proposal [1] and T103 proposal [2], respectively.

1.5 Beam time request

Beam loss (2 hours), linearity of beam-loss monitor response (0.5 hours×1 or 2) scanning of the most upstream beam-line magnets (4 hours), and reproducibility check (1 hour) are conducted during the HDBL commissioning under the shot-beam operation. The beam-loss stability check (1 hour) and the evaluation of the beam optics and the beam-line performance are conducted simultaneously during the A-line operation under the continuous beam.

We request 33 hours of beam timein total, including 9 hours for the HDBL commissioning, 8 hours for the detector commissioning and 16 hours for the performance evaluation. Using delivered positively charged beams, the detector commissioning is performed at a momentum of 5 GeV/c, and the test experiment for performance evaluation is conducted at momenta of 3 and 10 GeV/c.

The following table summarizes the beam time requirements.

Beam line:	High-momentum beam line in the secondary beam mode
Beam polarity:	Positive
Beam momentum:	3, 5 and 10 GeV/c
Beam time:	33 hours in total, 9 hour for the HDBL commissioning, 8 hours for detector commissioning(5 GeV/c), and 16 hours for performance evaluation(3 and 10 GeV/c)

2 Test experiment to collect and measure muon beams

We propose a test experiment to show the possibility of delivering muon beams at the B-line. Secondary pions produced at the Lambertson magnet transported in the upstream half of the beam line, and produced muons from the pion decay are provided in the downstream half. For this purpose, we will reduce the magnet currents in the downstream part (after the h24 magnet) of the B-line to 60% or 85% of those in the upstream part. The muons will be separated from the beam pions at h24. The swept beam pions will be absorbed by the downstream magnets in the switchyard. This is the first trial to set beam-line parameters with different momenta depending on beam-line magnet in the B-line. We will additionally test a muon mode with two selected momenta for muons just after the ordinary secondary beam mode used by P93 for each momentum of pions. We request another beam time of 1.5 hours in total for the confirmation of muon delivery.

Below are the summary of request.

Beam line:	High-momentum beam line in the secondary beam mode
Beam polarity:	Positive, as P93 expects to use.
Beam momentum:	3(1.8, 2.6), 5(3, 4.3), and 10(6, 8.5) GeV/c for pions (muons), as P93 expects to use
Beam time:	1.5 hours (15 minutes for each muon momentum)

2.1 Setup: Secondary Beam profile monitors

We have proposed a test experiment P93 to confirm the properties of secondary beams at the B-line [1]. We will employ the P93 beam monitors to measure the muon profile. The beam monitor system for the secondary beams are placed after the most downstream quadrupole magnet, q2f, of the B-line. The layout of the system is shown in Fig. 5.

2.2 Experimental Plan

2.2.1 Muon measurement

We will change beam-line parameters (magnet-current setting) to extract a muon beam, to be described in details in the next subsubsection. We will measure the muon profile: (1) intensity, (2) spatial distribuion, and (3) purity. For (1) and (2), we will use the same timing counters and fiber trackers used in the P93 measurement. For (3), we will set a muon filter (MF) in the P93 setup, as shown in Fig. 5. The MF is composed of 4 plastic scintillators and 3 iron blocks. Each scintillator and iron block have volumes of 20×20 cm^2(cross section)×1 cm(thick) and 20×20

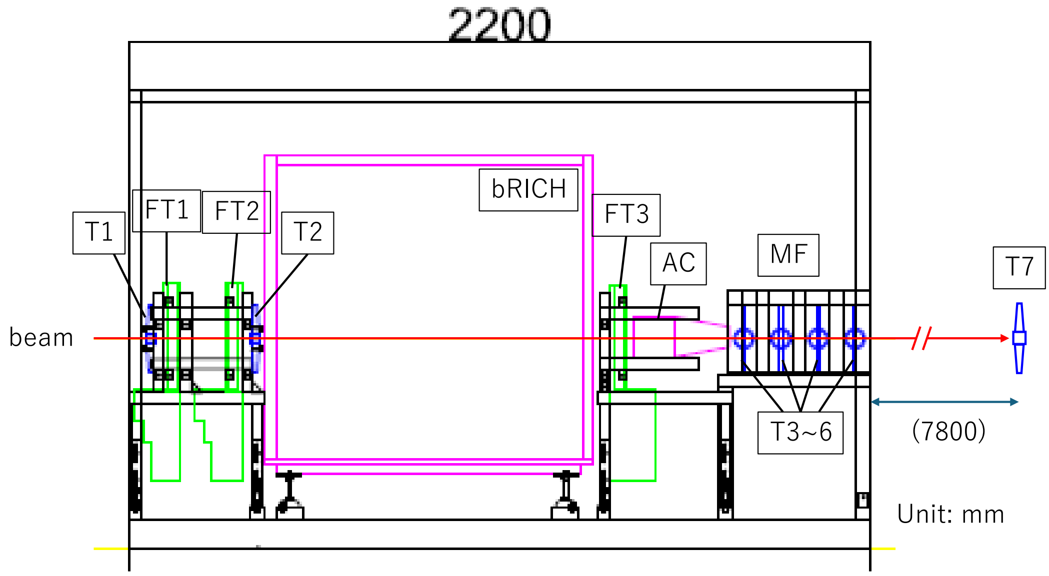

Figure 5: Layout of the beam monitor system. T1∼T7: plastic scintillators, the size of each scintillaor is a cross section of 20×20 cm^2 and 1 cm thick, FT1∼3: scinttilating fiber trackers, X(0°)U(30°)V(-30°) configuration, with ϕ0.5-mm and ϕ1-mm fibers are used for FT1,2 and FT3, respectively. bRICH: a ring imaging cherenkov counter with aerogel radiators of the refractive index of 1.02. AC: a threshold-type cherenkov counter with aerogel radiators of the index of 1.007. MF: a muon filter composed of 3 iron blocks and 4 plastic scintillator (T3∼T6), the size of each iron block measures a cross section of 20×20 cm^2 and a thichness of 10 cm.

cm^2(cross section)×10 cm(thick), respetively. They are placed alternatingly to estimate contamination of hadrons by measuring attenuation of the beam. We will use the measured attenuation length (effective absorption length) of hadron beams during the P93 measurement.

2.2.2 High-momentum muon beam line

The B-line in the J-PARC hadron experimenal facility is operated to deliver a small fraction of the primary protons of 30 GeV for the E16 experiment [3]. The plan view of the B-line is shown in Fig. 6. 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 reduce transferred 30-GeV protons to 0, remaining secondary pions of 10^5 per spill passing through the B-Line. Here, we call this operation mode π20. A test experiment, P93 [1], has been proposed to study the π20 beam line and the preparation is in progress under the P93 task force.

A pion decays into a muon and a muon neutrino in 26 nano seconds at rest. As illustrated in Fig. 7, 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

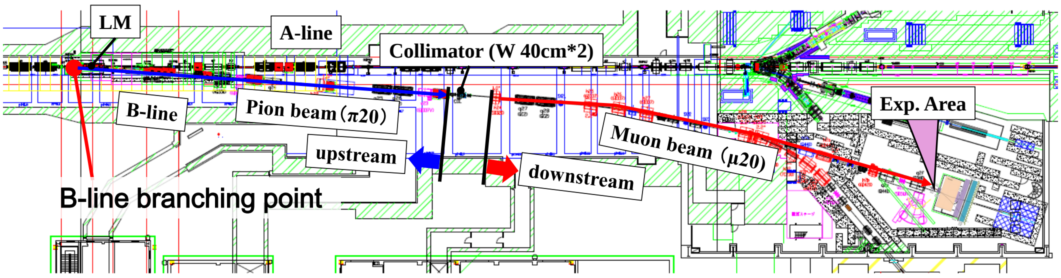

Figure 6: Current layout of the B-line. It is branched from the A-line at the so-called the Lambertson magnet. A small fracion of the primary protons are splitted by the Lambertson magnet into the B-line. The B-line can be operated to collect and transfer secondary particles produced at the Lambertson magnet.

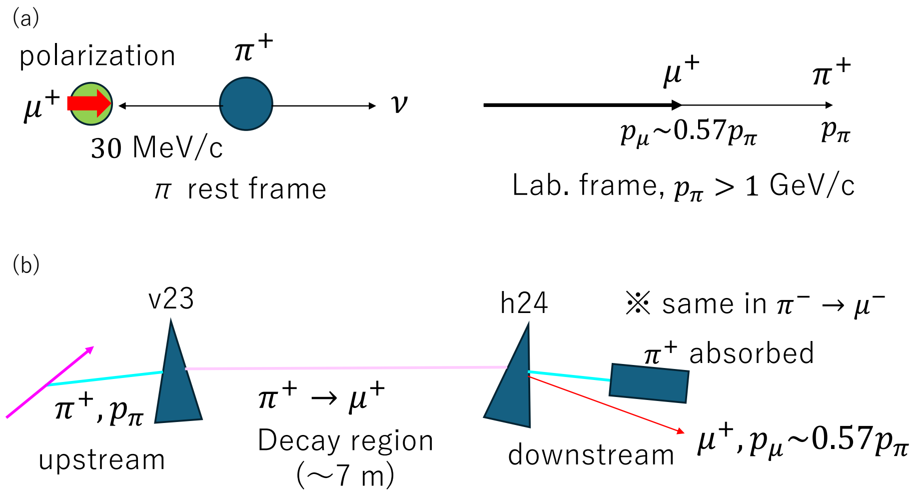

Figure 7: (a) Graphical illustrations of a pion decay into a muon and a neutrino in the pion rest frame and the laboratory frame. In the pion rest frame, the muon is emitted in the opposite (backward) direction to the pion travelling direction. In this case the muon momentum is 57% of the pion momentum in the laboratory frame. (b) Concept of the $\mu 20$ mode. A part of pions passing though the upstream part of the beam line decay into muons (and neutrines) 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.

an optimized design to separate the backward-decaying muons from the beam pions completely. We call this new operation mode of the beam line as μ20. A concept of the μ20 mode is illustrated in Fig. 7(b). A secondary beam is focused once at the collimator placed at a distance of approximately 60 m from the origin. Vertical and horizontal bending magnets (v23 and h24) are placed upstream and downstream of the collimator, respectively. The maximum opening gaps of the collimater are as wide as 120 mm both horizontally and vertically. In the μ20 mode, we will simply operate the upstream part of the beam line to v23 vertical with a parameter set at a certain central momentum and the downstream part from h24 at 60% of the central momentum set in the upstream. The backward-decaying muons from pion decays occurred in the drift space between v23 and h24 ($\sim$7 m) are collected and transferred through the downstream part of the beam line. The beam pions are swept out since it is out of acceptance of the downstream part and will be absorbed by the downstream magnets in the switchyard. We demonstrated with a simulaion if this concept works. Figure 8 shows expected intensities of muons and beam pions at the end of the beam line in the cases of parent pions at 10 and 20 GeV/c as a function of momentum set for the downstream part of the beam line. Here, we assume 420-W loss at the Lambertson magnet. One can transfer sideward-decaying muons by setting a bit higher momentum set of magnetic parameters in the downstream. According to an ion optical simultion with the Decay-TURTLE code [6], muons of up to 88% of the parent pion's momentum can be transferred without pion contaminations. We expect $\sim$300 and $\sim$500 muons per second at 6 and 8.5 GeV/c in the case of a pion beam at 10 GeV/c. The expected beam profile of backward-decaying muons at 6 GeV/c at the end of the beam line is shown in Fig. 9. The μ20 beam line would provide unique opportunities for imaging with muon beams at a momentum range of 0.5$\sim$20 GeV/c, as described in the next subsection.

2.3 Background of the present muon measurement

High-momentum muons of multi-GeV/c are useful for the so-called muon radiography. According to the multiple Coulomb scattering theory, the standard deviation f the scattering angle distribution ($\theta_{\rm rms}$) of a muon passing through a material is described as,

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

where L and X_0 are the path length and the radiation length of the material, respectively. Since the velocity of the muon greater then $\sim$1 GeV/c is almost β=1, $\theta_{\rm rms}$ is propotional to the inverse of the muon momentum (p) and depending on X_0 that is the quantity intrinsic to the material. Figure 10 plots $\theta_{\rm rms}$ estimated for various materials of 50-cm long as a function of the incident muon momentum. One can estimate density distribution in the material through measuring $\theta_{\rm rms}$. For a simulation, we considered the cases where 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 long, each of which as a 2×2 cm^2 cross section, inserted in the center of the

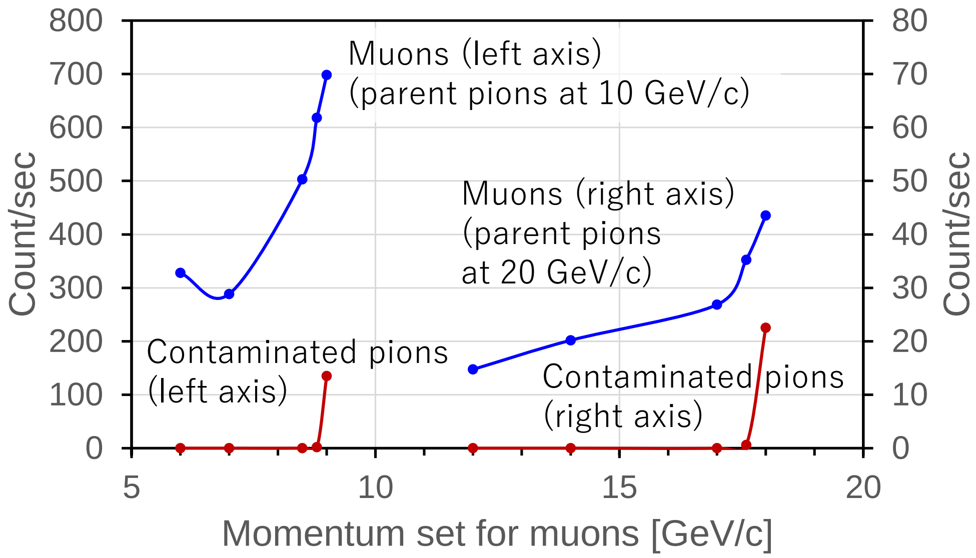

Figure 8: Muon and pion intensities at the end of the beam line in the cases of parent pions at 10 and 20 GeV/c as a function of momentum set for the downstream part of the beam line.

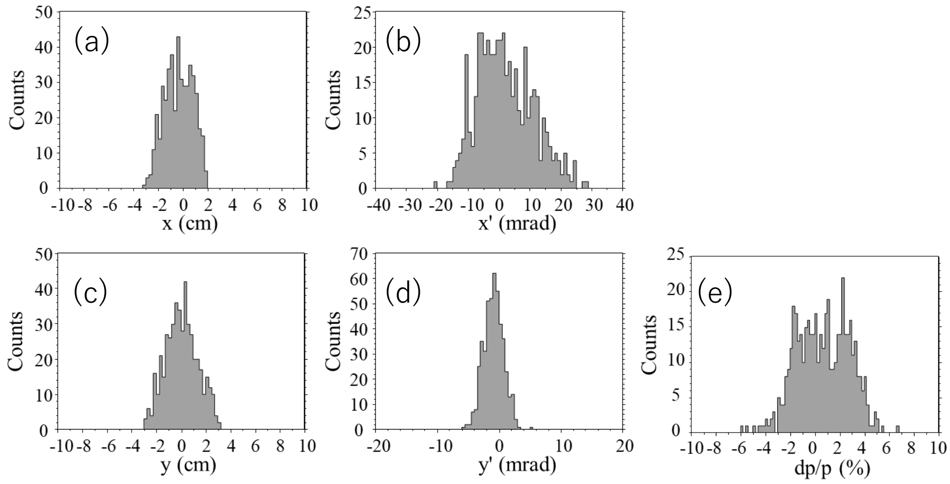

Figure 9: Muon profile at the end of the beam line estimated by the Decay-TURTLE ion-optical simulation code [6] for backward decaying muons at 6 GeV/c (parent pions at 10 GeV/c).

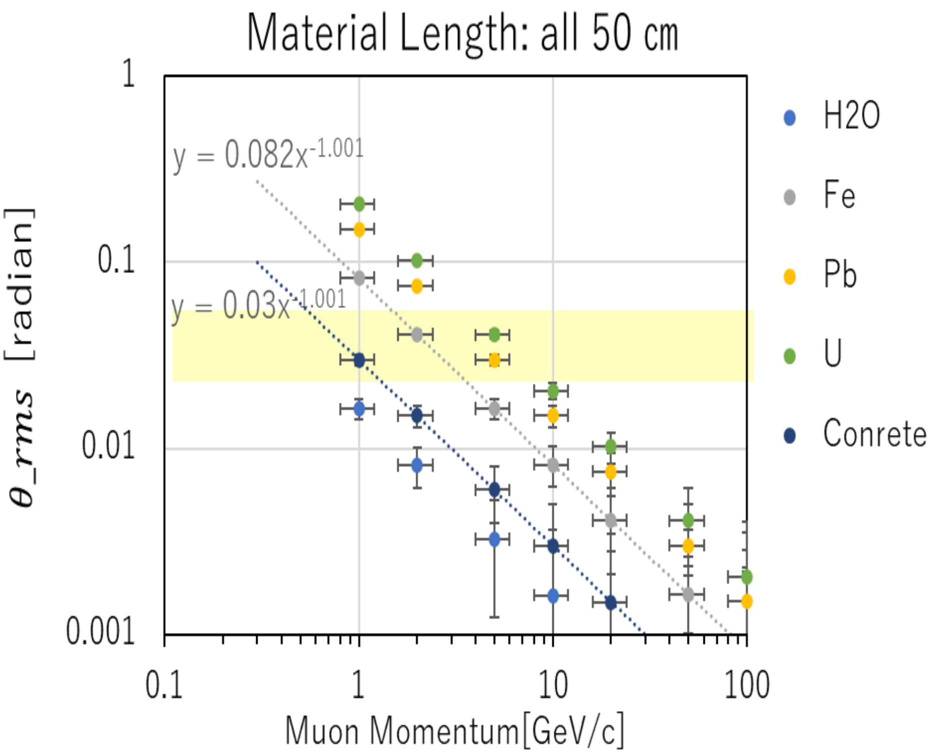

Figure 10: Standard deviation width of Coulomb multiple scattering angle, θ_{rms}, estimated for muons passing through water, concrete, standard rock, iron, lead, uranium of 50 cm long as a function of muon momentum.

block with keeping a distance of 10 cm, as illustrated in Fig. 11. Figure 12 shows the expected θ_{rms} as a function of the muon incident position. The scattering angle θ_{rms} is enhanced at the position of the iron bar. When we plot θ_{rms} normalized to that at the origin, $X = 0$, (Fig. 12(b)), it is independent of the incident momentum. This means that $\theta_{\text{rms}} p$ is sensitive to the averaged radiation length $\bar{X}_0$ defined as $L/\int dZ/X_0(Z)$.

We recently received a JST K Program Grant for developping a portable muon four-momentum measuring system and a high-momentum muon source [7]. The muon measurement in the present proposal is related to this grant. We are planning to carry out an experiment to demonstrate a muon radiography with above mentioned sample scatters by using the high-momentum muon beams. The present muon measurement provides basic information to evaluate feasibility to perform the muon radiography.

Owing to this grant, we will introduce polarity changing devices for the B-line magnet power suppliers. After introducing the polarity changing devices, P93 will be able to study negative secondary particles.

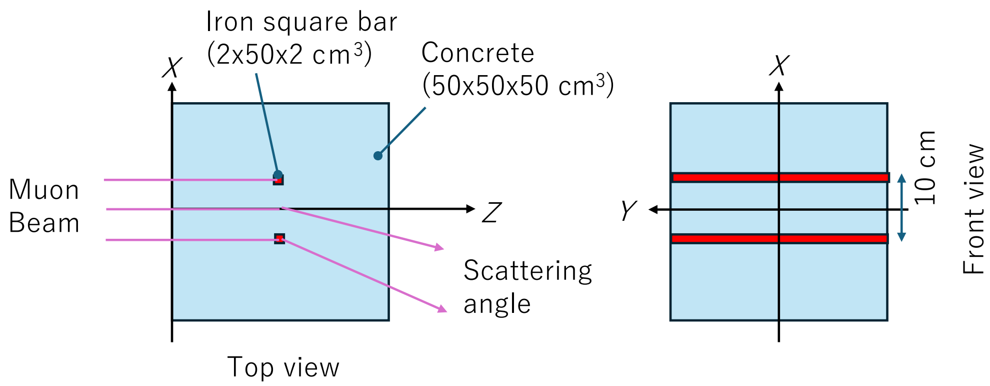

Figure 11: Concrete block of 50×50×50 cm^3 considered as a scatterer by muons in the simulation. A pair of iron square bars of 50 cm length, each of which has a cross section of 2 cm by 2 cm, are inserted in the center of the block with keeping a distance of 10 cm.

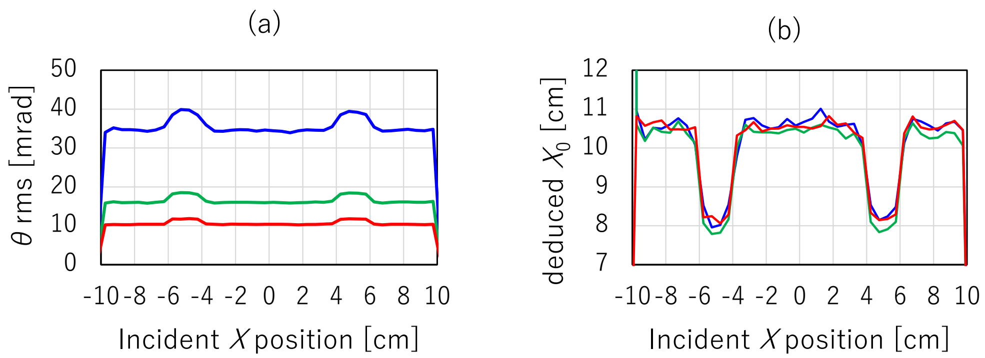

Figure 12: (a) $\theta_{\rm rms}$ distribution as a function of the incident position (X). (b) X_0 deduced from the measured $\theta_{\rm rms}$ as a function of the muon incident position X.

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