Retrospective of my 24-year "RIBF life"

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1 Introduction

Ever since I joined RIKEN in 1979, I have devoted my efforts to the construction of the heavy-ion accelerator facility and the promotion of nuclear physics and applications of heave-ion beams. In December 1986, I completed Japan's first ring cyclotron (separate sector cyclotron) named RIKEN Ring Cyclotron (RRC) under Professor H. Kamitsubo, and in 1987, I proposed the "RI Beam Factory (RIBF)" as my dream, which eventually led to the creation of the world-class RI beam facility. Then, in 1997, the RIBF project was approved, and I undertook the construction of RIBF with the world's first superconducting ring cyclotron (SRC) as its main component. In December 2006, 20 years after the commissioning of the RRC cyclotron, I successfully led the new facility to the start of its operation. Currently, the RIBF is being utilized by the international nuclear physics community as the world's leading fast RI beam facility. In April 2006, the RIBF, the RIKEN BNL Research Center in the USA, and the RIKEN RAL Muon Facility in the UK were integrated to create the RIKEN Nishina Center for Accelerator-Based Science, and I was appointed as the first director of the Center. In September 2009, I stepped dawn, and now, I am devoted to upgrading the RIBF as the senior advisor to the Center. Here, I look back on the 24 years (from 1987 up to 2011) I devoted to the RIBF project.

2 Overview of RIBF

The RIBF[1)] consists of a 22-year old facility and a new facility. These two facilities are connected to each other underground. The layout of the RIBF is shown in Fig. 1. The RIBF is now capable of providing all ions at 345 MeV/nucleon.[2)] RI beams are produced via in-flight uranium fission or the projectile fragmentation of stable isotopes.

Consider uranium fission for instance. A uranium 35^+ beam obtained from the 28 GHz superconducting ECRIS[3)] is pre-accelerated by the newly operational RILAC II,[4)] and injected into the old RRC cyclotron. The energy of the RRC beam is boosted up to 345 MeV/nucleon by the new cyclotron cascade of fRC, IRC, and finally the superconducting ring cyclotron, SRC.[5)] The 35^+ uranium ions are charge-stripped twice before and after the fRC cyclotron, from 35^+ to 71^+ at 11 MeV/nucleon and from 71^+ to 86^+ at

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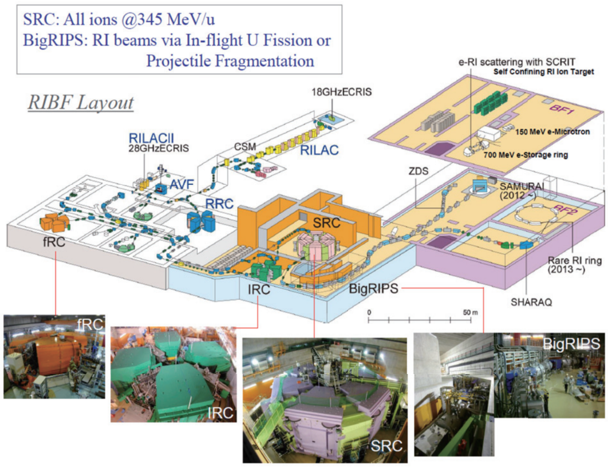

Fig. 1. Layout of the RIBF

51 MeV per nucleon. This charge stripping is now processed by an ordinary thin carbon foil (presently, the short life-time of the stripper is a serious bottle neck to increase the uranium beam intensity). The 345-MeV/nucleon uranium beam from SRC is transferred to the production target, and fission fragments are isotopically selected and collected by the large-acceptance superconducting BigRIPS.[6)]

The superconducting ZeroDegree spectrometer (ZD)[6)] and SHARAQ spectrometer[7)] are used for the experiments, and the large-acceptance superconducting SAMURAI spectrometer[8)] has been commissioned for experiments early in 2012. The unique electron-RI scattering ring with the self-confining RI ion target (SCRIT) has been completed.[9)] This ring will allow the precision measurement of charge distribution, namely proton distribution inside unstable nuclei, for the first time. The construction of Rare-RI ring was completed in 2013.[10)] It will allow precision mass measurements with the accuracy better than 1 p.p.m. for quite rare RIs with a productivity of 1 particle per day. The RIBF is now exhibiting its powerful potentiality to explore the nuclear world that was previously not accessible. In November 2008, 45 new radioactive isotopes were discovered in only a 4-day experimental run and with only 0.3 pnA beam intensity.[11)] Among them, palladium-128 is speculated to be the origin of the second peak in the solar isotope abundance. In another two years, this uranium beam intensity will be increased by 400 times by installing a novel pressurized He-gas charge stripper having infinite lifetime. This decisive breakthrough has been devised by my younger colleague, Dr. H. Okuno.[12)] RIBF will greatly expand our known nuclear world up to around pink-

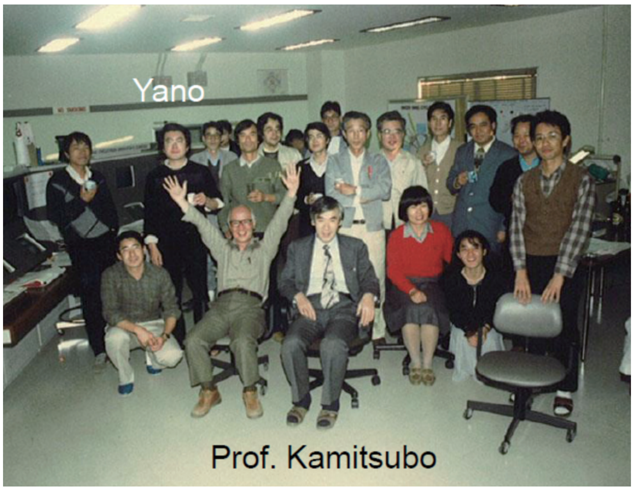

Fig. 2. Celebration of the first beam extraction from the No. 5. cyclotron (RRC) at 15:34 on Dec. 16, 1986. Twenty years later, the first beam from the No. 9 cyclotron (SRC) was produced.

coloured (in-flight fission) and sky-blue-coloured (projectile fragmentation) regions, which contain a hypothetical r-process pathway (green arrow) to create the uranium element at the moment of super-nova explosion, when we will achieve a primary beam intensity of 1 pμA for all ions. The RI-intensity produced at the edge of the regions is estimated by the GSI's simulation program EPAX2.[13] The significant challenge of uncovering the mystery of the element genesis has begun.

3 RARF

Let us look back on the 24 years, devoted to the RIBF project, from 1987 to date.

The RIKEN Nishina Center[14] established in 2006 is also my creation, and it is the first Japanese research center named after one of our great pioneering scientists. Dr. Nishina is called the Japanese father of nuclear science, and he mentored the first two Japanese Nobel Prize winners, Professors H. Yukawa and S. Tomonaga. Furthermore, the development of Japanese accelerators was initiated from his cyclotrons. I spent three and half years as the first director of the RIKEN Nishina Center, and now my younger colleague, Dr. H. En'yo, has succeeded me. Professor W.F. Henning, the former director of GSI, was appointed as the deputy director in charge of RIBF in 2010.

Figure 2 shows a photograph of our team celebrating the first beam extraction from the RRC cyclotron. The memorable moment occurred at 15:34 on December 16, 1986. Twenty years later, the first beam came out from the SRC cyclotron.

In 1987, Prof. M. Ishihara and I wrote a news article

Fig. 3. Cover page of the popular Japanese science magazine "Parity" published in June, 1987.

on the commissioning of the RIKEN Ring Cyclotron in the popular Japanese science magazine "Parity." A photo of the RRC cyclotron was shown on the cover page, as shown in Fig. 3. In the article, we wrote that our future dream is to create the world's leading "RI beam factory."

4 From RARF to RIBF

In the same year, when the discovery of high-T_C superconductivity was a hot topic, I was invited to attend a panel discussion on superconductivity and atomic energy. In this panel presentation, I presented a very conceptual drawing of the RI beam factory based on a superconducting sector-magnet cyclotron. In my scheme, I would later add an SRC and an RI beam collider downstream of the then newly operational RRC cyclotron.

In 1995, eight years after the RRC commissioning, a two-year R&D budget of nearly $2M was approved. By then, the RIBF plan consisted of a single big 150 MeV/nucleon SRC and a MUlti-use Experimental Storage rings, MUSES.[15] MUSES aimed at realizing the world's first electron-RI beam collider. However, this SRC had a serious problem in its design. In 1996, we had to conclude that the beam injection to this SRC was impossible because the central region was too narrow to set up the injection elements. This was the first hurdle we struggled to overcome.

Incidentally, the same year, I was invited over the phone by Professor B. Sinha, the then director of the VECC, in Calcutta, India to his office to take the photograph shown in Fig. 4 of us shaking hands to celebrate the conclusion of an MOU. During the flight

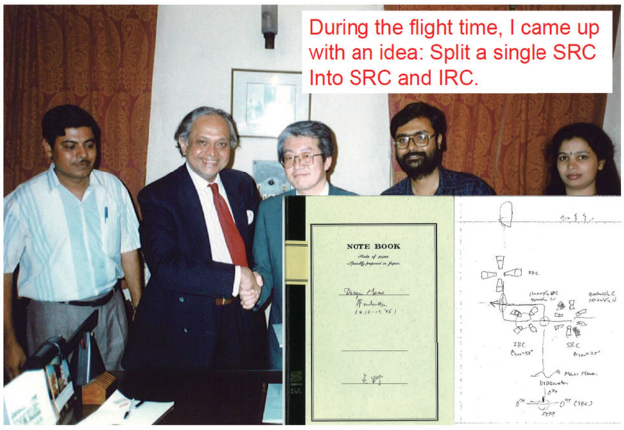

Fig. 4. VECC-RIKEN MoU conclusion meeting at Calcutta, India in 1996.

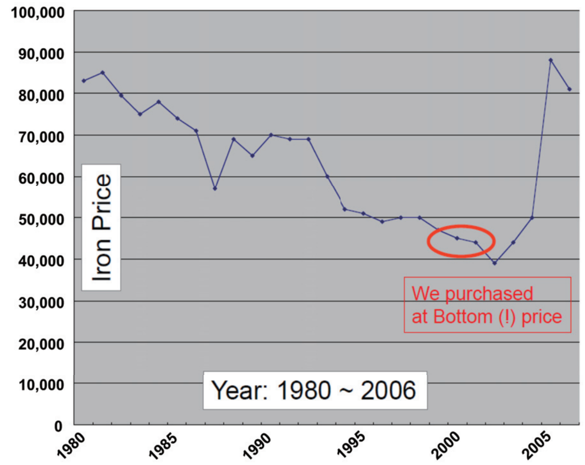

Fig. 5. Yearly trends in iron price from 1980 to 2006.

from Narita to Calcutta, I came up with an idea that the single big SRC should be split into smaller but with larger central-region SRC and an IRC cyclotron having a structure similar to the RRC.

The inset of Fig. 4, my memo in the travel note book where I jotted down this idea. In 1997, the construction budget was approved. In the figure, "SRC" and "IRC" can be seen.[16] We requested $750M in total, but I was strongly requested by the government to reduce this cost by a significant amount. However, we still had serious problems in the SRC design. In 1998, I concluded that this SRC design included too many technical problems to be solved, and all the problems are due to the large valley-region leakage flux in the long term.

After recognizing this serious design drawback, I could not sleep well until, in 1999, I decided to cover whole valley regions with thick iron plates to absorb leakage flux. This was the simplest solution to solve all the problems.[17] The only problem was that the required mass of iron amounted to 8,000 tons, which is 1,000 tons heavier than the Eiffel Tour in Paris. Thus, the world's first, strongest, and heaviest SRC was born. This structure has self-radiation shielding capability as well. In November 2005, full excitation of the SC sector magnets was achieved.

Figure 5 shows the yearly trends of iron price from 1980 to 2006. We purchased 8,000 tons near the period when the price was minimum. In order to construct this super-facility, this stroke of luck was indispensable.

In 1999, an RIA project of the USA based on SC linacs was proposed, and the "white paper" of the project stated that the 150 MeV/nucleon uranium beam planned to be supplied through the RIBF project is insufficient to efficiently produce RI beams by in-flight fission. Instead, 400 MeV/nucleon should be achievable.[18] Then, in 2001, I decided that we add

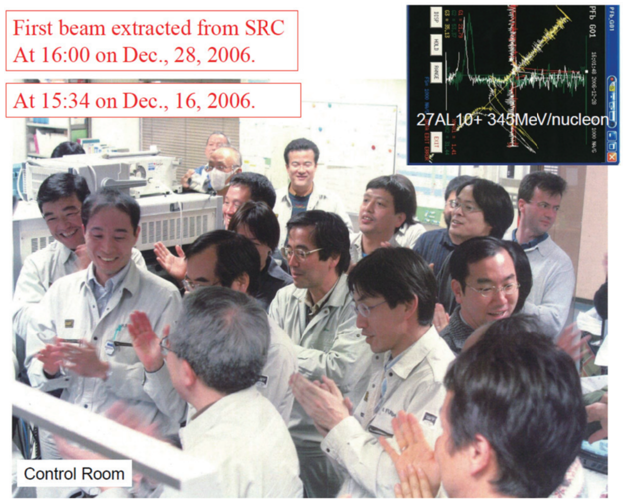

Fig. 6. A photo of the RIBF control room taken when the first beam was extracted from the SRC at 16:00 on December 28, 2006.

one more inexpensive cyclotron, fRC, to upgrade the final energy to 340 MeV/nucleon. Moreover, BigRIPS should be a large-aperture SC separator that can accept large-emittance fission fragments. These are the present design.[17]

5 The first beam and beyond

The first beam was extracted from the SRC at the moment indicated in Fig. 6, I had been declaring for years to the international accelerator community that the first beam would be extracted exactly 20 years after the first beam was extracted from the RRC cyclotron. Although the beam was slightly delayed, we almost well were successful.[19] "Science" magazine and "Nature" magazine reported the completion of RIBF.

In June 2007, the International Nuclear Physics Conference (INPC'07) was held in Tokyo, and I was given an extra session to deliver a flash report on the first outcome of RIBF: the discovery of a very neutron-rich isotope, palladium 125, by the in-flight fission of a 345-MeV/nucleon uranium beam. Incidentally palladium 112 was discovered using Dr. Nishina's cyclotron.[20] In his experiment, he discovered a much more surprising "symmetric fission" of uranium by fast neutrons, unlike the well-known "asymmetric fission" by slow neutrons. When closing my talk, I declared that a great endeavour has begun to explore areas of the nuclear world that have been inaccessible thus far. In the opening session of the conference, the Emperor delivered a very moving message to the audience about the tragedy of Japan and Japanese people caused by the atomic bombs and the role of the nuclear physics community.

Incidentally, during my directorship since 1992, I enjoyed the honour of guiding the Emperor on a tour of our cyclotron facilities twice, first in 1992 and then in 2006. I believe that now, the Japanese Emperor and Empress are the most informed royal couple in the world on cyclotrons.

How about MUSES? In 2001, the GSI reported that the luminosity obtained in MUSES is too low to create scientific impacts because the RIKEN system is based on a DC beam, rather than a pulsed beam. We absolutely agreed. Therefore, in 2003, I decided to give up the MUSES project, and instead decided to construct much better cost-effective high-performance alternatives, namely the SCRIT for precision charge-distribution measurement by electron scattering (this novel scheme was devised by my younger colleague, Dr. M. Wakasugi), and the Rare RI ring for precision mass measurement. The top of Fig. 7 shows a photograph of the completed electron-RI scattering system, and the bottom diagram shows its principle, the essence of which is that we utilize the unfavorable "ion trapping" phenomenon positively. We published two PRL papers on the experimental proof of principle.[21]

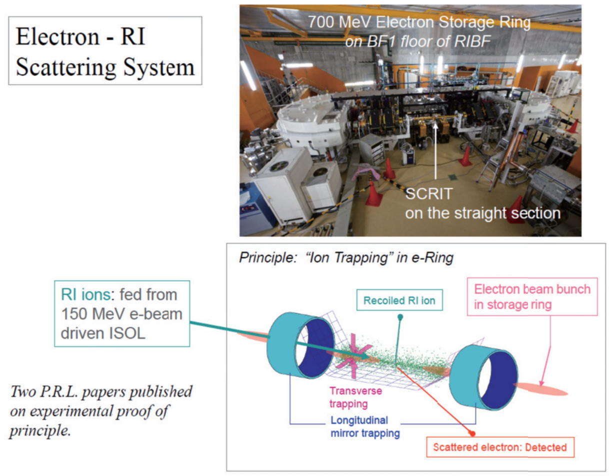

Fig. 7. Self-confining RI ion target (SCRIT) for e-RI scattering experiments.

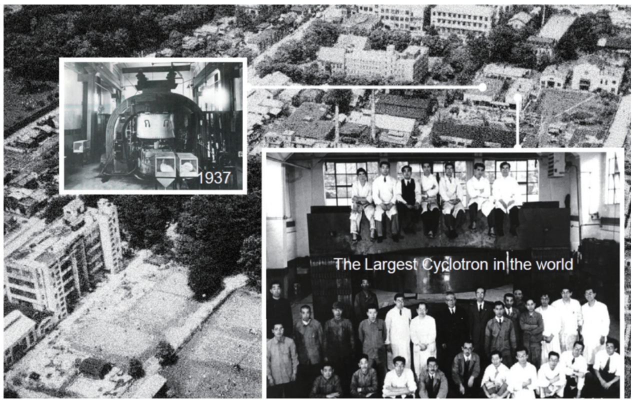

Fig. 8. Dr. Nishina's cyclotrons and the original RIKEN campus.

6 Dr. Nishina's dream

One day before the first International Particle Accelerator Conference (IPAC'10) in Kyoto, Japan, "Special lectures to commemorate the 120-th anniversary of Birth of Yoshio Nishina" was held. In this lecture meeting, distinguished Professors presented talks about Dr. Nishina and the advancement of particle accelerators and their applications in Japan. One of the lecturers, Professor M. Craddock, spoke about a very suggestive and impressive review story of Japanese cyclotrons from Dr. Nishina's pioneering work up to the present RI Beam Factory. The lecture notes can be viewed on RIKEN Nishina Center's home page.

Figure 8 shows photographs of Dr. Nishina's cyclotrons. This old aerial picture shows the original RIKEN campus, which was located near the center of Tokyo. On the top-right corner of this picture, there used to be Nishina's laboratory. The two buildings indicated in white dots housed his No. 1 and No. 2 cyclotrons. The No. 2 cyclotron, commissioned in 1944 just before the end of World War Two, was the world's largest cyclotron at that time, and was about to start experiments. However, as many of you know, these cyclotrons and at the same time Dr. Nishina's dream were killed by the War, as shown in the "Life" magazine issued in December 1945 (Fig. 9).

Since then, sixty six years have passed. I believe now that Dr. Nishina's dream has been realized. However, my dream will take a little more time to come true.

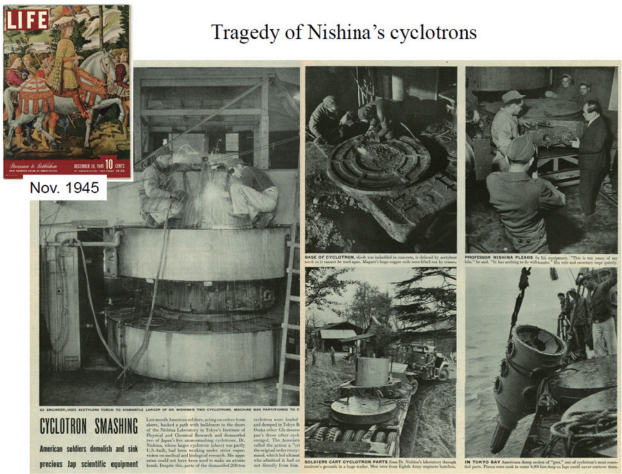

Fig. 9. Disassembling of No. 1 and No. 2 cyclotrons reported in "Life" magazine in 1945. ©1945 LIEF.

Acknowledgments

I wish to give my special thanks to many, many Japanese and foreign colleagues and collaborators and the presidents of RIKEN, especially Professor A. Arima. Without his strong support, this big project could not have started. Furthermore, I wish to express my gratitude to the International Advisory Committees (IACs) and the International Technical Advisory Committees (TACs) of the RIBF project, which have continuously led us in the right way, to the Governments that have strongly supported this project, and also to the companies that have helped us realize RIBF.

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