THE RESULT OF BEAM COMMISSIONING IN J-PARC 3-GeV RCS

H. Harada#, H. Hotchi, P.K. Saha, Y. Shobuda, N. Hayashi, K. Yamamoto, M. Yoshimoto, F. Tamura, M. Yamamoto and M. Kinsho, J-PARC/JAEA, Tokai, Japan
S. Kato, Graduate School of Science, Tohoku University, Sendai, Japan
Y. Irie, T. Koseki, K. Satou, Y. Sato and M. Shirakata, KEK, Tsukuba, Japan

Abstract

The 3-GeV RCS of J-PARC is a high-power pulsed proton driver aiming at 1 MW output beam power. The RCS was beam commissioned in October 2007. From the results obtained in the beam tuning, we re-optimized the operating point for high-intensity beam, where the RCS has successfully achieved high-intensity beam trials of up to 420 kW by using the painting-injection technique for transverse and longitudinal plane. Then, remaining beam loss was found to be caused by scattering at the charge-exchange foil, and the RCS has successfully localized the loss at the installed injection collimator. Additionally, the RCS has successfully reduced the beam halo of the extracted beam by introducing longer second harmonic RF voltage. This paper will discuss the results of operational parameters away from the design set points, minimization of beam loss, localization of beam loss using new collimator and beam-halo reduction of extracted beam.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multipurpose proton accelerator facility [1,2], comprising a 400-MeV linac, a 3-GeV rapid cycling synchrotron (RCS), a 50-GeV main ring synchrotron (MR), and three experimental facilities that are a meterials and life science experimental facility (MLF), a hadron experimental hall (HD), and a neutrino beam line to Kamioka (NU). In this chain of accelerators, the RCS has two functions as a proton driver to produce pulsed muons and neutrons at the MLF and as an injector to the MR, aiming at 1 MW output beam power.

The RCS was commissioned in October 2007 and the output beam power has been steadily increasing following progressions in beam tuning and hardware improvements. So far, maximum beam powers for user operation and beam tuning (single shot) are 280 kW and 420 kW-equivalent beam, respectively.

Since starting the beam tuning, the RCS has performed optics parameter tuning, measurement of lattice imperfections, transverse painting-injection study, tune survey and so on. In these beam tests, we found several lattice imperfections, and the RCS cannot have large transverse-painting emittance and suppression of large incoherent tune spread. So, operating point for higher output beam power has been re-optimized in order to keep the tune spread away from integer resonance line. In this paper, we present the measured result of lattice imperfections, the beta modulation and the improved operating point.

So far, the RCS has successfully achieved high-intensity beam trials of up to 420 kW at less than 1% by using the painting-injection technique for transverse and longitudinal plane. In this paper, we show the result of measured and numerically simulated beam survival for painting-injection parameters.

The RCS has a high dose rate area at the downstream of charge-exchange foil after routine user operation. We found that the beam losses were caused by large scattering at the foil. From the view point of hardware maintenance, reduction and localization of the beam loss is main key issue. As measure of the issue, we installed the additional collimator in summer 2011. In this paper, we describe the new collimator system and localization results of beam experiments.

As an injector to MR, the RCS has another issue of beam halo reduction. The physical aperture of BT line to neutron target (3-NBT) is 324π mm mrad. On the other hand, the collimator aperture of 3-50BT line is 54π mm mrad. Therefore, it is important to reduce beam halo of extracted beam from RCS. In this paper, we present the result of beam halo reduction by introducing longer second harmonic RF voltage pattern of RCS.

RESULTS OF BEAM TUNING

Lattice property and operating point

In design stage, we performed thorough investigations of the basic lattice property, looking, in particular, for intrinsic lattice imperfections in the ring, and to find better operating point (6.68, 6.27) for high-intensity beams.

We found several lattice imperfections of the RCS ring in the beam experiments. Such imperfections generally make a distortion of the lattice super-periodicity and drives random lattice resonances. As the result, dynamic aperture and tune ability degrease, especially, they have a significant impact on high intensity operation.

In the RCS, beam injection is performed with a horizontal local bump orbit formed by four sets of rectangular type pulse dipole magnets called shift bump magnets (SB). This method generates edge focus at the entrance or exit of each SB, causing beta function modulation during beam injection. We performed the beta function measurement with/without local injection bump in the ring (the technical details of optics measurement in the RCS are described in [3]) and the measured and calculated beta function are shown in Fig.1. From this

#hharada@post.j-parc.jp

ISBN 978-3-95450-118-2

measurement, the strength of the edge focus was evaluated to be –0.0067 T per edge, which corresponds to around 1% of the main quadrupole field strength at beam injection.

Another major lattice imperfection was found in the extraction section, which arises from the leakage of static magnetic fields generated by the extraction beam line DC magnets (3 septum magnets and 1 bending magnet) into the ring. In order to reduce the leakage field, we installed additional magnetic shields. Although this achieved a 40% reduction [4], there is still significant leakage field remaining. We measured a closed orbit distortion (COD) caused by the field and estimated it. The dipole field components for horizontal and vertical plane were evaluated to be 0.0022 and 0.0002 Tm, respectively. These COD was correctable by steering magnets. However, such a leakage field generally includes higher-order field components, especially, normal and skew quadrupole field components. The normal quadrupole filed component was evaluated to be 0.0098 T from the optics measurements. On the other hand, the skew quadrupole components was estimated to be –0.0022 T from a horizontal-vertical coupling measurement, namely by observing an orbit leak to the vertical plane by a horizontal single kick.

The above imperfections greatly degrease the dynamic aperture at beam injection. Therefore, the RCS couldn't have the large injection painting emittance for transverse plane, namely the incoherent tune spread doesn't suppress significantly. On the basis of the above investigation of the lattice property, and taking into account space-charge induced resonances such as fourth-order systematic resonances, we searched operating tunes for high-intensity beams. High-intensity beam trials of up to 420 kW were performed at operating point of (6.45, 6.42). This operating point allows the space-charge tune shift to avoid serious multipole resonances.

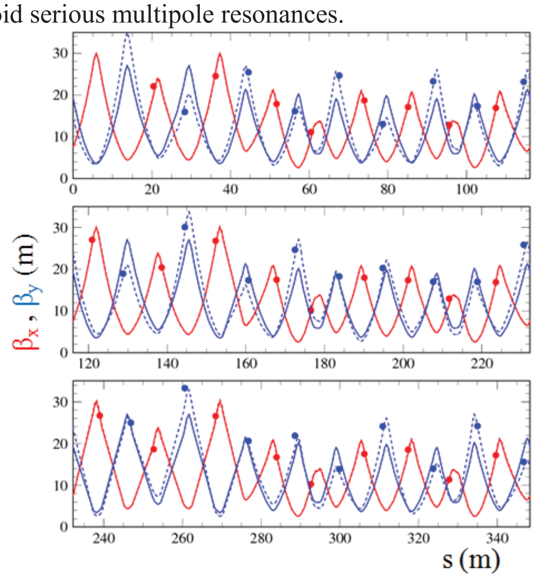

Figure 1: Horizontal (red) and vertical (blue) beta functions along the ring, where the circles show those measured when the injection bump in active, while the colid cures correspond to the beta functions when the injection bump is inactive.

Measures against beam loss for high-intensity beam trials

As reported by H. Hotchi in last HB2010, the RCS has successfully achieved high-intensity beam trials of up to 420 kW at less than 1% by using the painting-injection technique for transverse and longitudinal plane [5]. At first, beam intensity survivals of 420 kW for longitudinal painting injection patterns have been checked by DCCT. As better parameter of longitudinal painting injection in the present beam tuning experiment, the momentum offset injection is –0.2%, and the second harmonic RF voltage was employed typically with an amplitude of 80% of the fundamental one during the first 1 ms, decreasing to 0 kV in the next 2 ms. Also its phase was linearly swept from –100 to 0 degrees over an injection duration of the first 0.5 ms. Details of longitudinal painting injection is described in [6] and [7]. At second, transverse painting injection with correlated painting of 100π mm mrad has been combined with the longitudinal painting injection. Details of the beam-based adjustment procedure of the transverse painting are described in [8] and [9]. The time dependence of the circulating beam intensity from injection through extraction is shown in Fig.2. In this figure, we can see that the beam loss appears only for the first several ms in the low-energy region, where the space charge effect is the most serious. As the painting injection progresses, the observed intensity loss is gradually reduced, and mostly recovered. The corresponding simulated results, plotted as black solid curves in the figure, well reproduce the measured intensity losses patterns.

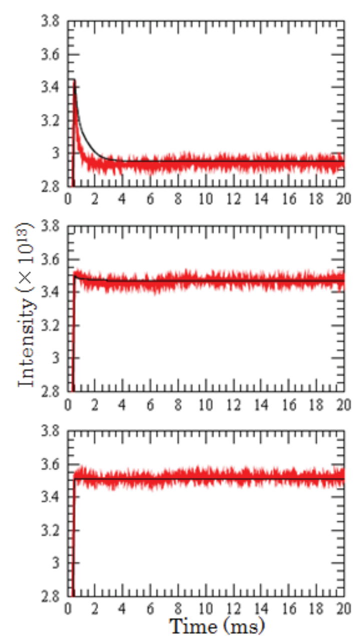

Figure 2: Time dependence of the circulating beam with no painting (top), longitudinal painting (middle) and longitudinal + transverse painting (bottom). In the figure, the corresponding numerical simulation results are plotted as black curves.

ISBN 978-3-95450-118-2

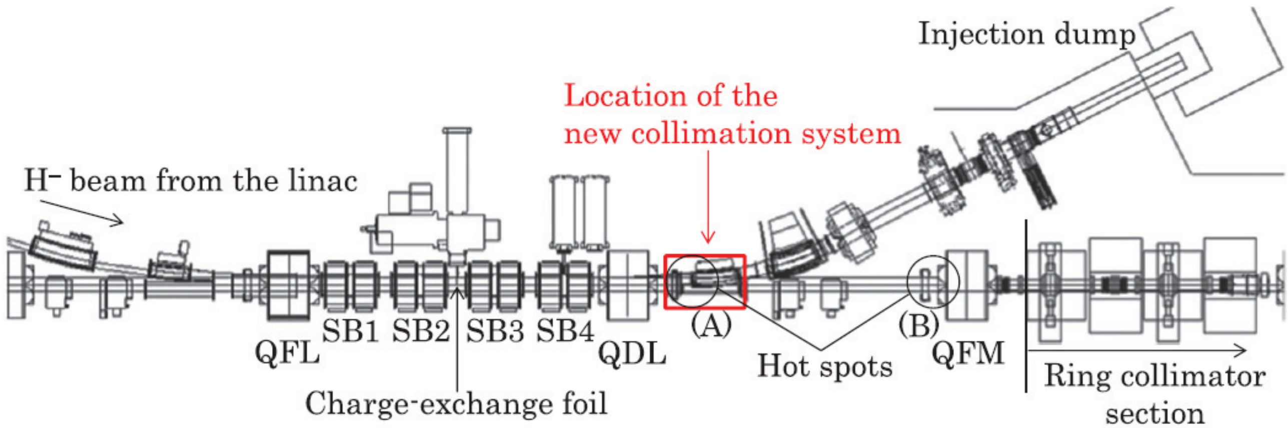

Figure 3: Schematic of the RCS injection section where (A) and (B) correspond to the hot spots downstream of the foil.

Measures against foil-scattering beam loss during beam injection

As reported by P.K. Saha in last HB2010, the uncontrolled beam loss caused by the nuclear scattering especially, by the large-angle multiple Coulomb scattering at the charge-exchange foil is the most considerable issue in the RCS injection [10]. Though most of the foil-scattering beam loss is well localized on the ring collimator section, a part of it (10^{-4} to 10^{-3} of the injected beam) generated several hot spots (~6mSv/h on the chamber surface in the 210 kW routine user operation) between the foil and the ring collimator. The schematic of the RCS injection section is shown in Fig.3. The hot spots are (A) and (B) in Fig.3. The horizontal physical aperture of these spots is narrower than other beam ducts, where the scattered particles hit intensively to these beam ducts. The charge-exchange injection scheme with a foil inevitably involves foil-scattering beam loss, which cannot be completely eliminated. Therefore, as for the foil scattering beam loss, the localization, as well as the minimization of the foil-hitting rate during injection by introducing transverse painting and by adjusting the position and dimension of the foil, are key issues.

In order to localize the uncontrollable beam loss component, we introduced a new collimation system [11] during the period (summer 2011) of recovery from the damage caused by the East Japan earthquake. The new collimation system installed at hot spots (A) is shown by red boxes in Fig.4. The lower plot in Fig.4 corresponds to the tracking simulation result with the new collimation system. This collimation system consists of two copper blocks (absorbers) 200 mm long along the beam, which provide sufficient stopping power for protons in the injection energy region (400 MeV). The copper blocks are installed horizontally in the vacuum chamber covered with a 450 mm-thick iron radiation shield. The unique feature of this collimation system is that the position and angle of the absorbers are independently adjustable. This function is essential for obtaining sufficient collimation efficiencies for large-angle events scattered on the foil. The beam loss monitor (BLM) signal at the hot spot (B) observed both without and with the new collimator. The new collimation system decreased the integrated value of the BLM signal by an order of magnitude from the original value, as expected.

This collimation system has already been introduced to the current 210 kW routine user operation, and has been proven to be effective in preventing machine activation downstream of the foil. The current residual radiation is maintained with a sufficiently permissible level of ~0.5 mSv/h on the chamber surface, which corresponds to less than one-tenth of the previous level. Details of the new collimation system, its design, and the adjustment procedure for the position and angle of the absorbers, are described in [12].

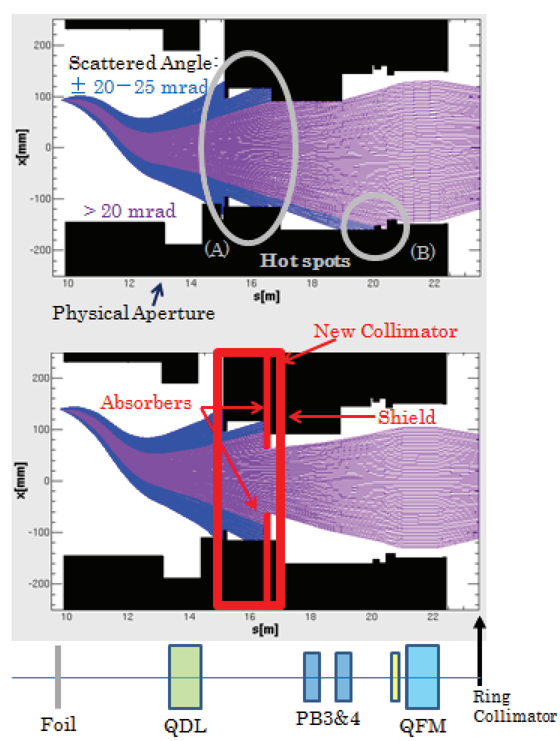

Figure 4: Trajectories of particles scattered on the charge-exchange foil (horizontal plane) calculated without (upper) and with (lower) the new collimation system.

ISBN 978-3-95450-118-2

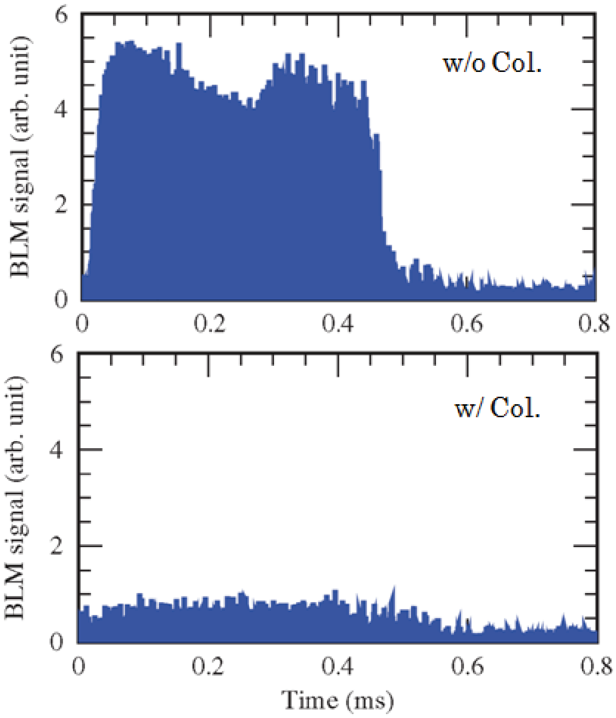

Figure 5: Scintillation-type BLM signals at the hot spot (B) observed without (top) and with (bottom) the new collimator, where the width of the signal corresponds to the injection pulse length of 0.4 ms used in this measurement.

Measures against beam halo for high-intensity beam

We have so far made steady progress on the beam loss issues in the RCS. Another main issue for the RCS is to improve the quality of the extraction beam, namely to realize beam halo for high-intensity extracted beam. This is essential particularly for beam injection to the MR, since the MR has a relatively small physical aperture (81π mm mrad) compared to that of the 3-NBT (324π mm mrad, which is similar to the RCS ring collimator aperture). In the 3-50BT, a beam collimation system is installed and its aperture is typically set at 54 to 60π mm mrad in order to remove a beam halo/tail component of the RCS beam. For the MR injection, it is necessary to pass the beam through the 3-50BT collimator within the acceptable beam-loss level.

For 420 kW-intensity beam with above painting injection parameters, the beam loss in the RCS ring was minimized. However, we found to have remarkable emittance growth after 1 ms from numerical simulations. Although this emittance growth contributes very little to the beam loss in the RCS, it causes a major part of the beam loss at the 3-50BT collimator. From the simulations, we could find how emittance growth proceeds following the decrease of the bunching factor after 1 ms, and this decrease of the bunching factor corresponds to the fall time of the second harmonic RF voltage after 1ms. If the bunching factor decreases in this low-energy region, a portion of the beam particles reaches the integer lines of $\nu_{x,y} = 6$. It is necessary to control further charge density after 1 ms as well as during beam injection. Therefore, only the second harmonic RF voltage pattern of the longitudinal painting on the basis of the above consideration was improved. The improved pattern is shown in Fig.6. They have different duration (3 to 5 ms), where the shorter pattern (3 ms) corresponds to the original one. We have experimentally confirmed the improvement of bunching factor for first 6 ms. The bunching factor measured with the wall current monitor (WCM) for shorter and longer second harmonic RF voltage patterns are shown in Fig.7, where the corresponding numerical simulation results are plotted as black curves, which are in good agreement with the measured ones.

We measured the beam loss of a 420 kW-intensity beam extracted from the RCS for these patterns at the 3-50BT collimator. In this measurement, the 3-50BT collimator aperture was set at 54π (horizontal) and 60π (vertical) mm mrad and the absolute value of the beam halo component was evaluated with a 43 m-long air-ionization type BLM covering the entire 3-50BT collimator area (the BLM is reported in [13] by K. Satou). As the result, the beam loss at the 3-50BT collimator reduced 2% to 0.8% by the improvement of the second harmonic RF voltage pattern, and the extraction beam halo is maintained at a sufficiently low level for beam intensities of up to 420 kW. If the RCS delivers the 420 kW-intensity beam to the MR with a typical operation cycle, the beam loss of 0.8% at the 3-50BT collimator corresponds to 208 W in power, which is much less than the present capability of the 3-50BT collimator (2kW). Details of numerical simulation results of emittance growth and experimental results of beam-halo measurement are described in [14].

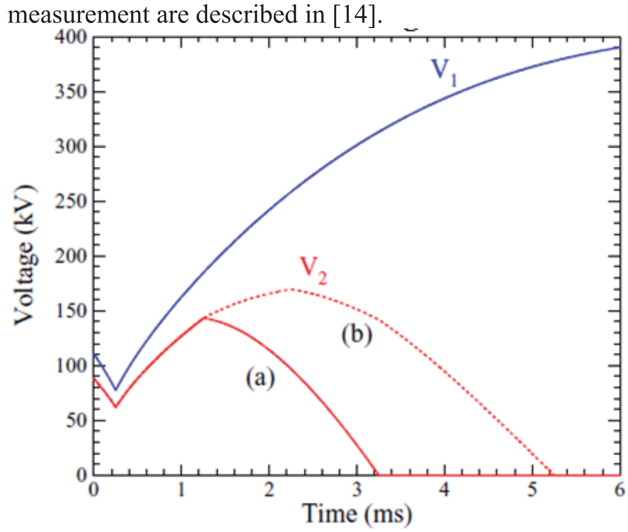

Figure 6: Second harmonic RF voltage patterns (V_2) with different durations (a) and (b) used for the longitudinal painting in the present work, in which the shorter pattern (a) corresponds to the original one and the longer pattern (b) corresponds to the improved one. V1 means fundamental harmonic RF voltage patters for beam acceleration.

ISBN 978-3-95450-118-2

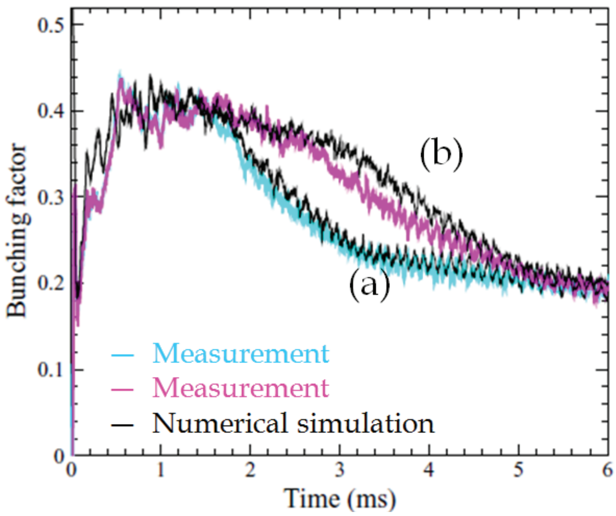

Figure 7: Bunching factor for the first 6 ms measured with the WCM for the shorter (light blue) and longer (pink) second harmonic RF voltage patterns, where the corresponding numerical simulation results are plotted as black curves.

SUMMARY

The RCS beam tuning has proceeded well since the start of the beam commissioning. The ring optics and several lattice imperfections have also been found by the beam tuning and calculations, and operating point for high-intensity beam has been re-optimized. The major beam-loss issues observed in high-intensity beam trials of up to 420 kW have been solved. The beam loss for a 420 kW-intensity beam was successfully minimized to less than 1% by introducing the painting injection technique and beam loading compensation. Also, the remaining beam loss, which arises mainly from foil scattering during the charge-exchange injection, was localized by installing the new collimation system. As the result of the localization, the machine activation in the RCS for this routine beam operation is still maintained at a sufficiently low level. The output beam power for routine beam operation has a rump-up from 210 to 280 kW in June 2012. Another main issue for the RCS is to improve the quality of the extraction beam, namely to realize beam halo for high-intensity extracted beam. The longitudinal painting with longer-duration second harmonic RF voltage pattern has been improved the bunching factor, and consequently the extraction beam halo was successfully maintained at a sufficiently low level for beam intensities of up to 420 kW.

The linac will be upgraded in the 2013 summer-autumn period; the output energy will be improved from 181 to 400 MeV with the addition of the ACS linac section, and the maximum peak current will be increased from 30 to 50 mA by replacing the front-end system. With this upgrade of the linac, several hardware improvements will also be performed in the RCS [15]. The beam commissioning of the upgraded linac will start at the beginning of November 2013. Then, the RCS will start beam tuning with the upgraded injection energy of 400 MeV in December 2013, aiming at our final goal of the 1 MW output beam power.

ACKNOWLEDGMENT

The authors are also deeply grateful to the entire J-PARC project staff for their efforts in their continuous work operating and maintaining the J-PARC facilities. We would like to express our beam experiment to the linac, MR and the MLF group members for their indispensable support during the beam experiment. We are also grateful to Professor Y. Yamazaki, Professor A. Ando, Professor E. Takasaki, Professor K. Oide, and Dr. S. Machida for their valuable advice and fruitful discussions.

REFERENCES

[1] High-intensity Proton Accelerator Project Team: JAERI Report No. JAERI-Tech 2003-044.
[2] High-intensity Proton Accelerator Project Team: KEK Report No. 202-13.
[3] H. Hotchi et al., Phys. Rev. ST Accel. Beams **12**, 040402 (2009).
[4] M. Yoshimoto et al., *Proc. 2011 International Particle Accelerator Conference (IPAC'11)*, San Sebastian, Spain, 2011, p. 2412.
[5] H. Hotchi et al., Phys. Rev. ST Accel. Beams **15**, 040402 (2012).
[6] F. Tamura et al., Phys. Rev. ST Accel. Beams **12**, 041001 (2009).
[7] M. Yamamoto et al., Nucl. Instrum. Methods Phys. Res., Sect. A 621, **15** (2010).
[8] P.K. Saha et al., Phys. Rev. ST Acccel. Beams **12**, 040403 (2009).
[9] H. Harada, Ph.D. thesis (KEK Report 2009-7), Graduate School of Science, Hiroshima University, Higashi-Hiroshima, Hiroshima (2009).
[10] P.K. Saha et al., *Proc. Hadron Beam 2010 (HB2010)*, Morschach, Switzerland, p. 324.
[11] K. Yamamoto et al., *Proc. 2011 International Particle Accelerator Conference (IPAC'11)*, San Sebastian, Spain, 2011, p. 1605.
[12] S. Kato et al., *Proc. 2012 International Particle Accelerator Conference (IPAC'12)*, New Orleans, Louisiana, USA, 2012, p. 535.
[13] K. Satou et al., *Proc. 2012 International Particle Accelerator Conference (IPAC'12)*, New Orleans, Louisiana, USA, 2012, p. 837.
[14] H. Hotchi et al., Prog. Theor. Exp. Phys. 2012, 02B003.
[15] N. Hayashi et al., *Proc. 2011 International Particle Accelerator Conference (IPAC'11)*, San Sebastian, Spain, 2011, p. 2730.

ISBN 978-3-95450-118-2