NEW ARRANGEMENT OF COLLIMATORS OF J-PARC MAIN RING

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Abstract

The beam collimation system of J-PARC main ring has been prepared in order to localize the beam loss into the specified area, especially during the injection period. At the first time, it was constructed as a scraper-catcher system in horizontal and vertical planes which consisted of one halo-scraper and two scattered protons catchers, whose the maximum beam loss capacity was designed to be 450 W in the beam injection straight of the ring. In 2012, the scraper was replaced by two collimators with a movable L-type jaw for both planes. Two catchers remained at the same places, and they were used as collimators. This large change of design concept of main ring collimation system was required in order to increase the beam loss capacity more than 3 kW. The system worked well but unexpected loss spots still remained in the following arc and straight sections. The four-axis collimator was developed with movable jaw in horizontal, vertical directions adding tilt functions which has high cleaning efficiency. We have four four-axis collimators, two two-axis collimators, and two original catchers. The most effective arrangement of collimators was investigated in this report.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose accelerator facility in Tokai village of Ibaraki, Japan [1]. The 3 GeV beam from the rapid cycling synchrotron (RCS) is utilized in muon and many neutron beam lines. The main ring (MR) has been providing 30 GeV beam to the neutrino and hadron experiments since early 2009. The recent beam power has achieved 416 kW for the T2K neutrino oscillation experiment, which corresponds to 2.15e+14 protons per 2.48 s cycle [2]. We have about 2.7e+13 protons per bunch. It is important to localize the beam losses for the maintenance, and to handle the beam loss amount for the machine protection. In order to localize the beam losses, MR has the beam collimation system to remove the halo component from the circulating beam.

ORIGINAL DESIGN

The beam collimation system of J-PARC MR has been updated since 2011. The first collimation system started as a single scraper-catchers system which was an ordinary one for the ring accelerators for horizontal and vertical planes. As there are 216 quadrupole magnets in MR, the ring is addressed from address 001 to 216 by using their sequential number. We call as the insertion-A (INS-A) from QDX216 to QDX016 which corresponds to address 001 to 016. The beam collimation system was installed in INS-A as shown in Fig.1, where QFRs and QDRs indicated the focusing and defocusing quadrupole magnets with address numbers, respectively. It consisted of one halo-scraper, catcher-1, and catcher-2 which were often called as Col-1, Col-2, and Col-3. STR means a steering magnet. The scraper was installed in address 007, catchers were installed in address 008 and 010. The designed beam loss capacity was 450 W but we prepared the 1 kW capable system to have a leeway in an actual beam operation. The original collimation system was designed for the tune (νx, νy) = (22.41, 20.80) which was called as a mid-tune in 2006. The actual operating point was set to (22.40, 20.75) until May 2016.

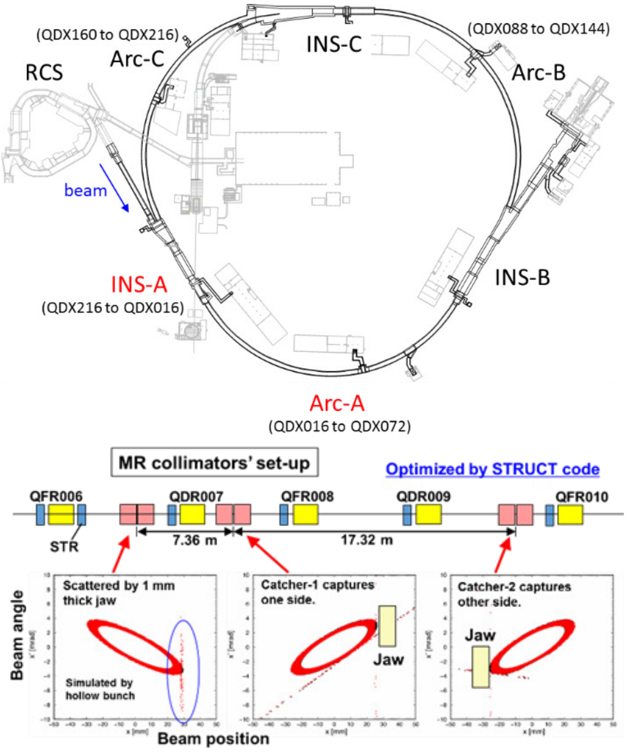

Figure 1: Schematic view of J-PARC MR and a layout of the original beam collimation system.

The scraper and catchers have a same radiation shield system. They have two cubic iron shields placed next to each other on beam line. Upstream shield can move to horizontal direction, and the other can move to vertical direction. Their movable range is +/-12 mm. Vacuum pipe which has scraper jaws or catcher jaws moves with the radiation shield. The vacuum pipe has a transverse position shift ability at the jaw positions by double bellows prepared at the middle and both ends. The beam loss distribution during the fast extraction (FX) operation in the circumference as a function of MR address number is

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ISBN 978-3-95450-178-6

shown in Fig.2. We have to take care that the gain of beam loss monitors (BLMs) from 213 to 020 were set to be 1/8 compared to the others. The amounts of beam loss around the catchers were 8 times higher in this scale. The specific beam loss spots in the Arc-A were addresses 026, 030, 033, and 037. The addresses 026 and 033 correspond to QFX026 and QFX033 which are focusing quadrupole magnets in the missing bend section where we have a dispersion peak. These beam losses seemed mainly due to off-momentum protons and unavoidable because we didn't have any momentum collimation system. The losses at addresses 030 and 037 found that they occurred in the bending magnets BM030 and BM037 from the results of residual radiation survey, which were upstream side of QDX030 and QDX037, respectively. Though they were suspected to be a leakage from catchers, the origin was not identified. The maximum beam loss point was address 011 which was the following cell of catcher-2.

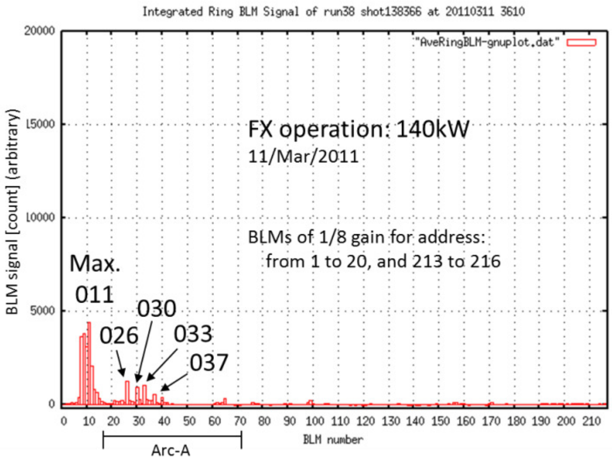

Figure 2: Beam loss distribution in the early days.

FIRST UPDATE

The first update started in 2011 introducing the movable wall-type radiation shield and secondary absorbers made of iron, and remodelling of water cooling system [3] for higher radiation capacity of collimator area. The update of beam collimation system itself was altered in 2012.

Scheme Change

The update plan started from investigating how to add one or more scraper-catchers system. We got the following results:

- Only one more scraper-catchers can be installed.
- Maximum beam loss capacity of collimation system will be limited to 2 kW which is not sufficient.
- As the MR operating point will largely change in future, we have to hold flexibility for tune, that is, betatron phase advance.

The beam loss capacity is limited by the concrete thickness of the accelerator tunnel as shown later. We decided to change the base design of beam collimation system in order to achieve the 3 kW beam loss capacity, that was, we threw the scraper away.

Solid Collimator

In order to remove the halo component at the one-passing of the beam, a collimator with thick jaw was developed. It is an ordinary type of a collimator in the beam transport line, and we call it as a solid collimator in this report. A solid collimator is shown in Fig.3. It consists of a solid iron base with LM guide rail and exchangeable mover unit with a special beam pipe. The central part of a mover unit transversely moves by the slide and lift-up system on the unit top. The beam pipe has a 300 mm long L-type jaw for both planes in the middle, and double bellows at each end in order to displace the jaw to horizontal and vertical directions. The solid collimator was designed to have shorter length than a catcher in order to install two modules in one cell which meant a space between quadrupole magnets. Thus, this collimator is often called as a short collimator. The beam loss capacity is 500 W for one unit.

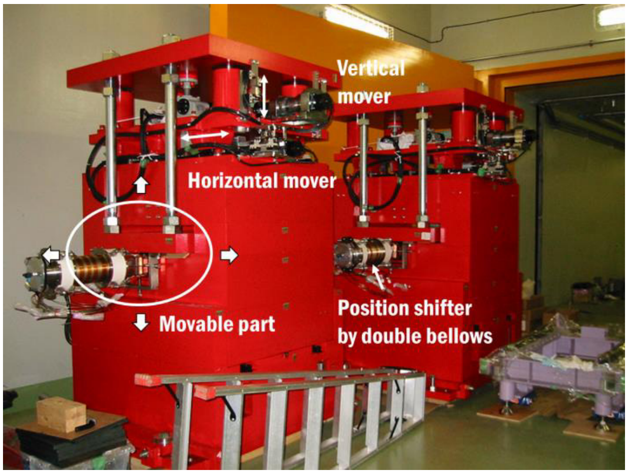

Figure 3: A solid collimator.

Replacement of the Scraper

The scraper was replaced by two solid collimators during three months summer shutdown period in 2012. The remained two catchers were also used as solid collimators. Then, we called them as Col-A, Col-B, Col-2, and Col-3 in this configuration from upstream side of the beam line, in order to avoid confusion from the collimator numbering. The system worked well and the beam loss distribution during the FX operation is shown in Fig.4. The specific beam loss spots existed at addresses 023, 033, and 037. As the beam loss at address 023 newly appeared in this configuration, it was a side effect of the scheme change. The protons scattered by some collimator jaws seemed to make this beam loss because the betatron phase advances in horizontal and vertical planes were about 160+2nπ degrees between them and BM023. The beam loss at address 011 which was the maximum beam loss point largely reduced due to the secondary absorbers installed in 2011.

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The measured dose rate of a residual radiation at the entrance of QFN017 found to be much higher, though the beam loss signal was not remarkable. The scattered protons change their momentum about 0.1% when they passed through a thin material such as a halo-scraper. On the other hand, the protons scattered at the jaw edges of solid collimators lost their momentum up to more than 10%. The off-momentum protons deviated from the design orbit in BM017 which is the first bending magnet of Arc-A, and hit the QFN017. This is also a side effect of the scheme change. It is better to prepare the hadron shield to protect QFN017.

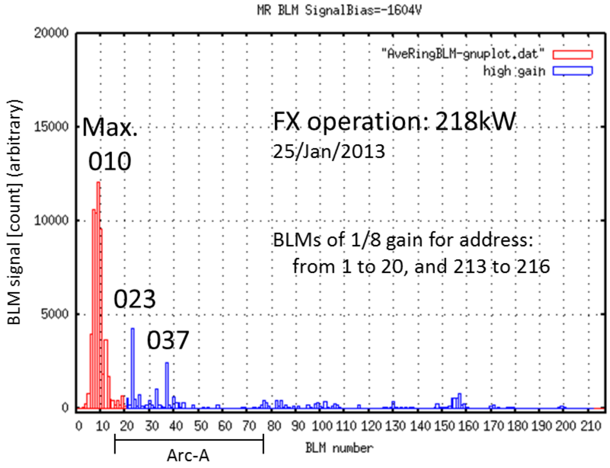

Figure 4: Beam loss distribution after the beam collimation system update in 2012.

SECOND UPDATE

The second update started in 2013. In this case, four solid collimators were additionally installed in addresses 008 and 009, removing the catcher-1 from address 008. Though the installation was planned in September 2013, it was postponed to the January 2014 because of an accident occurred in hadron experimental hall. The polarity and length of jaws were investigated and optimized [4] by using STRUCT code [5]. The material of jaw changed from tantalum to tungsten. The newly installed collimators were called as Col-C, Col-D, Col-E, and Col-F. The total beam loss capacity increased to 3.5 kW with seven collimators. The layout of collimators was confirmed to satisfy the boundary condition on the surface of accelerator tunnel as shown in Fig.5 by PHITS code [6].

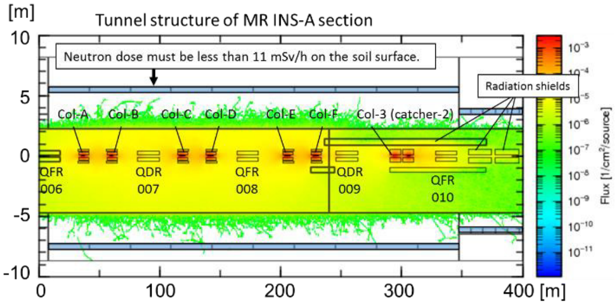

Figure 5: Neutron distribution with seven collimators.

The parasitic beam losses caused by collimator jaws were investigated and it was found that the beam loss tend to occur especially at addresses 023, 030, 037, and 044 where the lattice had a same structure BMnnn + QDXnnn. The fundamental beam responses with seven collimators were studied in April and May [7]. However, a vacuum problem was found on the collimator ducts produced in 2013. The second update was cancelled. Col-C, D, E, F were removed from the beam line, and catcher-1 was reinstalled to the original position, that is, the beam collimation system returned to the configuration in October 2012.

THIRD UPDATE

As the result of investigation with respect to the beam-jaw angle, it suggested that the controllable incline of collimator jaw was important to suppress the loss spots in downstream area.

Four-axis Collimator

The rotation and tilt mechanism were added to the solid collimator in order to change a beam-jaw angle in both planes. We call it as a four-axis collimator. A four-axis collimator is shown in Fig.6. A range of rotation and tilt are set to +/-5 mrad which required by the tunability for MR operating points. The mover unit of this collimator was designed to have compatibility to the existing solid iron base.

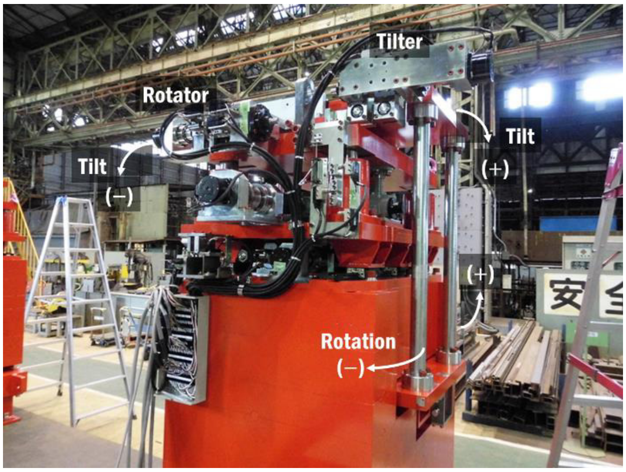

Figure 6: A four-axis collimator.

The beam loss improvement due to the jaw incline system is shown in Fig.7. In this case, only Col-CH was inserted. When a beam-jaw angle was improper, unexpected beam losses appeared not only in Arc-A but also Arc-B. The beam loss distribution in Fig.7 shows the zoom up window below the usual scale one. When the beam-jaw angle was matched, unexpected beam losses were largely suppressed. As shown in Fig.8, some beam loss points have the minimum plateau. On the other hand, some points go to an opposite way like address 026. We optimized the jaw incline for the total beam loss.

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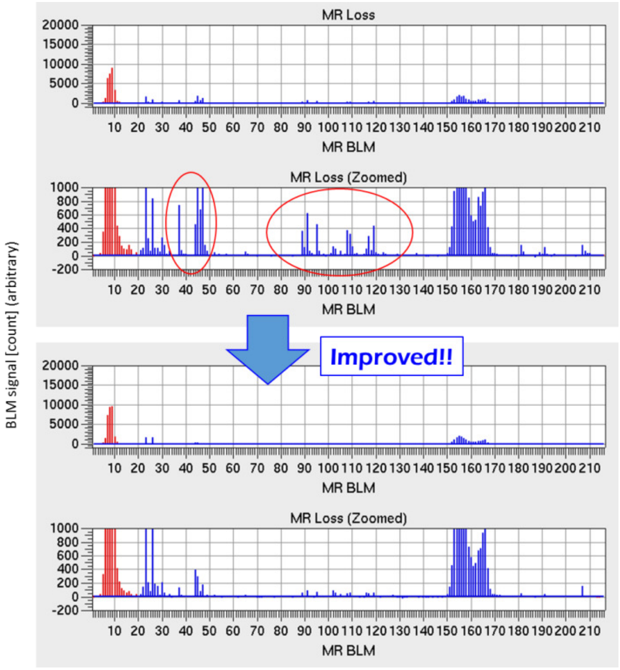

Figure 7: Effect of beam-jaw angle.

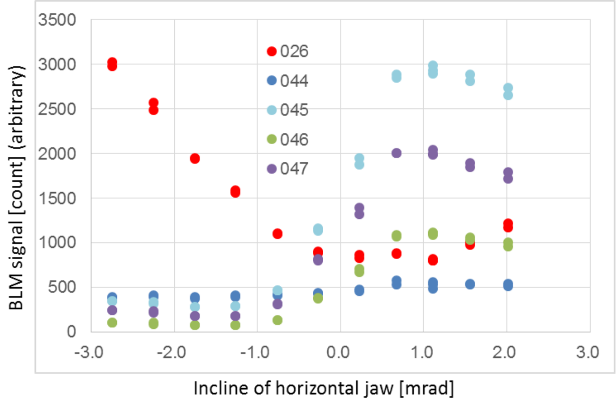

Figure 8: Beam losses as a function of jaw incline.

Operation at (21.35, 21.43)

Since May 2016, we have changed the operating point from (vx, vy) = (22.40, 20.75) to (21.35, 21.43) for the FX operation toward the higher beam power beyond 400 kW. The responses of each collimator jaw were investigated, again. At the beginning, Col-AH and Col-AV were set to the aperture of 70π mm mrad. Here, we call the horizontal jaw of Col-A as Col-AH, the vertical jaw of Col-A as Col-AV, in same way for other collimators hereafter. The specific beam loss spots are addresses 023, 026, 030, 033, 044, 082-084, 102, 116-124, 130, 131, 137, 147, 148, 174, and 202 as shown in Fig.9a. Because the signals from addresses 154 to 168 are reflections from the beam dump, we can ignore them. The mechanism of beam losses in Arc-B and after (from 102 to 202) is not well known. The beam loss at address 023 can be eliminated by using Col-BV as shown in Fig.9b. It is a good thing of this operating point because it was difficult on the previous tune.

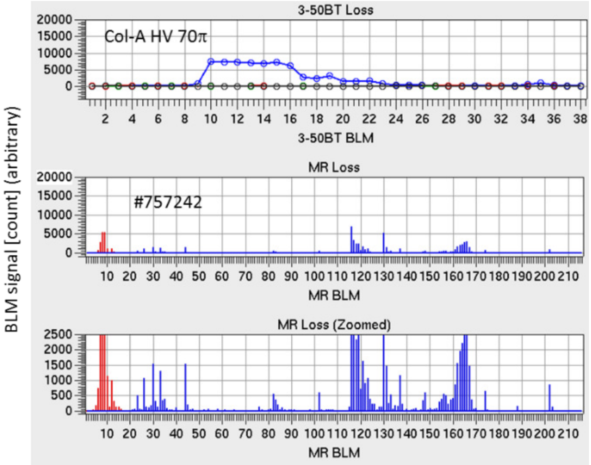

Figure 9a: Beam loss distribution with only Col-A (H and V) on the operating point (21.35, 21.43).

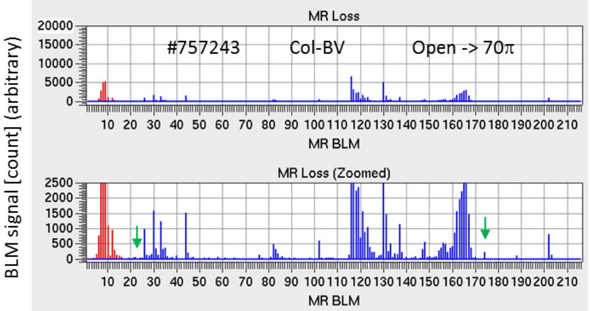

Figure 9b: Effect of Col-BV. Beam loss at address 023 disappeared.

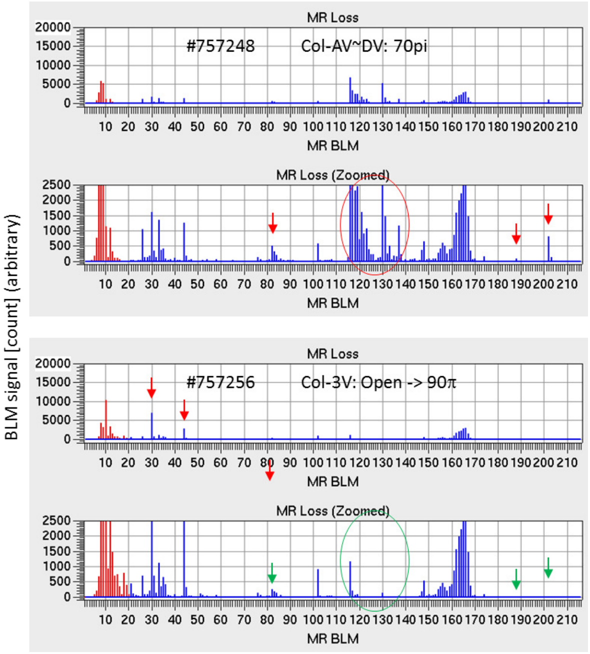

Figure 9c: Effect of Col-3V.

The beam losses from addresses 082 to 203 can be eliminated by using Col-3V as shown in Fig.9c. After the same method was repeated in horizontal plane, the final beam loss distribution with five collimators is shown in

Fig.9d. The parasitic beam loss spots survived at addresses 030, 044, 102, and 116. The beam losses at addresses 030, and 116 can be reduced by inserting Col-3V more, however, beam losses at addresses 044, 102, around 018, and around 036 increase. Though the Col-3V should be a key device, we cannot use it effectively, because it makes significant parasitic beam losses in the following section especially in Arc-A. It should be replaced by a four-axis collimator. For the user-run of 416 kW FX operation, all the collimators were retuned and the Col-3H and Col-3V were eased.

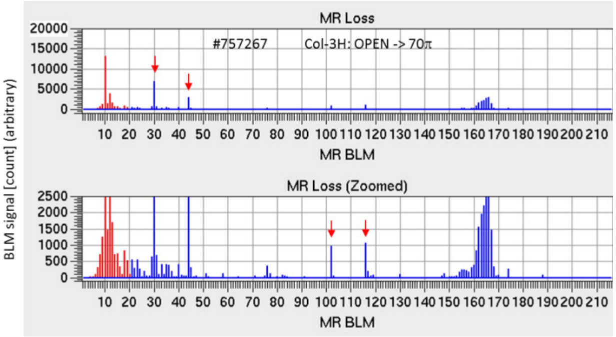

Figure 9d: The final beam loss distribution with all (five) collimators.

FOURTH UPDATE (FUTURE)

We summarize the available devices for the beam collimation: two catchers (Col-2 and Col-3), two solid collimators (Col-A and Col-B), and two four-axis collimators (Col-C and Col-D). Then we assume that we can prepare more two four-axis collimators, that is, we will have up to Col-F for short collimators. The MR operating point will be chosen to (21.35, 21.43) in the next beam time, however, it might be changed in several years later.

Re-arrangement

The requirements for the next update of beam collimation system are taken into account. Though the roll of Col-3 is important, the side effect producing parasitic beam losses is a large problem. It should be replaced by a four-axis collimator. As Col-A and Col-B don't have a incline mechanism, they release scattered protons in the lower reaches. It is good that they remain at the uppermost stream part of beam collimation system. In order to catch the leak protons from Col-A and Col-B by the following collimators, the jaw polarity of Col-C or Col-D should be turned to the opposite side. The catchers should be used before address 009. It is possible to install a catcher and a four-axis collimator in one cell. When we reuse a catcher, the side effect should be considered carefully because the leakage of scattered protons seems to be large. Then, it is good not to use a catcher if the beam loss capacity of collimation system was secured sufficiently.

CONCLUSION

The fourth update is planned in 2018. It consists of the following procedures:

1. Col-3 will be removed.
2. Col-C will be moved to the address 010 instead of Col-3. It will be called as Col-F
3. New Col-C which has a jaw in opposite side will be installed.
4. New Col-E will be installed at upstream side of QDR009.
5. Proton and neutron absorber will be prepared between BM017 and QFN017 in order to protect QFN017.

The final layout of the beam collimation system is shown in Fig.10.

Now, another plan is also under consideration, and we are preparing the beam test in this winter which uses the new halo-scraper. The fourth update will be decided in next year taking that result into account.

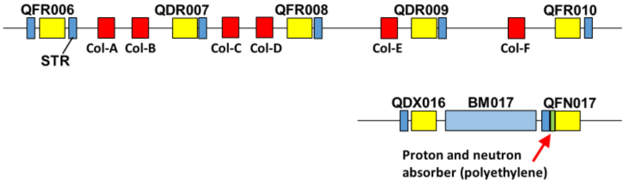

Figure 10: Final layout of beam collimation system.

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ISBN 978-3-95450-178-6