PROSPECT OF RIKEN RI BEAM FACTORY FOR COMING 5 YEARS

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RIKEN Radio Isotope Beam Factory RIBF is currently providing the world most powerful heavy-ion beams up to uranium. The status of RIBF is presented together with its prospect for coming five years.

1. Introduction

RIKEN Nishina Center for Accelerator-Based Science was named after Yoshio Nishina who is known to be the father of Japanese Nuclear Physics. He became Chief Scientist of RIKEN in 1931 and built two cyclotrons completed in 1937 and 1944. The second one was the world largest at that time, but was destroyed and abandoned into deep Tokyo Bay just after the World War II. Since then, 70 years have passed and RIKEN presently has its 9th cyclotron in operation, the world most powerful cyclotron SRC, Superconducting Ring Cyclotron.

Nishina Center was inaugurated in 2006 by unifying all the laboratories in RIKEN which were studying nuclear physics or anything related to accelerator-based science. We have three facilities operating in the world. In the US at Brookhaven National Laboratory, RIKEN-BNL Research Center is our base to participate in the PHENIX experiment at RHIC, Relativistic Heavy Icon Collider. The polarize-proton acceleration at RHIC is led by RIKEN's initiative. In the UK at Rutherford Appleton Laboratory, we are operating a facility to perform muon science. Until recently when J-PARC became operational, it provided the most powerful muon beams in the world. And lastly and most importantly, we are operating Radio Isotope Beam Factory, RIBF, the major subject of this manuscript, at Wako-city in Japan.

Following the two cyclotrons built by Yoshio Nishina, RIKEN built other 2 after the World War II. Those early 4 machines had retired already. The 5th, 6th, 7th, 8th and 9th are still alive and very active. We operate those 5 cyclotrons in cascade. The linac (named RILAC1 which synthesized three events of element 113th) and the 5th and 6th cyclotrons were built more than 20 years ago, so that we call them the old facility. Using them as injectors, 7th, 8th and 9th are built. This cyclotron cascade is operational since 2007.

The successful start of RIKEN RIBF has ignited a world-wide competition on the next-generation RI-beam factories. As one can find in Table 1, FAIR at GSI, FRIB at MSU and SPIRAL2 at GANIL are chasing us up. Very recently RISP (Radio Isotope Science Project, formerly called KoRIA), to be built in the new Korean research institute BSI, joined the race with a very aggressive plan. We expect we will continue to be at the top for coming 5 years, but some years beyond that we will not be the best any longer and we may have to prepare for it.

Table 1. World competition of RI-beam facilities. The superiority of RIKEN RIBF will certainly remain for 5 years, but not for 10 years
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Year	07	08	09	10	11	12	13	14	15	16	17	18	19	20
RIBF RIKEN	↑ Start Exp						↑ Facility Complete					↑ Up-grade Expected		
FAIR GSI			↑ Start Construction						↑ Start Exp		↑ Facility Complete			
FRIB MSU							↑ Start Construction						↑ Start Exp	
Spiral2 GANIL		↑ Start Construction						↑ Start Exp			RI acceleration Expected later			
RISP BSI						↑ Start Construction					↑ Start Exp			

Before entering the main subject of this manuscript, let us mention our very recent discovery. On August 12th in 2012, we have observed the third decay chain of the 113th element, which contained 6 consequent alpha decays connected deeply into known nuclei. It was also followed by electron capture and another alpha decay. This beautiful event was published in Ref. 1 and orally reported for the first time to the world in this EXON2012 symposium by Kosuke Morita.

2. RIBF Accelerator Complex

Schematic view of RIKEN RIBF is shown in Figure 1. The operation mode of RIBF is rather complicated as can be seen in Figure 2. The major running mode is so-called fixed frequency mode at 345 MeV/A with which we can accelerate any nucleus. To change the energy, we need to skip fRC. The beam energy becomes variable up to 400 MeV/A, but mass number dependent. For light ions

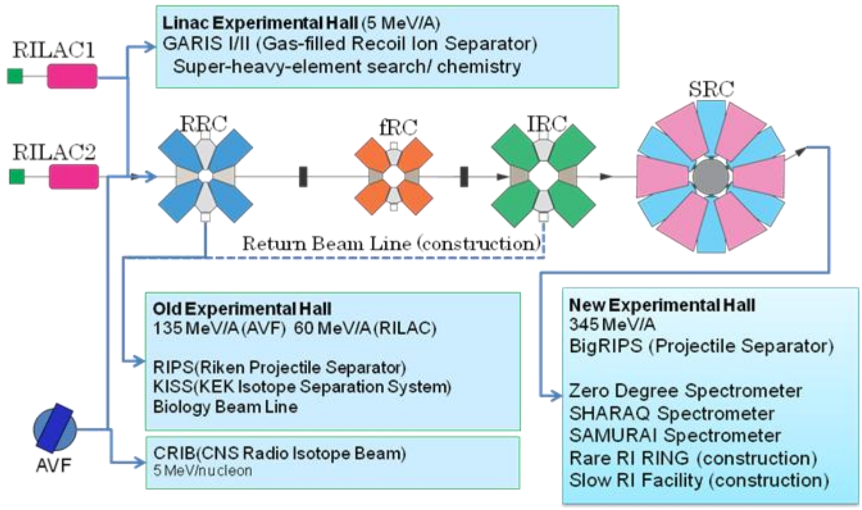

Figure 1: Schematic view of RIKEN Radio Isotope Beam Factory, RIBF. RIKEN Linear Accelerator (RILAC1/2) and AVF Cyclotron are the injectors. RIKEN Ring Cyclotron (RRC), fixed-frequency Ring Cyclotron (fRC), Intermediate Ring Cyclotron (IRC) and Superconducting Ring Cyclotron (SRC) are operated in cascade. Two charge strippers are placed after RRC and fRC.

with *m/q=2* we can use AVF instead of the RILAC to reach higher energy than 400 MeV/A.

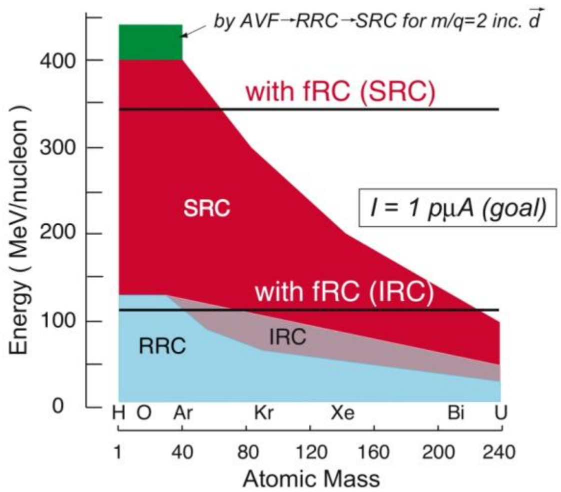

Figure 2: Acceleration modes of RIBF

Recently we commissioned a new compact injector RILAC2 specialized for heavy nuclei larger than xenon. By introducing this, RILAC1 can be operated solely for super heavy element searches or anything of similar kind.

The biggest difficulty we had faced at for the high intensity operation of uranium beam was charge strippers. We were using carbon foils at the exits of RRC and fRC. The stripping efficiency was reasonable but the life time was too short, especially the life time of the first stripper was only 12 hours. We decided to switch them to gas strippers, the first one to helium and the second one to nitrogen (lately we found He gas with a carbon foil is more effective). We modified fRC to accept lower charge states, like 65+. The developments have been finished and we started using them for users beam time this year.

The Figure 3 shows our record of beam intensities with the bullets and the outlook with the lines. For lighter ions we have reached our design goal of 1000pnA. This corresponds to 6.2kW of beam power for oxygen's case.

Heavier ions we had problems as mentioned before but gradually being solved. This year we have broke many records, ^{48}Ca with 415pnA and ^{70}Zn with 100pnA. For uranium we expected to reach 5pnA and actually reached 15pnA in the November-December beam time in 2012. Our goal for U beam is 100pnA, which we expect to reach in 2015.

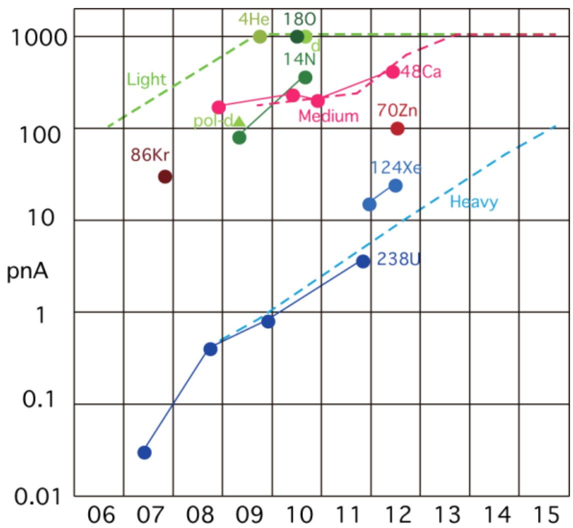

Figure 3. Achieved beam intensities (bullets) and the prospects (lines) until 2015.

To exceed the uranium intensity of 100pnA we need a new idea to be ready in 5 years from now, before other competitors in the world become active. One of the ideas we are discussing seriously is to modify the fRC to super conducting. By doing so, we can eliminate the first charge stripper by transferring the RRC beam directly to fRC. This will be a major kick for intensity upgrade by a factor of five (Option-1 in Table 2). The other option is to introduce two stages of super conducting LINAC, the first stage for SHE experiments and the second directly to fRC (Option-2 in Table 2).

Table 2. Beam Status of RIBF with the prospects and up-grade options.
Design parameters of FRIB at MSU are also listed as reference.

<table>
<tr><th></th><th></th><th>RIBF
Present</th><th>RIBF
2015</th><th>RIBF
Option 1</th><th>RIBF
Option 2</th><th>FRIB
Goal</th></tr>
<tr><td rowspan="3">Beam
Current
(pnA)</td><td>Heavy
(Xe-U)</td><td>15.0-37.0</td><td>50-100</td><td rowspan="3">1,000</td><td rowspan="3">10,000
(exceed present facility rad. limit)</td><td rowspan="3">8,000</td></tr>
<tr><td>Medium
(^{48}Ca)</td><td>415</td><td>1,000</td></tr>
<tr><td>Light
(^{18}O)</td><td>1,000</td><td>1,000</td></tr>
<tr><td colspan="2">Uranium Wattage</td><td>0.3kW</td><td>4kW</td><td>80kW</td><td>800kW</td><td>400kW</td></tr>
<tr><td colspan="2">Beam Energy/nucleon</td><td>345MeV</td><td>345MeV</td><td>345MeV</td><td>345MeV</td><td>200MeV</td></tr>
<tr><td colspan="2">#stripper</td><td>2(He/N2+C)</td><td>2(He/N2)</td><td>1(Gas)</td><td>2(Gas)</td><td>1</td></tr>
<tr><td colspan="2">Configuration.</td><td>RILAC2
RRC
fRC(69+)
IRC,SRC</td><td>RILAC2
RRC
fRC(65+)
IRC.SRC</td><td>RILAC2
RRC
SC-fRC
IRC,SRC</td><td>SC-LINAC
fRC,IRC,SRC</td><td>SC-LINAC</td></tr>
</table>

3. RIBF Experimental Facilities

As was illustrated in Fig. 1, when other injectors are used, RILAC1 can be exclusively used for GARIS1/2 (GAs filled Recoil Ion Spectrometer), i.e. super heavy element search. Beams from AVF and RRC are also used in the old experimental hall; RIPS, KISS and CRIB (see Fig. 1). A return beam line from IRC back to the old experimental hall is under construction.

Most importantly SRC provides beams to BigRIPS, two-stage RI separator with 9 Tm of bending power for 345 MeV/nucleon beam. The beam of separated RIs goes to either of Zero-Degree Spectrometer (ZDS), SAMURAI spectrometer or SHARAQ spectrometer.

Concerning decay spectroscopy with stopped RIs, EURICA is presently in place using ZDS as a beam transport. EURICA is an acronym of EUro Riken Cluster Array, which used to be the GSI RISING detector, invited to the Far-East to enhance the gamma-ray spectroscopy at RIBF by far beyond. After the shake down, it starts the experiments in November 2012 and will continue to stay in RIKEN for two years to complete 100 days of beam time approved already in RIBF Program Advisory Committee.

SAMURAI is Superconducting Analyzer for MUlti-particle RAdio Isotope beam with 7 Tm of bending power. The construction was completed in the spring 2012 and several experiments have beam performed until now. The major research subject is reaction studies with kinematically-complete measurements by detecting multiple particles in coincidence. The first experiment was to measure Coulomb break-up of halo nucleus ^{22}C, accumulated 2n correlation data with ample ^{22}C beams from BigRIPS. In flight gamma-decay experiments can also be done with SAMURAI by combining the NaI gamma-ray detector DALI2. SAMURAI is the biggest experimental apparatus in RIKEN (besides the cyclotrons of course) so that we welcome further international participations.

SHARAQ is an acronym of “Spectroscopy with High-resolution Analyzer and Radio Active Quantum beam” and was built by the University of Tokyo. The momentum resolution of 8100 has been achieved using dispersion-matching technique and the goal is 10000. By using SHARAQ as a beam transport, rare RIs go to the Rare-RI Ring currently under construction. This ring can be viewed as a 24-sector ring cyclotron. RIs are triggered at the exit of BigRIPS, which invokes the kicker into the ring. With a careful tuning of magnet, isochronous circulation of RIs will ensure the mass resolution of 10^{-6} within a momentum bite of 0.5%.

The other option is to accept the beam fragments from BigRIPS into a gas catcher called Slow-RI, to use them in experiments like beta-NMR studies. We are lucky that the construction of Slow-RI is approved in the governmental supplemental budget of JFY2012. It will be ready for users in a year or two.

RIKEN RIBF now has an electron storage ring, second hand from Sumitomo Industrial Company. Using the storage electrons we do electron scattering experiment with SCRIT, Self-Confined RI Ion Target. RIs are self confined around the electron beam and the mirror potentials along the beam. Test experiments with stable nuclei were successful, recorded the luminosity of 2×10^{27} with 240mA of electron beam. For the moment we are commissioning the uranium ISOL bombarded also with the electron beam. In future, a combined operation with the Slow-RI system is foreseen.

BigRIPS can be viewed as a versatile spectrometer. We recently demonstrated a method to produce highly spin-aligned RI beams via two-step nucleon transfer. This method can be used for *any* projectiles. The results can be seen in Ref. 2.

4. Summary: RIBF Operation and Management for coming 5 years

The SRC-BigRIPS combination is operational since 2007. As you can find in Figure 4, RIBF becomes fully operational from 2010, with a temporal break

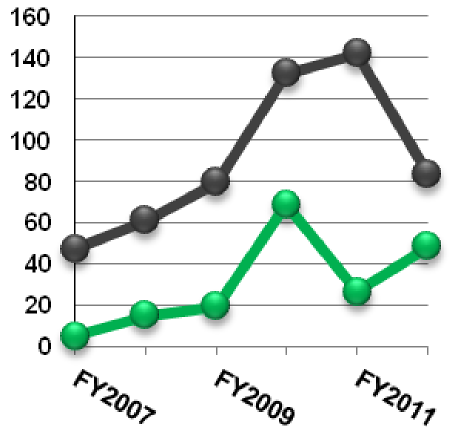

Figure 4: The machine time history for experiments using BigRIPS. The upper line is for the number of days with SRC is operational. The lower line is the days with RIs delivered for users. The values for FY2012 are for a half year.

occurred in 2011 due to the earthquake. Up to now the number of days for the approved experiments by the PAC is close to 500 days. Within that about 200 days are executed and 300 days are in the backlogs. We hope to execute 90 days of user beam time in 2012. From the next year on, we are foreseeing 8-month operation, which corresponds to 100-120 user-beam-days per year, even though the budgetary limitation due to the aftermath of the earthquake is rather severe.

By 2015 we aim to have 345MeV/A U beam reaching 100pnA (7 times to go). We will measure the major characteristics of ~100 key unstable nuclei close to R-process path and/or vicinity of the magic numbers, in order to solve the mystery of element genesis and to establish the ultimate picture of nucleus.

We set the priority of beam development as follows. The 1st priority is to increase uranium intensity, and the 2nd priority is to increase Xe intensity. In principle they are on the track. There are approved proposals asking ^{86}Kr and ^{76}Ge. Those are our 3rd and 4th priority to be ready in two-three years of time. To save the beam switching overhead, the operation is scheduled to maximize the beam time for SRC-BigRIPS experiments. This leads to campaign-type beam operation, so that we keep announcing a rough sketch of beam plan for coming two years (see Ref. 3).

In advancing the research program at RIBF, users' contributions have been very significant indeed. When we sum up all the contributions from users, it reached 45M$ while RIKEN has spend 49M$ up to now for the experimental facilities (excluding the accelerator construction which is 450M$). This is very good deal. For the moment, CNS (Center of Nuclear Study) of the University of Tokyo, Niigata University and KEK are under the User Institute Contract with RIKEN, placing their branch at RIBF and operating their own facility at RIBF. This is an advanced concept of synergetic-use laboratory, aiming something more than user laboratory or shared-use laboratory. We would like to extend this scope worldwide and wish to invite more international participations. We will establish the RIBF consortium covering experiment and theory. So please consider to have your branch at RIKEN Nishina Center. We are willing to serve you the world best RI beams.

Acknowledgments

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