# MUSES Project at RIKEN RI Beam Factory

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**Abstract**

We will construct two different types of storage rings at RIKEN RIBF. Accelerator complex including these rings is called MUSES. One is an accumulator cooler ring (ACR). An electron cooling device and a stochastic cooling device will be installed in the ACR. The RI beams quickly cooled by the combination of the two cooling methods are not only used for experiments at the ACR but also transported to the double storage ring (DSR). The DSR is a new type of storage ring, it can accept not only RI (heavy ions) beams but also electron beam. In this paper, we present outline of the MUSES project at the RIBF. Two kinds of unique experiments, which are main subjects at the MUSES, are also briefly introduced.

## 1 Outline of MUSES Project

The Radioactive Isotope Beam Factory (RIBF) is an expansion of the existing heavy ion accelerators facility at RIKEN [1]. The construction of the RIBF is separated into two phases. The first phase consisting of an intermediate ring cyclotron (IRC, K=950), a super-conducting ring cyclotron (SRC, K=2500), an RI beam separators (Big RIPS) and some experimental halls has been started from this year. The second phase is named MUSES (Multi-USe Experimental Storage rings) project [2]. The MUSES is an accelerators complex consisting of another RI beam separator (RIPS-M), an accumulator cooler ring [3] (ACR), a booster synchrotron ring [4] (BSR), a 300-MeV electron linac [5] (e-linac) and double storage rings [6] (DSR). Figure 1 shows a plan view of the RIBF. Heavy ion beams from the RRC (Riken Ring Cyclotron K=540) are boosted up to 400A MeV for light ions and more than 100A MeV for heavy ions by the IRC and the SRC. With this beam energy, we can produce RI beams for all elements using projectile-fragmentation process. Details of the SRC and the IRC are described elsewhere [7,8].

### *1.1 RI Beam Separator*

At the downstream of the SRC, we construct two RI beam separators. The separator (Big RIPS) provide RI beams for the experimental halls, and another (RIPS-M) for the MUSES system. The primary beam is supplied for three separators with time sharing technique (see Fig. 3). A pulse beam with the beam intensity of 100 particles μA (pμA) is supplied for RIPS-M, and the maximum duty factor is $10^{-3}$ (the beam duration of 30 μsec and the interval of 30 msec). DC beams with the intensity of 1 pμA are supplied for the Big RIPS. About 3000 radioactive isotopes including about 1000 new isotopes can be used for experiments with those separators. The RIPS-M used for the MUSES has a momentum acceptance of ±2.5 % and an angular acceptance of ±10 mrad. The momentum spread of the RI beams from the RIPS-M is expected to be ±0.5 %. Since this value is too large from the cooling time in the ACR point of view, we place debunchers at about 80-m downstream of the RIPS-M. The momentum spread is reduced to ±0.15 % by the debunchers. The maximum RF voltage required here is totally 4.23 MV [9].

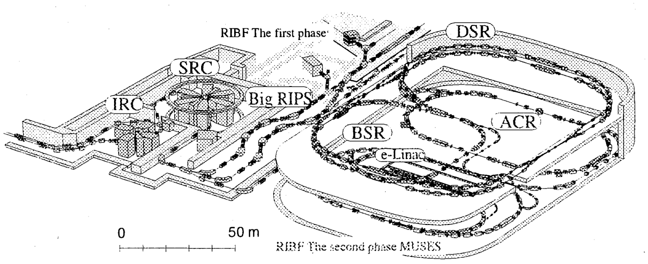


Fig. 1. Plan view of RIBF and MUSES

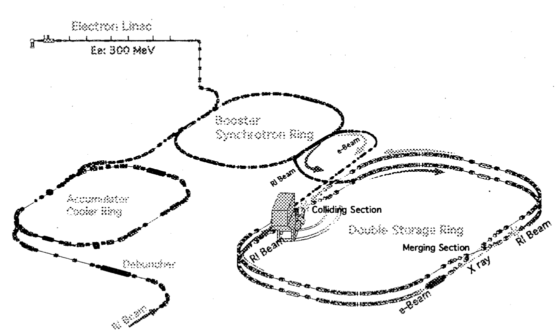


Fig. 2. Schematic view of MUSES accelerator system

### *1.2 Accumulator cooler ring (ACR)*

Figure 2 shows schematic view of the MUSES system. The RI beams are injected into the ACR by means of a multi-turns injection method (about 30 turns per one injection). The transverse acceptance of the ACR is 125π mm·mrad and the momentum acceptance is ±2 %. Injected RI beam is stacked by controlling the supplied RF voltage and the frequency in the ACR. After RF stacking process, the beam is cooled down in both the transverse and the longitudinal directions by combination of a stochastic cooling [10] and an electron cooling methods [11]. A cycle of the injection, i.e. the multi-turns injection, the RF stacking and the cooling, is repeated until that the number of stored particles reaches to the equilibrium number which depends on the lifetime of the RI and the space charge limit. This cycle is shown in Fig. 3(b). If we do not need the cooling, only the stacking process takes about 30 msec. This is why the maximum duty factor of primary beam for the RIPS-M is $10^{-3}$.

Figure 4 shows typical results of analytical calculation

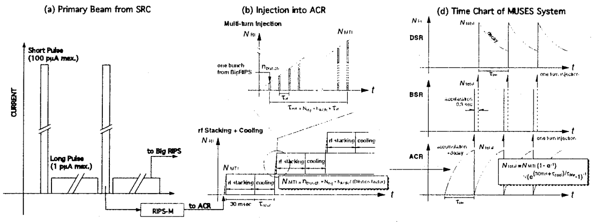


Fig. 3. Time chart of MUSES operation.

of the stochastic cooling time vs. number of stored particle, assuming the pickup impedance of 100 Ω, the temperature of the pre-amplifier of 20 K, the system band width of 2 GHz, and the output power of main amplifier of 10 kW. Since the number of radioactive isotopes for one injection cycle is expected to be less than $10^7$ particles, we can find that the cooling times in both directions are less than 100 msec. On the other hand, typical results of the electron cooling simulations shown in Fig. 5 tell us that the cooling time is roughly less than 1 sec. In this case, the electron beam temperature is 20 meV and 0.05 meV in transverse and longitudinal directions, respectively, and the electron beam current is 4 A. The stochastic cooling method is suitable to be used as pre-cooling for injected hot beams, which has large momentum spread and large emittance, because this is, in principal, the feedback system. The electron cooling method is effective the for pre-cooled beams. The combination of the stochastic cooling and the electron cooling makes the cooling time shorter than that for the case of only the electron cooling. The total cooling time is expected to be, roughly speaking, less than 1 sec for all RI beam in our estimation. Details of the ACR, the injection system and the cooling devices installed in the ACR are described in Refs. [3,9-11].

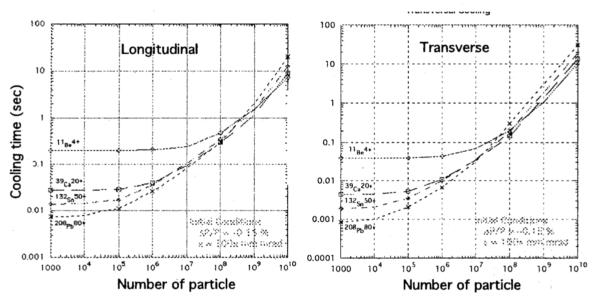


Fig. 4. Cooling time of stochastic cooling.

The ACR itself is not only a cooling device but also an experimental device. We provide an electron cooler, schottky devices, four dispersive positions in arcs section (the maximum dispersion is 4.52 m), two achromatic straight sections where internal targets can be placed, etc. in the ACR so that the ACR is responsible to various experiments.

*1.3 Booster Synchrotron Ring (BSR)*

The cooled RI beam is extracted from the ACR and injected into the BSR to boost up to the required energy, and the beam is immediately transported to the DSR as shown in the time chart of Fig. 3(c). The BSR has a circumference of 179.7 m, the maximum magnetic rigidity of 14.6 Tm, a repetition rate of 1 Hz and the acceleration time of 0.3 sec. The ion beams can be accelerated up to 1.4 GeV for proton and 0.8A GeV for uranium at maximum. Relatively wide range of RF frequency of 25-53 MHz is required to boost up to the maximum energy [12]. Two kinds of extraction methods are provided [13], which are a fast (one turn) extraction and a slow extraction using 1/3 resonance technique. The fast extraction is for transporting the beams to the DSR, and the slow extraction is used for experiments at the experimental halls. The BSR can accept not only ion beams coming from the ACR but also an The electron beam can be accelerated from 300 MeV up to required energy.

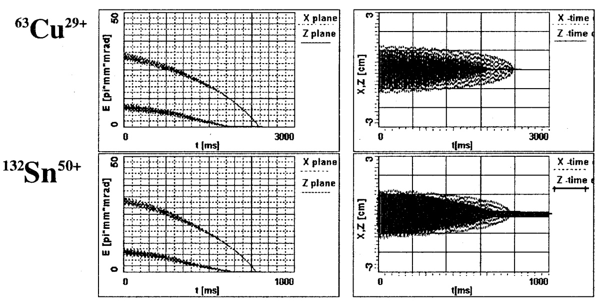


Fig. 5. Simulations of the electron cooling.

*1.4 300-MeV Electron Linac*

Depending on the use of the electron beam at the DSR, either the single bunch or the full bunch operation mode is chosen in the BSR. Corresponding to that, the operation mode of the e-linac is also changed to the short-pulse mode (1-nsec pulse length, 1-A peak current) or the long-pule mode (5-μsec pulse length, 100-mA peak current). The e-linac is driven by the RF frequency of 2856 MHz and the length is about 30 m including a SW type of pre-buncher, a TW type of buncher, and 5 CG type of acceleration tube [5].

*1.5 Double Storage Ring (DSR)*

As shown in Fig. 2, the DSR is a new type of experimental storage ring that consists of vertically stacked two rings, which are called e-ring and I-ring, respectively. It has a circumference of 269.5 m and two colliding points in long straight sections, which are called the colliding section and the merging section, respectively. The colliding section is for nearly head-on collision experiments and the crossing angle is 20 mrad. The RI-electron collision experiment, which is described later, is planned at the colliding section. The betatron function of the RI beams and the electron beam at the colliding point are designed to be 10 cm and 2 cm, respectively, and the collision length is 10 cm. On the other hand, the merging section with the crossing angle of 175 mrad is for the ion-ion merging experiments. In this section, we can make low energy collision experiments such as a fusion reaction. In this straight section, the RI-X-ray colliding section is also provided. An undulator is installed as a source of high brilliant X ray in this section as describing later. The DSR has different operation modes

**Table 1**. Specifications of the ion and the electron beams in the presently designed DSR.

| | e-Ring Large emittance mode | e-Ring Small emittance mode | I-Ring Colliding mode | I-Ring Merging mode |
|---|---|---|---|---|
| Harmonic No. | 450 | 450 | 48 | 48 |
| Momentum compaction | 0.042 | 0.0014 | 0.039 | 0.039 |
| Betatron tune $\nu_x/\nu_y$ | 6.754/8.164 | 16.046/9.106 | 6.235/5.018 | 5.637/5.732 |
| Emittance $\varepsilon_x/\varepsilon_y$ ($\pi\mu$mrad) | 0.97/0.01 at 1 GeV | 0.0016/0.0047 at 1 GeV | 1.0/1.0 typical | 1.0/1.0 typical |
| Betatron function $\beta_x/\beta_y$ (m) | 0.02/0.02 [a] | | 0.1/0.1 [a] | 0.6/0.6 [b] |
| Natural chromaticity $\xi_x/\xi_y$ | -37.7/-90.7 | -29.7/-34.7 | -62.7/-47.6 | -11.4/-10.3 |
| Momentum spread ($10^4\Delta E/E$) | 2.64 at 1 GeV | 2.74 at 1 GeV | | |
| Radiation loss (keV/turn) | 10.6 at 1 GeV | 10.6 at 1 GeV | | |

[a] at the colliding point.

[b] at the merging point.

corresponding to different types of collision experiments. There are the colliding mode and the merging mode for the RI (ion) beams. For the electron beam, we have the small emittance operation mode required to produce high brilliant X ray, and the large emittance operation mode is also required to get larger luminosity for the RI-electron collision experiment. According to requirements for the small emittance mode, a double bend achromatic (DBA) lattice is adopted in the arc section and the emittance of order of $10^{-9}$ mrad is presently designed. On the other hand, the emittance for the large emittance mode is designed to be about $10^{-6}$ mrad. Specifications of the ion and the electron beams for each operation mode are summarized in Table I, and details of design of the DSR is described in Refs. [6,14].

## 2 Experiments at the DSR

### *2.1 RI-Electron Collision Experiment*

One of unique experiments at the DSR is the RI-electron collision [15]. We are interesting in the elastic scattering (e,e') from which we can determine the nuclear charge distribution of RI's. Physical interests are the proton skin structure, the neutron skin/halo structure, difference in collective structure between protons and neutrons etc. in RI's which have unbalanced numbers of protons and neutrons. This experiment allow us to make systematic study on these problems. This kind of study, which has so far been performed only for light elements, can be extended to heavier elements.

In our estimation, required range of momentum transfer value for electron scattering is $q$=0.5 - 2 fm$^{-1}$ to determine the charge distribution around the nuclear surface. This

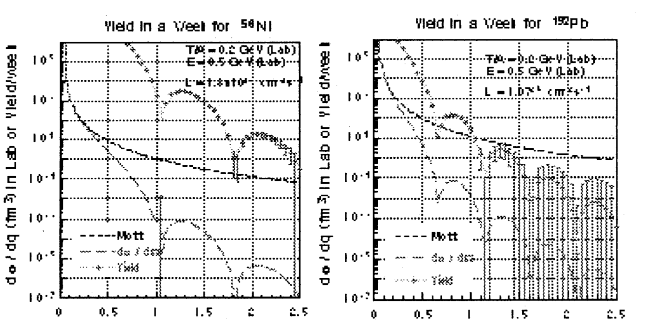


Fig. 6. Expected yield of the electron scattering experiment.

corresponds to the scattering angle from 10 deg. to 60 deg. in the laboratory frame for the case of electron beam energy of less than 1 GeV and the RI beam energy of less than 1A GeV.

The essential point of this experiment is that how big luminosity can we have at the DSR. According to our calculation [16], we can precisely determine the nuclear charge distributions for RI's for the case of the luminosity of more than $10^{27}$ cm$^{-2}$s$^{-1}$, that corresponds to isotopes having the life time of more than 1 min. Figure 6 shows examples of the expected yield of the electron scattering for one-week beam time. Here we assume the electron beam current in the DSR is 500 mA.

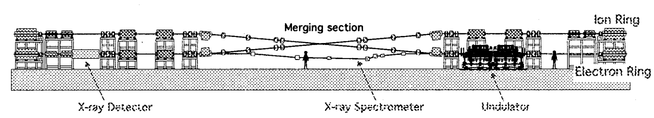


Fig.7. Experimental setup for RI-X-ray collision experiment.

### *2.2 RI-X-ray collision experiment*

The purpose of this experiment is to determine the mean square nuclear charge radii $<r^2>$ and the electromagnetic moment by means of isotope shift measurements in the 2S-2P (so called D1 transition) atomic transition of the Li-like RI ions [15,17]. We provide an undulator [18] and an X-ray spectrometer as a monochromatic X-ray source placed near merging section in the e-ring as shown in Fig. 7. Output X-ray from the spectrometer is injected again into the I-ring and collides with the circulating Li-like RI ions at the detector position. Requirements on the X ray for this experiment are follows. The X-ray energy is 30 - 800 eV to excite the D1 transition of Z>40 elements, and the energy resolution is about $\Delta E_x/E_x=10^{-4}$. The X ray intensity should be at least $10^{12}$ photons/sec/0.01%b.w. at the RI-X-ray colliding section. If we satisfy these conditions, we can measure the isotope shift for quite small number of RI beam stored in the DSR, even if only one ion is in the DSR.

To get the required specifications of the X ray, we have to store 500-mA electron beam in the small emittance operation mode of the DSR. As shown in Table I, the specifications for the small emittance mode is the same like the third-generation synchrotron-light source. In such machine, instability of the electron beam is always big problem especially at lower energy. The instability is caused by the ring-broadband impedance and the narrow-band impedance at the high-Q cavities. We are now investigating the instability [19] and designing the vacuum tube and cavities of the DSR.

## 3 Concluding Remarks

In this paper, the outline of the MUSES accelerator system and typical experiments proposed at the DSR are described. The key issue of the e-RI collision experiment is the available luminosity. It is found that the luminosity can be reached up to $10^{27}$ $cm^{-2}sec^{-1}$ for the nuclei of which the lifetime is 1 min. To get such high luminosity, the important factor of the accelerator aspect is the cooling-stacking of the RI beam in the ACR, optimized lattice structure of the DSR, synchronous collision at the colliding point, and the beam-beam effect. Optimization on these problems are now in progress. For another experiment, RI-X-ray collision, the most important thing is how to get stable and large-current of the electron beam under the low-emittance operation mode in the DSR. The special design is needed for every components of the vacuum tube and cavities, and effective feedback system has to be installed in the DSR. They are also now in progress.

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