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Citation: *AIP Conf. Proc.* **1412**, 423 (2011); doi: 10.1063/1.3665344

View online: <http://dx.doi.org/10.1063/1.3665344>

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Industrial Application of Radioactive Ion Beams at the RIKEN RI Beam Factory

Tadashi Kambara^a, Atsushi Yoshida^a, Yoshiyuki Yanagisawa^a, Daisuke Kameda^a, Naoki Fukuda^a, Tetsuya Ohnishi^a, Toshiyuki Kubo^a,
Ryuji Uemoto^b, Akira Nagano^b and Hiroyuki Uno^b

^a Nishina Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

^b S. H. I. Examination & Inspection, Ltd., 1501 Imazaike, Saijo, Ehime 799-1393, Japan

Abstract. The Radioactive Ion Beam Factory (RIBF) at RIKEN is a heavy-ion accelerator facility that can provide intensive beams of radioactive isotopes (RI beam) produced at in-flight RI-beam separators. While the facility is used for experiments of various basic research fields, a new project has been started to open the facility to non-academic proposals from industry. We show an overview of the RIBF and the project of industrial use, and present a utilization of an RI-beam for development of wear diagnostics of industrial materials.

Keywords: RI Beam, wear diagnostics, tracer

PACS: 29.38.Db, 81.40.Pq, 82.80.Jp

RIKEN RI BEAM FACTORY

RIKEN is an independent administrative institution under the Ministry of Education, Culture, Sports, Science and Technology of Japan for research and development of science and technology. It carries out experimental and theoretical works in the fields of physics, chemistry, biology, and medical science engineering from basic research to applications.

The accelerator-related research activities in RIKEN are performed at Nishina Center for Accelerator-Based Science (RNC). One of its major research facilities is the Radioactive Ion Beam Factory (RIBF), which is a heavy-ion accelerator complex located in Wako near Tokyo [1]. The RIBF has five cyclotrons and a heavy-ion linac, which can produce the world's most intense ion beams of a whole range of elements from hydrogen to uranium up to 350 MeV/nucleon.

The RIBF consists of two parts. The old part of the facility, completed in 1987, has a linac (RILAC), an AVF cyclotron and a ring cyclotron called RRC. The RILAC and the AVF cyclotron have their own beam lines and can be operated stand-alone for experiments. The RRC post-accelerates a beam from either the RILAC or AVF and boosts the energy by a factor of 17. The maximum energy of the beam from the RRC is 135 MeV/nucleon for light ions injected from the AVF, and 63 MeV/nucleon for heavier ions from the RILAC. The new part of the facility, which was completed in 2006, has three ring cyclotrons, fRC, IRC and SRC, as post-accelerators of the RRC up to 350 MeV/nucleon. Figure 1 shows a plan view of the RIBF where the right hand side is the new facility (shaded), and Fig. 2 shows the conceptual diagram.

As a remarkable feature of the RIBF, beams of various radioactive nuclides (RI beams) are produced by in-flight type RI-beam separators and are used for experiments. An intense beam of stable nuclei from the accelerators passes through a solid target, and a mixture of radioactive nuclides with nearly the same velocity as the primary beam is produced through projectile fragmentation or in-flight fission reactions. Then the desired nuclide is selected from the mixture by a magnetic separator and sent to the experiment. The RIBF has two RI-beam separators, the RIPS in the old part [2] and BigRIPS in the new part of the facility [3].

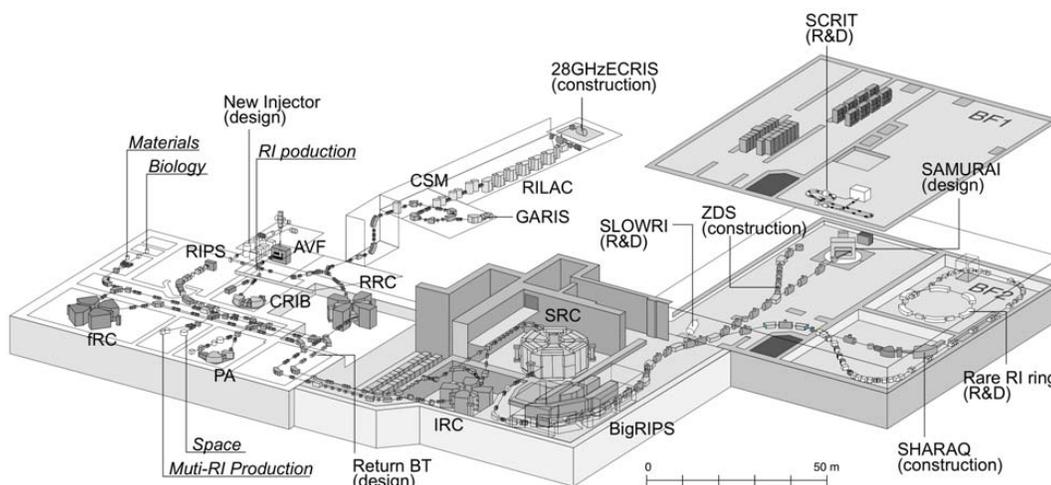


FIGURE 1. Plan view of the RI Beam Factory.

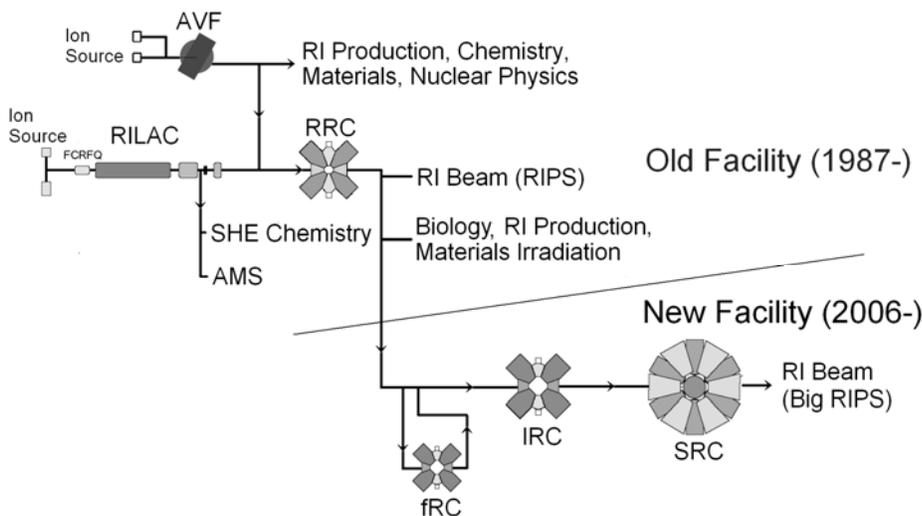


FIGURE 2. Conceptual diagram of the RIBF accelerators.

The new part of the RIBF is dedicated to cutting-edge experiments of nuclear physics. The BigRIPS accepts the heavy-ion beam from the SRC and produces an intense RI beam in a whole range of elements up to uranium. The BigRIPS has been used for various experiments since 2007. The facility and experimental devices are being continuously developed and improved.

On the other hand, the old part of the RIBF with more than 20 years of history is used for experiments of various fields such as atomic physics, solid state physics, chemistry, biology, and engineering besides nuclear physics. The RIPS after the RRC, built in 1987, is one of the earliest RI-beam separators in the world and can deliver RI beams of elements lighter than Fe. It is used for experiments of nuclear physics and materials research, but the experiments of nuclear physics are gradually shifting to the BigRIPS. Experiments of other fields at the old part of the RIBF use ion beams of stable nuclides.

The RIBF is open to academic proposals of scientific research and developments from institutions all over the world. The proposals are reviewed on the basis of scientific merit and originality by either a nuclear physics program advisory committee (NP-PAC) or a materials and life science program advisory committee (ML-PAC), depending on the field. RNC allocates beam time of the accelerators to the proposals that have been accepted. The user should publish the results of their experiments.

INDUSTRIAL APPLICATIONS AT THE RI BEAM FACTORY

In November 2009, RNC started a new project, “Promotion of applications of high-energy heavy ions and RI beams”, that aims to open the RIBF accelerators to non-academic users in Japan. In the project, the old part of the RIBF facility with the AVF cyclotron, RILAC, RRC, and some experimental instruments including the RIPS are available for non-academic proposals from users including private companies. Beam times are allocated to the approved proposals, and the users pay the beam time fee to RIKEN. The users can exclusively possess the results and the intellectual properties obtained by the use of RIBF and are not required to publish them. In order to encourage the use of RIBF by those who are not familiar with the utilization of ion beams, the first two beam times in each proposal can be assigned free of charge, i.e. they would be trial uses.

The proposals are reviewed by a new program advisory committee, the industrial PAC, which was set up in December 2009. The standard of acceptance is not scientific originality of the proposal but its feasibility, impact to the society and advantage of using the RIBF over other facilities. The industrial PAC has met twice in 2010 and approved five proposals as trial uses. They include accelerator mass spectroscopy (AMS), simulation of cosmic rays to test semiconductor devices, and wear diagnostics of machine parts with implanted tracer nuclei, the last of which will be described in more detail in the following subsection.

Example: Wear Diagnostics of Industrial Materials with RI Beams

Overview of the Method

The present-day society is supported by many kinds of machines in industry, infrastructure, transportation, and private homes. The evaluation of lifetime of the machine parts is important for effective maintenance and prevention of sudden failure of the machine systems. One of the factors that determines the lifetime of machine

parts in motion is wear. A method called Thin Layer Activation (TLA) is used to evaluate the wear of machine parts utilizing radioisotopes as tracers. The surface of the machine part that gets worn out is activated, and the amount of removal of the material due to wear is evaluated by the decrease of the measured radioactivity. Continuous γ -ray detection from outside of the machine enables real-time diagnostics of wear in running machines. In conventional methods, the sample is activated through nuclear reactions by a direct ion-beam irradiation. This method is applicable for metals and alloys with elements that can be efficiently activated by ion-induced reactions and that are resistant to the radiation damage and heat by the beam irradiation.

Nowadays, various kinds of new materials like ceramics and plastics are used in machine parts. The chemical composition and radiation resistance of these materials often don't allow the conventional method of activation, and a different method of activation has been proposed in which radioisotopes produced outside of the sample are implanted [4]. This method is in principle applicable for any kind of materials regardless of their element composition and is almost non-destructive since the heat and radiation damage is much lower than with the conventional method. In addition, the depth profile can be adjusted by the energy and the direction of the RI injection relative to the surface. Several methods have been proposed for implantation of RI, such as acceleration of radioisotopes produced at a remote facility [4], or the use of reaction products ejected from a beam-irradiated target placed close to the sample [5, 6]. In the former case, it is necessary to handle RI with a high activity at the ion source under strict safety regulations, and in the latter case, different nuclides can be implanted in the sample.

Use of RI Beam at RIBF

An alternative possibility is to produce the RI beam from a stable-nuclide ion beam with an in-flight type RI-beam separator. Recent development of a high-intensity heavy-ion accelerator permits production of RI beams intense enough for the implantation of tracers. In order to check the feasibility of this method, a proposal titled "Development of wear analysis technique of industrial materials with radioactive beam (Na-22)," was submitted to RNC by S.H.I. Examination & Inspection Ltd. The purpose of the proposal was to establish the procedure for implantation and to evaluate the intensity, uniformity, and depth profile of the implanted RI. Actual wear diagnostics requires a high radioactivity and a uniform distribution of the implanted RI in the material. The proposal was approved by RNC, and two trial uses were executed in 2009 and 2010 where a beam of radioactive ^{22}Na with a half life of 2.6 years was produced at the RIPS and implanted in test materials.

The setup of the RI-beam implantation is shown in Fig. 3. A primary beam of ^{23}Na was accelerated by the RILAC and the RRC up to 63 MeV/nucleon with intensity up to 1 μA (particle μA). At the RI-beam separator RIPS, it passed through a 1.5mm-thick beryllium target. A radioactive ^{22}Na beam was produced by the neutron-loss reactions such as $^{23}\text{Na} + ^9\text{Be} \rightarrow ^{22}\text{Na} + n + ^9\text{Be}$ in the target. The beam after the target was magnetically separated by the dipole magnet D1 so that the primary ^{23}Na ions were blocked by the D1-slit while the lighter reaction fragments including ^{22}Na were led to a wedge-shape degrader (F1-Deg). The ^{22}Na ions were selected by the energy-loss in

the F1-Deg and following magnetic analysis by the D2 dipole magnet. After the F3 chamber, the RI beam was extracted from vacuum to atmosphere through a Kapton window and the intensity was monitored with an ionization chamber. The beam energy was adjusted by fixed and variable degraders. The variable degrader was an Al-plate tilted relative to the beam and the angle was programmable. A 20-mm diameter collimator was placed just before the sample. A 20-mm diameter collimator was placed just before the sample.

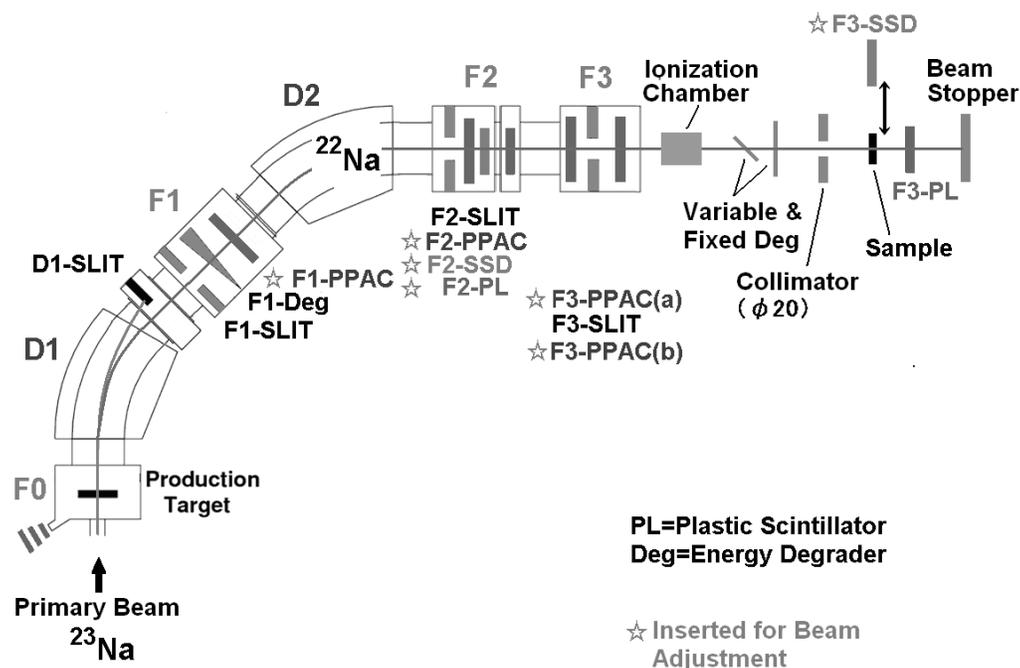


FIGURE 3. Setup of RIPS for RI-beam implantation.

Before the irradiation of the samples, the energy distribution of the RI ions was monitored with a solid-state detector (F3-SSD), and the angle of the variable degrader was programmed to optimize the depth profile. The samples implanted were some industrial materials, machine parts, and Al-foil stacks for measurements of the three-dimensional distribution of implanted RI. The Al foil stack consisted of 60 sheets of 6 μm thick Al foils with an effective diameter of 18 mm.

Results

After the implantation, the radioactivity of the samples was measured with HP-Ge γ -ray detectors. About 172 kBq of ^{22}Na was found to be implanted in a machine part sample during about 26 hours of beam time while the primary ^{23}Na beam intensity was about 1 μA . The intensity of the implanted ^{22}Na beam was estimated to be 2×10^8 /s. Figure 4 shows a γ -ray spectrum from the Al-foil stack. The two prominent peaks originate from the β^+ decay of ^{22}Na . The one at 511 keV is from the annihilation of positrons and the other at 1274.5 keV is from the daughter nuclide ^{22}Ne .

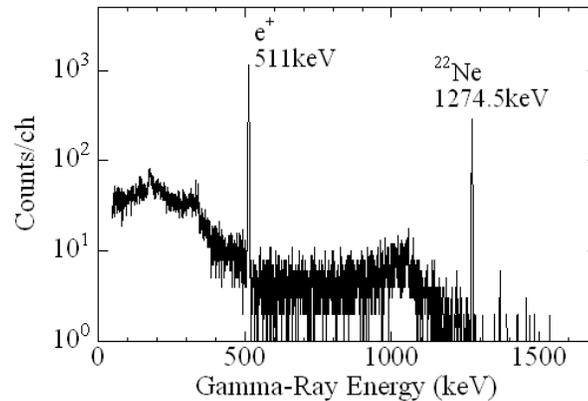


FIGURE 4. Gamma-ray spectrum of Al-foil stack.

The three-dimensional distribution of the implanted ²²Na was evaluated with γ -ray measurements of the layers of the Al-foil stack. The γ -ray distribution on each of the foils was taken by an imaging plate to visualize the two-dimensional beam-spot profile at different depths. The distribution was found to be somewhat uneven, so the machine-parts sample was continuously rotated in the beam spot during implantation to average the distribution.

The depth profile was obtained by the γ -ray intensity measurement of each layer. Figure 5 shows the result where the activity of the stack is shown as a function of the thickness of the layers removed from the beam-incident surface of the stack, as a simulation of the removal of the material due to wear of a machine part. The result looks reasonably linear down to a depth of 80 μm .

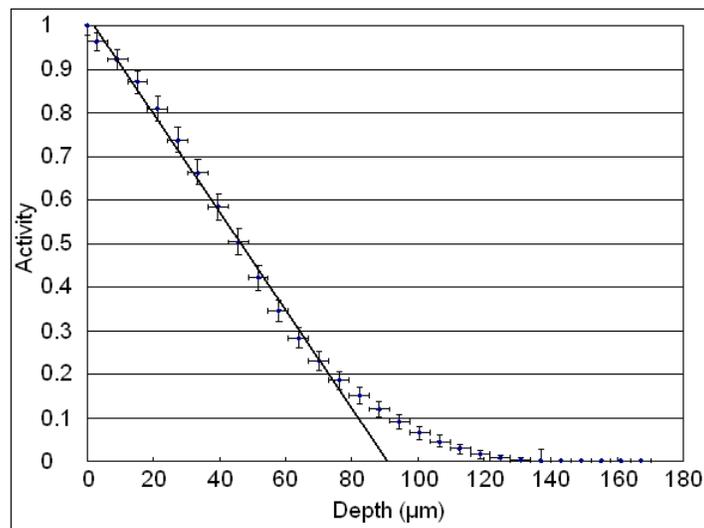


FIGURE 5. Depth profile of the implanted ²²Na ions.

According to these results, this method of activation looks promising for the wear diagnostics. The results are being scrutinized at the company to determine whether the method is technically and commercially practical.

SUMMARY AND PROSPECTS

The RI Beam Factory of RIKEN is a world class research facility with high-intensity heavy-ion accelerators and powerful RI beam separators. In addition to basic research of sciences at the RIBF, a new project has been started to open the old part of the RIBF to industrial applications that makes most use of the unique features of the facility. Several proposals have been approved and beam times were executed. One of them described here is the Thin Layer Activation (TLA) method which aims to develop diagnostic techniques for machine part wear utilizing an implanted RI beam as a tracer. Two trial uses were executed with a radioactive ^{22}Na beam implanted into sample materials for the evaluation of feasibility of the method. As a result, the intensity and quality of the RI beam looks acceptable for the present purpose.

Compared with the conventional method of implantation where radioisotopes obtained from remote facilities are ionized and accelerated, the present method of in-flight production and separation can provide RI beams with higher energies and a wider selection of nuclides. In the present case where the RI should be implanted in the vicinity of the surface, the beam energy should be degraded by insertion of degrader plates, which may also degrade the quality of the beam. On the other hand, a large penetration range of a high-energy RI beam can enable direct implantation of RI tracers to desired places in materials in atmosphere. A possible application is to implant a short-lived positron-emitting RI like ^{15}O into the coolant or lubricant of a running machine directly through the tubing wall, and trace the motion of the fluid by PET in real time.

ACKNOWLEDGMENTS

The authors thank the accelerator staff members for their operation of the ion source and accelerators to supply an intense and stable ^{23}Na beam. The project of the industrial use of RIBF was supported by grant-in-aid "Sharing advanced facilities for common use program" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) from November 2009 to September 2010.

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