Proposal for the second stage of the P93 experiment (Evaluation of the properties of the secondary particles delivered at the high-momentum beam line)

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ver. June 16, 2025

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Executive Summary

Second stage of the P93 experiment

We propose a test experiment to evaluate the properties of the delivered high-momentum secondary beam: intensity, profile, and abundance of secondary particles at the high-momentum beam line. This proposal describes the second stage of the P93 experiment, including the reproducibility check of beam loss at the A-B branching point and evaluation of optics and properties of the secondary beam. Reproducibility check of beam loss, linearity of the beam-loss monitor response and scanning of the upstream beam-line magnets are performed during the beam-line commissioning by the hadron experimental facility group (HDBL commissioning) using the shot-beam operation. The evaluation of optics and properties of secondary beam are conducted simultaneously when the A-line is operated under the continuous beam. We request 52 hours in total, which include 6 hours for HDBL commissioning, 4 hours for detector commissioning and 42 hours for studying the properties of delivered secondary particles.

Beam line:	High-momentum beam line in the secondary beam mode
Beam polarity:	Positive and Negative
Beam momentum:	2, 5, 8, 10, 15 and 20 GeV/c for negative particles
	20 GeV/c for positive particles
Beam time:	52 hours in total,
	6 hour for the HDBL commissioning,
	4 hours for detector commissioning, and
	42 hours for evaluation of secondary beam properties

Test experiment to measure properties of the muon beam

In addition, we propose a test experiment to measure properties of the muon beam after completing the secondary particle study at the B-line. We would like to measure the intensity and purity of the muon beam produced from pions at 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%, 75%, 80% and 85% of those in the upstream part in order to collect and separate muons from undecayed pions. We request beam time of 8 hours in total for measurement of muon beam properties.

Beam line:	High-momentum beam line in the μ20 mode
Beam polarity:	Negative, as P93 expects to use.
Beam momentum:	2(1.2, 1.5, 1.6, 1.7), 5(3, 3.8, 4, 4.3), and
	20(12, 15, 16, 17) GeV/c for pions (muons),
	as P93 expects to use
Beam time:	8 hours in total

1 Introduction

We are aiming at realizing the $\pi20$ beam line that can provide high-intensity and high-momentum secondary beams at momenta ranging from 2 to 20 GeV/c. We propose a test experiment to evaluate the designed beam optics and to obtain operational information for the construction of the full $\pi20$ beam line from the actual beam extraction. Beam characteristics such as beam intensity and profile are essential technical information for the charmed baryon spectroscopy experiment (E50) [1]. This test experiment is a solid step in the construction of the $\pi20$ beam line for the realization of E50. It is necessary to understand the beam optics and beam properties to define the secondary beam production source point. The source (SM collimator of the Lambertson magnet) can be defined at the A-B branching point in the test experiment. The beam optics and beam performance must be confirmed for the $\pi20$ beam-line design. Beam optics is strongly related to the trajectory and size of the secondary beam extracted in the high-p beam line. The design and construction of beam-line components such as beam-line magnets, and radiation shield require information on these orbits and magnitudes, which are estimated by measuring the secondary beam characteristics. Beam-loss control is necessary in the staging plan for the $\pi20$ beam line. The beam loss at the production target must be controlled according to the intensity and emittance of the primary proton beam at each beam time. Therefore, secondary beam extraction is definitely needed to confirm beam optics and beam properties for the full $\pi20$ construction.

We have already proposed experiments using high-momentum secondary beam at the high-p beam line. The stage-1 status are assigned for

- Spectroscopy of charmed baryons (E50) [1],
- Studies of non-strange dibaryons (E79) [2],
- Studies of the intermediate states coupling to ϕN (E95) [3], and
- Spectroscopy of Ξ baryons (E97) [4].

The proposal and Letter of Intents (LOI's) submitted are

- Spectroscopy of Ω baryons (P85) [5],
- Study of the generalized parton distributions [6],
- Study of Λp scattering [7], and
- Double anti-kaon production in a nucleus [8].

The high-intensity secondary beam at the Hadron Experimental Facility at J-PARC are essential for those experiments. At the present facility, no secondary beam with a momentum higher than 2 GeV/c can be provided. Therefore, we are aiming at realizing the $\pi20$ beam line to promote hadron physics research.

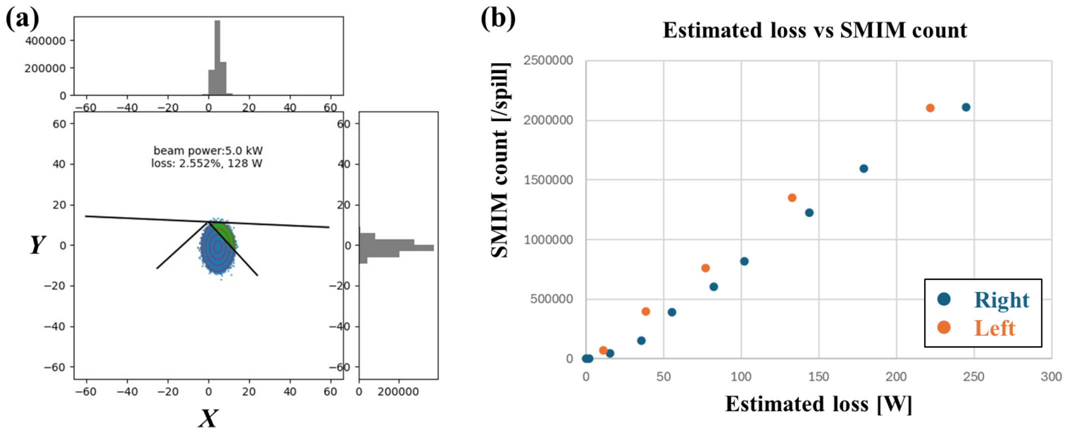

Figure 1: (a) Schematic drawing of the two-dimensional (X,Y) intensity map, or the profile, for the primary beam with the shape of the irradiation spot of the SM collimator location. A Gaussian distribution is assumed for the primary beam profile. The beam particles are plotted in the left panel together with contour lines up to four times of the standard deviation. (b) The correlation between the estimated beam loss and the measured SMIM count. Blue and orange points show the estimated beam loss when the primary proton beam hits on the left and right sides on the figure (a), respectively.

2 Second stage of the P93 experiment

According to the original P93 proposal [9] and the first step T106 experiment [10], the following tests will be carried out in the second stage of the P93 experiment;

1. reproducibility check of beam loss at the A-B branching point and the current setting of the small (SM2) and large (SM3) septum magnets, and
2. evaluation of optics and beam properties such as intensity, profile, and abundance for negatively charged particles.

2.1 Reproducibility check of the beam loss and current scan of the septum magnets (SM2 and SM3)

We have measured the beam loss at the A-B branching point in the first step experiment, T106 [10]. In order to measure an accurate beam loss and calibrate the beam loss monitor (SMIM), we used the primary proton beam with a low intensity of ∼5 kW. We studied the amount of beam loss by changing the position of the primary proton beam and measured the SMIM count. Then, the beam loss was estimated by calculating the beam power with the shape of the irradiation spot at the SM collimator location as shown in Fig. 1(a). Gaussian position distributions are assumed in the profile of the primary beam. Consequently, the correlation between the estimated beam loss and the SMIM count was obtained as shown in Fig. 1(b). The beam loss as a function of the SMIM count was employed to estimate the beam loss with ∼30 and ∼80 kW in the T106 experiment. Finally, the estimated beam

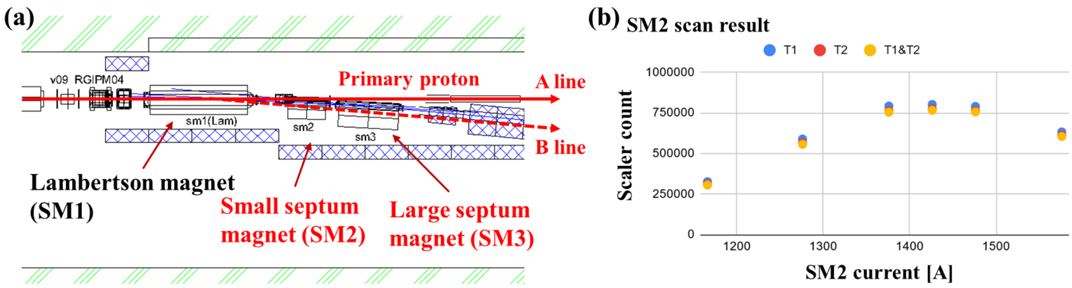

Figure 2: (a) Pair of septum magnets called the small septum (SM2) and large septum (SM3) located downstream of the Lambertson magnet. (b) Counts of secondary particles as a function of the SM2 current.

loss of ∼230 W with the primary beam power of 83 kW was used for the evaluation of optics and beam properties.

To check the reproducibility of the beam loss, we will carry out the same measurement as of the T106 experiment at the beginning. The measurement is to check of the reproducibility with a certain number of data points.

Although the beam power is expected to be ∼30 kW at the starting stage of the MR accelerator tuning, it can be used for the reproducibility check and we will compare the 30-kW data obtained in the T106 experiment. Furthermore, we also plan to improve the beam profile monitor and SMIM. The profile monitors are 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. However, the profile monitor for horizontal position didn't work in the T106 experiment. Thus, we will operate the horizontal profile monitor and improve the accuracy of beam profile measurement. It was found that the number of counts in SMIM was saturated at a rate higher than 10 Mcps. We plan to install an additional beam loss monitor (SMIMh) with a size smaller than SMIM. SMIM has has plastic-scintillator blocks with widths of 20 mm and 10 mm for horizontal and vertical directions, respectively, while we will install 3 mm squared size ones for SMIMh. We expect one order magnitude smaller counting rate for each block such as 1 Mcps so that the counting rate saturation can be suppressed.

In the T106 experiment, we scanned the magnet current of SM2 and SM3 as shown in Fig. 2. The reproducibility check of the setting values will be preformed after the beam loss study. Starting with the current setting of SM2 and SM3 determined by the T106 experiment at which the secondary beam intensity is maximum as shown in Fig. 2(b), a few points around the determined current setting are scanned by measuring the intensity of the delivered secondary particles. The current setting at which the secondary beam intensity is maximum is found by scanning, and those value are employed to SM2 and SM3.

We will perform the beam-loss study under the shot-beam operation during the beam-line commissioning by the hadron experimental facility group (HDBL commissioning). The estimated beam time for the shot-beam operation is 5 hours according to the T106 experiment. This beam time includes the reproducibility check of beam loss and septum magnet scan. After the reproducibility check, we

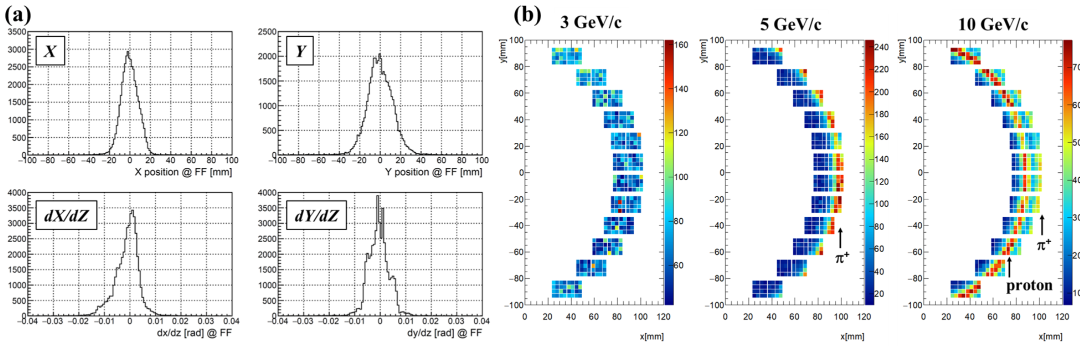

Figure 3: (a) The measured beam profiles of the scondary beam at 10 GeV/c. Horizontal (X) and vertical (Y) positions and angles of incidence with respect to the beam direction (dX/dZ, dY/dZ). (b) Hit pattern of the ring-imaging Cherenkov detector. The Cherenkov ring pattern of proton at 10 GeV/c was clearly observed in the most right figure.

also conduct the stability check under the continuous beam with the magnet current setting for negative particles for confirming the stable operation of polarity change devices. It is estimated that 1 hour is required for the continuous beam operation.

2.2 Evaluation of optics and beam properties using negative beams

We conduct the evaluation of the properties of secondary beam, mainly for negatively charged beam. The beam-loss condition and the magnet current of SM2 and SM3 determined from the studies described in Sec. 2.1 will be used. We perform the detector commissioning at the beginning of this study. The beam momentum of 10 GeV/c with positive charge is used with the same condition as the T106 experiment. The beam-line tuning involves scanning the magnet current while measuring the intensity and profile of the delivered secondary beam. By the same way as the T106 experiment, we will scan the currents for the transport magnets 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 currents of the dipole and vertical steering magnets are scanned to maximize beam intensity and to center the delivered secondary beam orbit. The magnet currents are verified by checking the beam intensity and 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 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 beam intensity against the collimator aperture by scanning the magnet current of the upstream

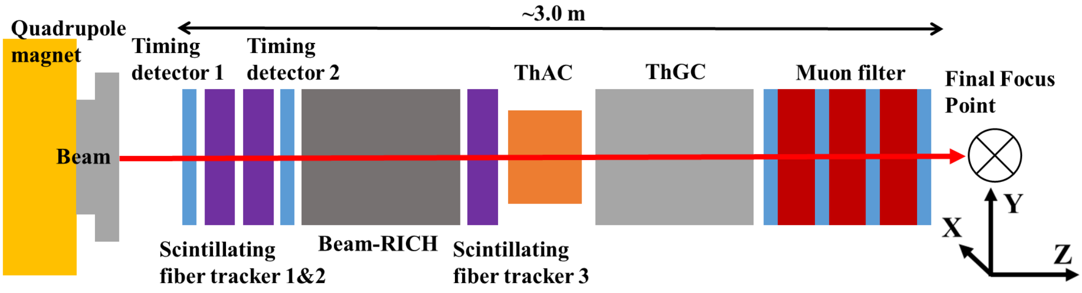

Figure 4: Schematic view of the experimental setup. Plastic scintillator timing detectors, scintillating fiber trackers, a RICH detector (Beam-RICH), a threshold-type aerogel (ThAC) and gas (ThGC) Cherenkov detectors, and a range counter for muon beam measurement (Muon filter) are used. All detectors are installed on the beam direction (z-axis) downstream of the most downstream quadrupole magnet, q2f, of the B-line. The distance is $\sim$3.0 m between the upstream timing detector and the final layer of the Muon filter.

quadrople magnets. Since these scanning processes are correlated, the processes must be repeated to obtain the optimum magnet current .

In the previous T106 experiment, we obtained the data of positively charged secondary beams to evaluate the optics and beam properties. We measured the intensity of 0.2, 0.6 and 1.4 M/spill including all positively charged particles such as π^+ and proton at 3, 5 and 10 GeV/c, respectively. Figure 3(a) shows the measured secondary beam profiles on the FF at 10 GeV/c. The distributions of horizontal and vertical positions and angles of incidence with respect to the beam direction were obtained with the sizes of $\sim$10 mm(σ) and $\sim$4 mrad(σ), respectively. The hit pattern of the ring-imaging Cherenkov detector was obtained as shown in Fig. 3(b). The Cherenkov ring pattern of proton at 10 GeV/c was clearly observed in the most right figure. We aim at obtaining the same data of the negatively charged secondary beam to evaluate the optics and beam properties.

We conduct the evaluation of beam optics and beam properties after fixing the primary proton beam power of $\sim$90 kW. We use the beam momentum of +10 GeV/c for the detector commissioning, and seven beam momenta of -2, -5, -8, -10, -15 and ±20 GeV/c for the evaluation of beam properties ("+" and "$-$" denote positively and negatively charged beams, respectively). The evaluation of the optics and properties of delivered secondary beam is performed simultaneously during the A-line operation under the continuous beam. We request the 46 hours beam time in total, which includes 4 hours for detector commissioning and 42 hours for evaluation of beam properties (6 hours per each momentum).

2.3 Experimental setup

Beam intensity, profile, and secondary particle abundance are studied in the experiment. 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

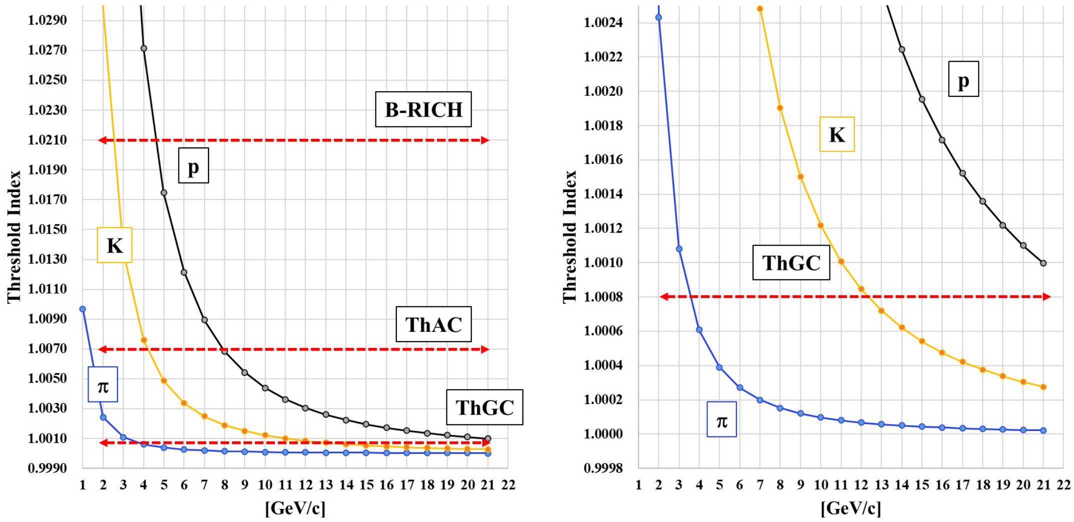

Figure 5: The threshold momentum range by each PID detector. Right figure is a close-up of the lower index region. Each particle with momentum below each dashed line with refractive index of the PID detector can produce Cherenkov light.

associated with the beam optics. The secondary beam particle abundance is studied by the particle identification detector.

The detector setup for the T106 experiment will also be used for the experiment. Detector setup is located at the most downstream of the last quadrupole magnet, q2f, of the B-line as shown in Fig. 4. We 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 (Beam-RICH) [12] and threshold-type aerogel Cherenkov detectors (ThAC) [13] for particle identification. A threshold-type gas Cherenkov detector (ThGC) will be used additionally for the higher momentum particle identification. The refractive index of Beam-RICH, ThAC and ThGC are 1.021, 1.007 and 1.0008, respectively. The threshold momentum range by each PID detector is shown in Fig. 5. Depending on the experimental conditions of the proposed and forthcoming experiments at π20, we plan to identify all secondary particle abundance ($\pi^{\pm}$, $K^{\pm}$ and $p/\bar{p}$) from 2 to 10 GeV/c while only $\pi^{\pm}$ (including $K^{\pm}$) and $p/\bar{p}$ are identified from 15 to 20 GeV/c. Although ThGC is a new additional detector from the previous T106 experiment, we plan to used a conventional gas Cherenkov detector [14] as ThGC. A range counter (Muon filter) is used for the muon beam measurenet as described in Sec. 3. All detectors have an effective area larger than 100 mm(x)$\times$100 mm(y), which is sufficient to cover the secondary beam passage for measuring the 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 [9] and T103 proposal [11], respectively.

2.4 Beam time request

Reproducibility check of beam loss, linearity of the beam-loss monitor response, scanning of the upstream beam-line magnets are performed during the beam-line commissioning by the hadron experimental facility group (HDBL commissioning) using the shot-beam operation (5 hours). The stability check of porality change devices (1 hour) and the evaluation of the beam optics and the beam properties are conducted simultaneously during the A-line operation under the continuous beam. We request 52 hours in total, which includes 6 hours for HDBL commissioning, 4 hours for detector commissioning and 42 hours for studying the properties of delivered secondary particles.

The following table summarizes the beam time requirements.

Beam line:	High-momentum beam line in the secondary beam mode
Beam polarity:	Positive and Negative
Beam momentum:	2, 5, 8, 10, 15 and 20 GeV/c for negative particles
	20 GeV/c for positive particles
Beam time:	52 hours in total,
	6 hour for the HDBL commissioning,
	4 hours for detector commissioning, and
	42 hours for evaluation of secondary beam properties

2.5 Beam time allocation

The present B-line is only capable of delivering the positively charged beam. In order to deliver the negatively charged secondary beam, it is necessary to install the polarity change device on the power supply of the beam line magnet of the B-line. We prepared the budget for the polarity change device [15]. The production and installation work of the devices are expected to be completed by the first half of Japanese fiscal year 2026 (JFY2026). Although the beam time allocation depends of the situation of the E16 experiment [16], the proposed experiment can be allocated after completing the installation of the polarity change devices.

3 Test experiment to measure properties of the muon beam

We propose a test experiment to measure properties of the muon beam after completing the secondary particle study at the B-line. We would like to measure the intensity and purity of muon beams produced from pions 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%, 75%, 80% and 85% of those in the upstream part in order to collect and seperate the decaying muons from undecayed pions. The pions will be absorbed by the downstream magnets in the switchyard. This beam line operation mode is called μ20 referred to the T106 proposal [10].

3.1 Setup: Secondary beam profile monitors

We have proposed the T106 test experiment to confirm the properties of the secondary beam at the B-line [10]. We will also employ the T106 beam monitors to measure the intensity and profile of muon beams. The beam monitor system for the secondary beam are placed after the most downstream quadrupole magnet, q2f, of the B-line. The layout of the system is shown in Fig. 4.

The Muon filter comprises four layers of scintillators and three absorbers made of iron blocks of volumes of 20×20 cm^2(cross section)$\times1$ cm(thick) and 20×20 cm^2(cross section)$\times10$ cm(thick), respetively. Photomultipliers (PMT: H6410) are attached to single side of each scintillator. In the previous T106 experiment, we found that the gain fluctuation of PMTs in the high-counting rate condition and high energy deposit events. Although we could analyze charged particle hits, we could not use energy deposit information. We will prepare a booster for PMTs and perform precise gain adjustment to study both minimum ionization events (muon beam) and high enegy deposit ones by hadornic reactions (hadron beam).

3.2 Measurement of the muon beam properties

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 T106 measurement. For (3), we will set a muon filter (MF) in the T106 setup, as shown in Fig. 4. The Muon filter is composed of four plastic scintillators and three iron blocks. 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 beam during the measurement.

The measured muon beam intensities in the T106 experiment were found to be several 100 – several 1000 /spill in the upstream part momentum at 3, 5, and 10 GeV/c while that of hadron beam is a few 100 k – a few M/spill. Figure 6(a) shows the effective absorption length of beam analyzed from the Muon filter data. The beam penetration was clearly observed by using the μ20 mode. We also found that the responses of effective absorption length of hadron beam could be explained by the Monte-Carlo simulation as also shown in Fig. 6(a). Then, we estimated

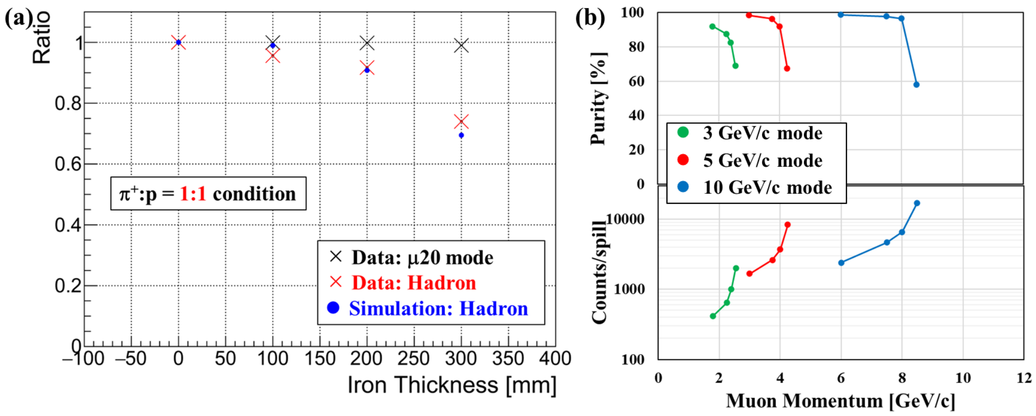

Figure 6: (a) Measured and simulated effective absorption length of beam at 5 GeV/c. Black and red crosses, and blue points show measured muon and hadron beam data, and simulated data, respectively. The counts of the first layer (iron thickness of 0 mm) is used for the normalization. The beam particle penetration was clearly observed by the μ20 mode. The particle abundance of π^+ and proton is equal weight for the hadron beam simulation. (b) Intensity and purity of muon beam for each beam momentum.

the purity of muon beams in each beam momentum. Those preliminary results of intensity and purity are summarized in Fig 6(b).

3.3 Beam time request

We will study properties of negatively charged muon beams at 2, 5 and 20 GeV/c. The maximum and minimum beam momenta at π20 are selected for evaluating the intensity and purity of muon beams. We compare the same momentum as of the T106 experiment so that the negatively charged muon beam at 5 GeV/c is selected. It takes 0.5 hours for each momentum (6 hours in total). In addition, the beam-line tuning of the downstream part of the B-line will be performed to study the muon beam response such as intensity, profiles and purity. In particular, it is important for the muography experiment to adjust the properties of muon beams with a wide position distribution and a straight angle of incidence with respect to the beam direction. We perform the tuning of the downstream part in the upstream one momentum at 5 GeV/c (2 hours). We request beam time of 8 hours in total for the measurement of muon beam properties.

The following table summarizes the beam time requirements.

Beam line:	High-momentum beam line in the μ20 mode
Beam polarity:	Negative, as P93 expects to use.
Beam momentum:	2(1.2, 1.5, 1.6, 1.7), 5(3, 3.8, 4, 4.3), and 20(12, 15, 16, 17) GeV/c for pions (muons), as P93 expects to use
Beam time:	8 hours in total

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