

RF SYSTEM FOR HEAVY ION CYCLOTRONS AT RIKEN RIBF

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Abstract

At RIKEN RIB-factory(RIBF) an accelerator complex as an energy booster which consists of superconducting ring cyclotron (SRC), intermediate-stage ring cyclotron (IRC) and fixed-frequency ring cyclotron (FRC) provides very heavy ion beams like uranium with an energy of 345 MeV/u [1]. The total beam power obtained up to now at the SRC is as high as 3 kW in the case of ^{48}Ca with an intensity of 170 pA. Recently we have succeeded in achieving stable and reliable operation of rf system for new cyclotrons. In this paper the present performance of the rf system and a recent development is reported.

OVERVIEW OF THE CYCLOTRON COMPLEX AS AN ENERGY BOOSTER

Acceleration Scheme of the Accelerator Complex

Three cyclotrons have been designed and built to boost the energy of the beam accelerated by RIKEN Ring Cyclotron (RRC) [2] for RI-Beam production. There we have three acceleration modes.

1. *very heavy ion ($A > 40$) mode*
RILAC \Rightarrow RRC \Rightarrow IRC \Rightarrow SRC
2. *high energy (uranium 345 MeV/u) mode*
RILAC \Rightarrow RRC \Rightarrow FRC \Rightarrow IRC \Rightarrow SRC
3. *light heavy ion ($A \leq 40$) mode*
AVF \Rightarrow RRC \Rightarrow SRC

The conceptual design of the cavities was described in ref. [3] and their construction and commissioning were reported in ref. [4] and [5]. In the end of 2006, ^{27}Al was accelerated in the mode 1 with an energy of 345 MeV/u as the first beam from the SRC. After that ^{238}U acceleration test in the mode 2 was performed extensively and the beam current of 0.4 pA was provided to a new-isotope search experiment. A high intensity beam of ^{48}Ca was accelerated in the mode 1 with a beam power of 3 kW. In the mode 3, ions whose mass number A is less than 40 can be accelerated with an energy of 440 MeV/u to the maximum. This year ^{14}N and polarized deuteron beams have been accelerated with an energy of 250 MeV/u in this mode. In Table 1 parameters for rf system for the new cyclotrons together with the RRC are summarized.

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Table 1: Parameters of the RF System

| item | RRC | FRC | IRC | SRC |
|------------------------|-----------------|-----------|-----------|-----------|
| freq. [MHz] | 18~45 | 54.75 | 18~42 | 18~42 |
| <i>mode 1</i> | $f_o^*(9^{**})$ | - | $2f_o(7)$ | $2f_o(6)$ |
| <i>mode 2</i> | 18.25(9) | 54.75(12) | 36.5(7) | 36.5(6) |
| <i>mode 3</i> | $f_o(5)$ | - | - | $f_o(5)$ |
| # of cav. | 2 | 2 | 2 | 4 |
| # of gap | 2 | 1 | 1 | 1 |
| V_{gap} [kV] | 300 | 500 | 650 | 650 |
| $P_{\text{w.l.}}$ [kW] | 150 | 100 | 150 | 150 |
| FT cav. | none | 1 | 1 | 1 |
| Harmonics | - | 3 | 3 or 4 | 3 or 4 |
| $P_{\text{w.l.}}$ [kW] | - | 20 | 20 | 60 |

*: f_o is a frequency of master oscillator.

**:(#) denotes a harmonic number $H=f_{\text{rf}}/f_{\text{beam revolution}}$

Requirements

Heavy ion cyclotrons have not only a wide acceptance of charge to mass ratio but also a wide energy ranges according to the purposes of physics experiments. The frequency range for new cyclotrons, SRC and IRC, are $18 \div 42$ MHz to meet that of the RRC. The FRC has been designed with a fixed frequency of 54.75 MHz to aim at an uranium acceleration with an energy of 345 MeV/u, while in the mode 1 the maximum energy of the uranium is 150 MeV/u.

In the acceleration modes 1 and 2, charge conversions getting a higher charge state are necessary to accept the beam due to the limitation of the magnetic rigidity of the succeeding cyclotrons. The conversion is made by using charge stripper (carbon foil) at the sacrifice of longitudinal emittance growth. Therefore the flattopping systems in the cyclotrons are essential. The rf third harmonic make the longitudinal acceptance as large as $\pm 16^\circ$.

In the operational aspect, stability of the acceleration field is a key issue and trouble-free is desirable. With stable rf system it is possible to make fine tuning of the accelerator cascades and to maintain the beam quality and the intensity during a long term physics experiment. To obtain much more reliability, improvement of the rf system has been made by fixing the problems turned out since the commissioning as described below.

CHARACTERISTICS OF THE RF SYSTEM

Here, the rf system for the SRC(K2600) is mainly described because the rf systems for other cyclotrons are basically the same and because it is the most severe case from the point of view of tolerance for rf stability providing a

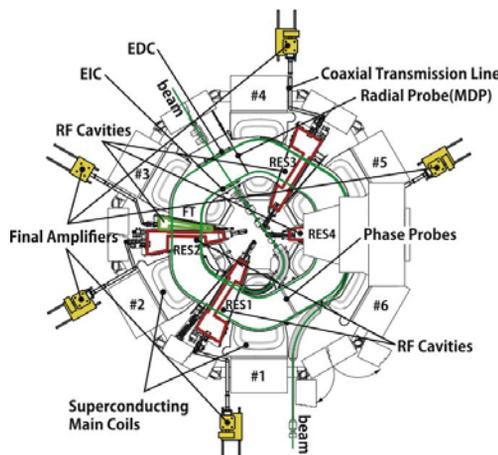
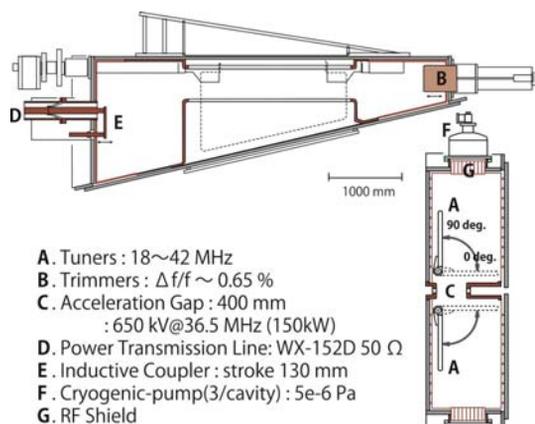


Figure 1: Schematic of the Superconducting Ring Cyclotron (SRC) as a final stage booster.

high beam current. The SRC consists of six superconducting separate-sector magnets with four acceleration cavities and one flattopping cavity (Fig. 1).

Acceleration Cavities

As shown in Table 1 the newly built cyclotrons have various harmonics (the ratio of the rf frequency to the beam revolution frequency); the single-gap structure is suitable. The resonant frequency of the cavities varies 18÷42 MHz by moving a pair of large capacitor-panels which rotate from 0° to 90° (see Fig. 2). The panel are supported by rotating shafts and are electrically connected to the cavity wall with copper sheets with a thickness of 0.2 mm. The tuner panels are adjusted symmetrically so as to make the leakage of rf field from beam aperture minimum. The maximum current density is 80 A/cm at the end part of the dee electrode of the machine center side. Sliding contacts which are attached between the cavity wall and the rotating shaft which supports the tuner panels have the maximum current density of 60 A/cm. The contacts are made of silver plated BeCu and their finger tips are made of sil-



- A. Tuners : 18~42 MHz
- B. Trimmers : $\Delta f/f \sim 0.65\%$
- C. Acceleration Gap : 400 mm
: 650 kV@36.5 MHz (150kW)
- D. Power Transmission Line: WX-152D 50 Ω
- E. Inductive Coupler : stroke 130 mm
- F. Cryogenic-pump(3/cavity) : 5e-6 Pa
- G. RF Shield

Figure 2: Schematic of the acceleration cavity for the SRC.

ver blended with carbon. The chassis of the cavity consists of two parts. One is stainless steel wall with a thickness of 40 mm to prevent collapsing under the pressure of the atmosphere and one is a copper sheet with a thickness of 4 mm inside the stainless steel chassis on which the water pipes are soldered in back side. The total amount of the cooling water is 300 l/min per cavity supposing the wall losses by rf currents amount to 150 kW. Without rf power the vacuum of the cavity reaches 1×10^{-6} Pa with three cryogenic pumps (10000 l/min via N₂) and with rf input of 100 kW the vacuum pressure is nominally 5×10^{-6} Pa which has been improved by fixing the heating problem of the rf shield (G in Fig. 2) attached in front of cryogenic-pump.

Flattopping Cavity

One flattopping cavity provides a harmonic field with a decelerating phase to make the longitudinal acceptance larger. The cavity is a single-gap resonator with a set of shorting plate to tune the resonant frequency. The frequency range is set from 72 MHz to 132 MHz so as to make the cavity compact. The harmonic of flattopping is 3 for the fundamental frequency range of 24÷42 while the harmonic 4 is adopted for lower frequencies. The maximum power dissipation is 60 kW. Since cutoff frequency of the beam aperture is 75 MHz, the set of shorting plates must be placed at the electrical symmetry positions, otherwise the beam probes (MDP and PP) and/or high voltage electrostatic channels (EIC, EDC) got damaged by rf heat loads.



Figure 3: Photo of installing the accelerating cavity(RES2) and the flattopping(FT) cavity to the valley area between the sector #2 and #3.

Amplifiers

The main rf amplifier is based on a tetrode THALES (SIEMENS) RS2042SK coupled with a tetrode THALES (SIEMENS) RS2012CJ with a grounded-grid circuit. Four power-amplifiers are installed and then the four acceleration cavities were excited by individual amplifiers driven by the same master oscillator. For the flattopping cavity, a newly developed amplifier which is based on a THALES (SIEMENS) RS2058CJ tetrode is adopted and excited using a tripled rf signal from a frequency multiplier. The

transmission coaxial lines between the amplifier and the cavity is about 15 m. Each lines was equipped with a sliding mechanism with a stroke of 1 m which makes possible to avoid exciting parasitic modes of the transmission line and output circuit by changing the total length of the transmission line [5]. The stray field of the superconducting sector magnet at the position of power tube is as large as 100 G with an excitation current of 5000 A for $^{238}\text{U}@345$ MeV/u. The power tubes worked well without any problem.

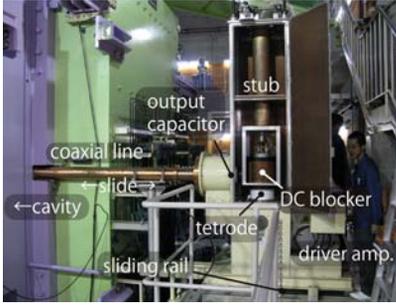


Figure 4: Photo of the main amplifier.

Tolerances

Here tolerances for rf amplitude and phase are considered. The rf system for the SRC consists of four acceleration cavities and one third-harmonic flattopping cavity. Then the energy gain per turn is denoted as

$$E_g = \sum_{i=1}^4 V_i \cdot \cos(\phi + \alpha_i) + V_{ft} \cdot \cos(3 \cdot \phi + \alpha_{ft})$$

Here ϕ is a beam phase, V_i, V_{ft} are gap voltages, α_i, α_{ft} are phase errors. According to the criterion in Ref.[7] by W. Joho, the error of the energy gain $\Delta E_g/E_g$ should be 10 times smaller than number of turns (i.e. $|\Delta E_g|/E_g < 1/10N$). In our case, the number of turns is about 350 on the average, and the amplitude of flattopping cavity is about 13% of the sum of the four acceleration cavities. The phase acceptance is set as $\pm 16^\circ$. Then tolerances for amplitude and phase were obtained as

$$\begin{aligned} \text{amplitudes : } & |\Delta V_i|/V_i < 3/10000 \quad (i = 1..4), \\ & |\Delta V_{ft}|/V_{ft} < 2/1000, \\ \text{phase : } & |\Delta \alpha_i| < 0.03^\circ. \end{aligned}$$

Note that the cavities are excited by individual amplifiers as mentioned, though the deviation due to the instability of the power line (i.e. 50 Hz, 300 Hz) occurs coherently. The errors due to the thermal deformations and the mechanical vibrations of the cavities and due to the electrical noise have no correlation with each other cavity. Those random errors are averaged over cavities and then are reduced by factor $\sqrt{4}$.

RF CONTROL

Low Level System

A block diagram of the RF control system is shown in Fig. 5. The reference signal from master-oscillator is multiplied if needed and divided by a power divider to deliver for each cavity. The phase of the cavity is detected by auto-phase-lock utilizing super-heterodyne and locked by frequency modulator (VCO). The amplitude is stabilized by auto-gain-control. The forward power and the reflected power at the feeder-line were detected to tune the resonant frequency of the cavity by a servo system. The main parts of the electric circuit of the feedback control are packed in a temperature controlled aluminum box so that the circuit works stably under a constant temperature with the temperature coefficient of $\Delta T_{\text{box}}/\Delta T_{\text{room}} < 0.03$ and is electrically well shielded. The measured temperature at the room where the rf controls are installed is typically $24.5 \pm 0.5^\circ\text{C}$ for 24 h.

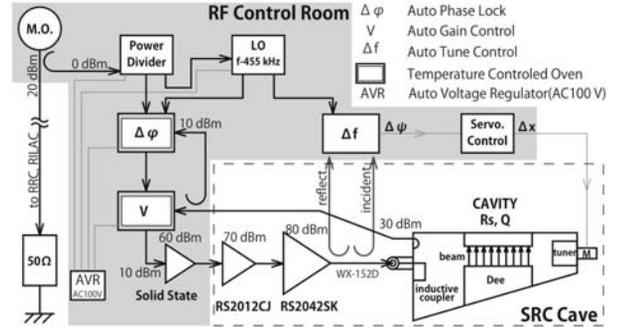


Figure 5: Block diagram of the rf system.

Monitoring System

Since the commissioning of the new facility, it has been pointed out that the monitoring of all rf of the cavities and the beam timing is crucial to handle the accelerator complex which employs 25 rf cavities. In the old facility the vector voltmeter (HP8508A) was used for a rf monitor. The HP8508A was discontinued more than 10 years ago and its accuracy and resolution were not enough. For the new system the amplitude and the phase resolutions of $\sim 0.01\%$ and $\sim 0.01^\circ$ are needed. A Lock-in amplifier is an instrument which extracts a component of a particular frequency of reference sinusoidal signal and calculates the amplitude and the phase, or I/Q component. The RF Lock-in Amplifier SR844 manufactured by Stanford Research Systems [8] has a bandwidth of $25 \text{ kHz} \div 200 \text{ MHz}$ which is suitable for our operational rf frequency range from $18 \div 165 \text{ MHz}$. A feasibility test was made [6] and we finally decided to introduce the instrument as a replacement of the vector voltmeter. The amplitude- and the phase-resolution of the SR844 are evaluated as better than $|\Delta V/V| \sim 10^{-4}$ and $|\Delta \phi| \sim 0.03^\circ$.

ACHIEVEMENTS

Ripples

Modulations of voltage and phase is caused mainly by a ripple of d.c. power supplies adopted to the amplifier. The ripples of power supplies (its main frequency component is 300 Hz) appear as an amplitude modulation and a phase modulation. The modulation of rf signal can be observed as a side-band spectrum by using a spectrum analyzer. For example, an amplitude modulation of $\pm 5 \times 10^{-4}$ and a phase modulation of $\pm 0.1^\circ$ correspond to the spectrum levels of -72 dBc and -61 dBc, respectively. Such a fast modulation can be removed/minimized by tuning a feed back loop (i.e. choosing a gain and a time constant) observing a strength of side-band spectrum. Finally the level better than -70 dBc at 300 Hz side-band has been obtained.

Long Term Stability

By using the newly introduced monitoring system, deviation of amplitudes and phases of the SRC cavities were measured. A block diagram of the measurement was shown in Fig. 6. During the measurement, rf parameters were not changed while the beams were provided to users. The beam was polarized deuteron with an energy of 250 MeV/u in the mode 3 and the frequency of the master oscillator was 13.7 MHz which was provided for an injector AVF and was doubled by frequency multiplier for the RRC and the SRC. The pickup signals of 27.4 MHz from the four acceleration cavities (RES1~4) were switched with an interval of 5 s and compared with the reference signal from the master oscillator by using a doubler mode of SR844. Note that the used pickups were outside the feedback loop so as to obtain the net deviation of the rf of the cavity. As a reference for the pickup signal of the flattopping cavity, the same signal as the signal from the frequency tripler for the excitation of the flattopping cavity. The measured voltage deviation and phase drift were plotted in Fig. 7 for 24 hours. The voltages stayed fairly within $\pm 0.03\%$. The phases were almost within ± 0.03 deg. (0.09 deg. for flattopping cavity) but the common drift of about $+0.05$ deg. was observed. The drift was thought to originate from the phase drift of the frequency doubler. The obtained stability was satisfactory for a precise experiment using a polarized deuteron beam.

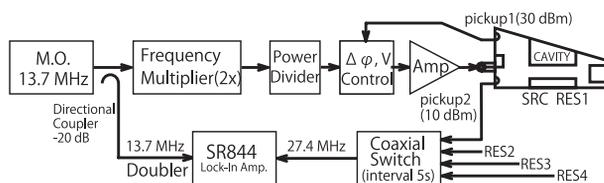


Figure 6: Block Diagram of RF amplitude and phase measurement for SRC.

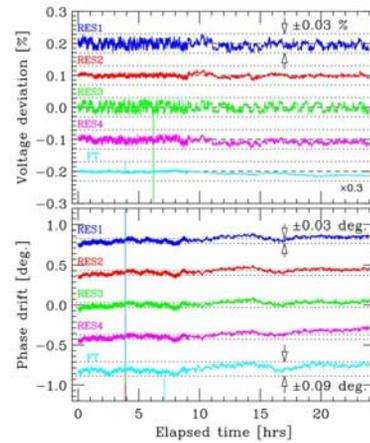


Figure 7: Amplitude and phase measured for 24 hrs.

Single Turn Extraction

RIBF has another aspect of a unique facility which handles the deuteron spin freely. The polarized ion source [9] provides polarized deuteron and its spin direction is rotated into horizontal plane by using a Wien Filter installed downstream of the ECR ionizer. Then the direction of the polarization axis on target can be selected freely as long as single-turn extraction is realized for the three cyclotrons in the mode 3. Single-turn acceleration is essential since the spin-precession ratio (g-factor) is not an integer so the spin direction varies turn by turn.

Here the protocol of the rf tuning is described: turn off the flattopping cavity and get an isochronous field observing by phase probes and make the beam-turn-pattern well-centered; set the phases of the acceleration cavities accelerating phase; change the voltage of the electrostatic injection channel to get off-centering; turn on the flattopping cavity and choose the phase and the amplitude of the flattopping cavity to make the beam profile as sharp as possible as shown in Fig. 8. The contamination of the turns was less than 0.01 %, though the transmission efficiency of the SRC itself was as low as 50 %.

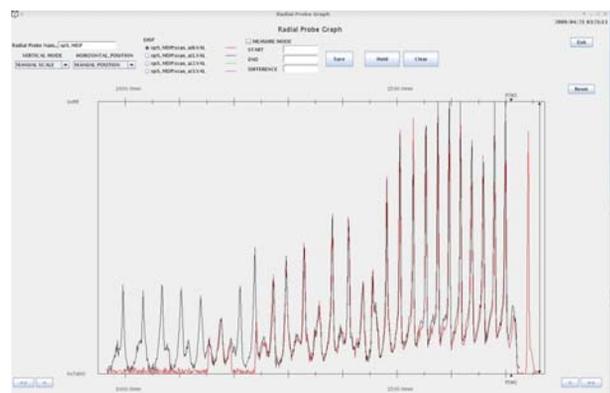


Figure 8: The turn pattern of polarized deuteron beam at 250 MeV/u.

OPERATION EXPERIENCES

Multipactor

In the initial stage of the commissioning of the SRC, the acceleration cavities were very difficult to be switched on due to a strong multipactor with the presence of the magnetic stray fields of the sector magnets. For the FRC and the IRC the multipactor was cleared by using a pulse excitation technique to pass through the voltage levels of multipactor, following dashed lines in Fig. 9. For the SRC the multi-

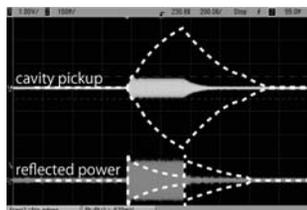


Figure 9: Profiles of the pickup signal from a cavity and the reflected power.

pactor was much more severe and it took more than one day to overcome it. In order to make the startup time shorter, conditioning with low power cw wave (cw) was tested instead of pulse and it turned out the new method works very well. By observing the level of the cavity pickup, the reflected power and the vacuum pressure, the level of the rf power is increased step by step until the cavity voltage becomes around 100 kV. Usually it takes only a few hours. It is enough to take 12 h for a careful conditioning. After the conditioning the cavity will be excited by a cw/pulse mode which recovers the voltage breakdown automatically turning the cw rf power to pulse mode to recover instantly in the case of voltage breakdown. If we see Fig. 7 carefully, sporadic losses of gap voltage are observed together with a breakdown of phase lock. It was caused by rf breakdowns in the cavity and automatically recovered within a few seconds.

The statistics of such breakdowns was counted and listed in Table 2. The number in round bracket counts the long loss when a manual recovery was needed. Until the 7th day after the initial conditioning the count per day was small.

Table 2: Summary of RF Breakdowns during an Experiment from May 1 to May 7(27.4 MHz. 100 kW/cavity)

| day | RES1 | RES2 | RES3 | RES4 | FT | all |
|-------|------|------|------|------|----|-------|
| 5th | 0 | 0 | 1 | 0 | 2 | 3 |
| 6th | 0 | 0 | 0 | 1 | 0 | 1 |
| 7th | 0 | 0 | 0 | 1(1) | 1 | 2 |
| 8th | 1 | 2(1) | 2 | 1 | 3 | 9 |
| 9th | 3(1) | 3 | 1 | 2 | 1 | 10 |
| 10th | 0 | 2 | 1 | 5(1) | 1 | 9 |
| 11th | 2 | 8(1) | 1 | 4 | 2 | 17 |
| total | 6 | 15 | 6 | 14 | 10 | 51(5) |

From the 8th day the counts increased extraordinarily and finally, after 11 days, it was required to have a cw conditioning for three hours. This is one of the major problem with the SRC cavities which disturbs providing beams for an experiment longer than 2 weeks.

Other Troubles

- The temperature of the fins of the rf shield for cryogenic pump was increased up to 300 °C and the temperature of the final stage of cryogenic-pump was increased to about 50 K. This trouble has been proved by installing a direct cooling with a water pipe and then the vacuum pressure has been improved by factor 2.
- The contact fingers attached between the cavity wall and the shaft which supports the capacitive tuner were burned out. The gap size where the contact fingers were inserted became larger when the capacitive tuner was opened at larger angles. This problem has been fixed by adjusting the shape of the contact fingers to fit the gap size.

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