Research Facility Development Division
Instrumentation Development Group
Rare RI-ring Team

1. Abstract

The aim of Rare-RI Ring (R3) is to measure the masses of short-lived unstable nuclei far from the beta-stability line. In particular, a high-precision mass measurement for nuclei located around the r-process pass (rare-RI) is required in nucleosynthesis point of view. The R3 completed the construction at the end of 2014, and has been performed commissioning experiments several times by 2017. Through the commissioning experiments, we confirmed the high ability of R3 as a storage ring capable of handling one event, and demonstrated that it is possible to perform the time-of-flight Isochronous Mass Spectrometry (IMS) in shorter than 1 ms. We have acquired an adequate efficiency to conduct the mass measurement experiments in the end of 2017. In 2020, a machine study was conducted using upgraded kicker system. We succeeded in extracting all injected nuclides in a single extraction and then the experimental efficiency became at least twice better than that achieved using the previous method, where different extraction timings were needed to extract all nuclides. Furthermore, the systematic uncertainty caused by different kick angles has been eliminated. The open question of the first mass measurement experiment in 2018 will be solved by performing mass measurement experiments utilizing the upgraded kicker system in 2021.

2. Major Research Subjects

(1) Further improvement of experimental efficiency and mass measurement precision
(2) Precision mass measurement for rarely produced isotopes related to r-process

3. Summary of Research Activity

In the commissioning experiments up to 2017, we confirmed the unique performances of R3 and demonstrated the time-of-flight isochronous mass measurement method. The ring structure of R3 was designed with a similar concept of a separate-sector ring cyclotron. It consists of six sectors and straight sections, and each sector consists of four rectangular bending magnets. Two magnets at both ends of each sector are additionally equipped with ten trim coils to form a precise isochronous field. We have realized in forming the precise isochronous field of 5 ppm with wide momentum range of $\Delta p/p = \pm 0.5\%$. Another performance required for R3 is to efficiently seize hold of an opportunity of the mass measurement for rare-RIs produced unpredictably. It was realized by constructing the Isotope-Selectable Self-trigger Injection (ISSI) scheme which pre-identified rare-RI itself triggers the injection kicker magnets. Key device was an ultra-fast response kicker system that has been successfully developed. Full activation of the kicker magnetic field can be completed within the flight time of the rare-RI from an originating point (F3 focal point in BigRIPS) of the trigger signal to the kicker position in R3.

Since R3 accumulates, in principle, only one event, we fabricated high-sensitive beam diagnostic devices in the ring. They should be applicable even for one event circulation. One of them is a cavity type of Schottky pick-up installed in a straight section of R3. The Schottky pick-up successfully monitored a single $^{78}Kr^{36+}$ ion circulation with the measurement time of less than 10 ms in the first commissioning experiment. We also confirmed that it is useful for fine tuning of the isochronous field. Another is a timing monitor, which detects secondary electrons emitted from thin carbon foil placed on the circulation orbit. The thickness of the foil is 50 μg/cm^2. This timing monitor is working well to observe first several tens turns for injected event.

We performed mass measurement in the third commissioning experiment by using unstable nuclei which masses are well-known. The masses of ^{79}As, ^{77}Ga, ^{76}Zn, and ^{75}Cu relative to ^{78}Ge were derived with the accuracy of less than 10 ppm. In addition, we have improved the extraction efficiency to 2% by considering the matching condition between the emittance of injection events and the acceptance of R3. This extraction efficiency was sufficient to conduct the accepted two proposals: mass measurements of Ni isotopes and mass measurements of Sn region.

In the beginning of 2018, we examined the feasibility of these two proposals in detail and decided to proceed with two proposals at the same period. In the beginning of November 2018, we have conducted the first experiment using R3 to measure the masses for ^{74,76}Ni in 4 days. After that, we also measured the masses for ^{122}Rh, ^{123,124}Pd, and ^{125}Ag in 4.5 days at the end of November 2018. These nuclei were successfully extracted from R3 with the efficiency of 1–2%. However, unexpected deviation from the evaluated values of literature remains in the masses obtained by detailed analysis. This open question is thought to be due to the following two reasons. One is that the TOF at R3 is mistaken because the target nuclei were extracted at a slope part of kicker field distribution. The other is that the absolute value of beta or magnetic rigidity determined for each extracted event is incorrect. In order to eliminate the former concern and verify the latter, we have improved the kicker system. This improvement achieves a flat-top of 100 ns for injection and a long flat-top of 350 ns or more for extraction.

A machine study was conducted using the upgraded kicker system in November 2020. We succeeded in extracting all events with different revolution times at once by realizing a long flat-top. Experimental efficiency became at least twice better than that achieved using the previous method, where different extraction timings were needed to extract all nuclides. In addition, it was confirmed that there is a risk that an incorrect mass will be derived when extracted events at a slope part of kicker field distribution, depending on an isochronous condition. On the other hand, the masses could be derived with the expected accuracy when extracted events at a flat-top part of kicker field distribution. Since each proposal mentioned above still has a machine time of several days, we will conduct mass measurement experiments using the upgraded kicker system in 2021 and solve the open question.

Members

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List of Publications & Presentations

Publications

[Original Papers]

D. Nagae, Y. Abe, S. Okada, S. Omika, K. Wakayama, S. Hosoi, S. Suzuki, T. Moriguchi, M. Amano, D. Kamioka, Z. Ge, S. Naimi, F. Suzaki, N. Tadano, R. Igosawa, K. Inomata, H. Arakawa, K. Nishimuro, T. Fujii, T. Mitsui, Y. Yanagisawa, H. Baba, S. Michimasa, S. Ota, G. Lorusso, Yu. A. Litvinov, A. Ozawa, T. Uesaka, T. Yamaguchi, Y. Ymaguchi, and M. Wakasugi, "Development and operation of an electrostatic time-of-flight detector for the Rare RI storage Ring," Nucl. Instrum. Methods Phys. Res. A **986**, 164713-1–7 (2020).

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[Proceedings]

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J. H. Liu, X. Xu, P. Zhang, P. Shuai, X. L. Yan, Y. H. Zhang, M. Wang, Yu. A. Litvinov, H. S. Xu, K. Blaum, T. Bao, H. Chen, X. C. Chen, R. J. Chen, C. Y. Fu, D. W. Liu, W. W. Ge, R. S. Mao, X. W. Ma, M. Z. Sun, X. L. Tu, Y. M. Xing, J. C. Yang, Y. J. Yuan, Q. Zeng, X. Zhou, X. H. Zhou, W. L. Zhan, S. Litvinov, T. Uesaka, Y. Yamaguchi, T. Yamaguchi, A. Ozawa, and B. H. Sun, "Improving the resolving power of isochronous mass spectrometry by employing an in-ring mechanical slit," Nucl. Instrum. Methods Phys. Res. B **463**, 138–142 (2020).

Yu. A. Litvinov, Th. Stoehlker, X. W. Ma, Y. H. Zhang, and T. Yamaguchi, "Nuclear physics research at heavy ion accelerators: Precision studies with stored and cooled exotic nuclei," J. Phys. Conf. Ser. **1401**, 012001-1–9 (2020).

Presentations

[International Conferences/Workshops]

S. Naimi (invited), "Status of R3 and new in-ring detectors," NucAR Workshop, Online, December 7–10, 2020.

S. Naimi (invited), "Development of a large-area position-sensitive detector for the Rare-RI Ring at Riken," TCHoU Workshop, Online, March 29, 2021.

[Domestic Conferences/Workshops]

濱川大貴（口頭発表),「稀少 RI リングのためのプラスチックシンチレータを用いた位置検出器の開発」, 日本物理学会 2020 年秋季大会, オンライン, 2020 年 9 月 14–17 日.

梶木大輔（口頭発表),「稀少 RI リングにおける周回周期の測定のためのデルタ線検出器の性能評価」, 日本物理学会 2020 年秋季大会, オンライン, 2020 年 9 月 14–17 日.

[Seminars]

Yu. A. Litvinov (oral), "Heavy-ion storage rings and their use for precision nuclear structure and astrophysics experiments," Seminar on Precision Physics and Fundamental Symmetries, Online, July 2, 2020.

Yu. A. Litvinov (oral), "Combining atomic and nuclear physics in ion storage rings," Online Lectures of the Matter and Cosmos Section (SMuK), Online, March 11, 2021.