OPERATING EXPERIMENCE WITH THE RF SYSTEM FOR THE SUPERCONDUCTING RING CYCLOTRON OF 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]. In December 2006, the SRC has become operational and it was succeeded to extract the first beam from SRC[2]. Since then, we have experienced various problems with the rf system for SRC and improvements have been made to achieve designed performance solving the problems one by one. This paper will discuss on our efforts to understand the source of troubles and improvements and modifications of the rf system.

RF SYSTEM FOR THE SRC

Superconducting Ring Cyclotron

The K2600 superconducting ring cyclotron (SRC) is the first superconducting separate-sector-cyclotron in the world [3]. The SRC consists of six superconducting sector magnets, four accelerating cavities and one flattop cavity (Fig.1). The rf system is frequency tunable from 18 MHz to 42 MHz so that the beam energy is variable to suite the optimum condition of secondary beam production. Up to now, a number of subjects of nuclear physics experiments utilizing beams of ^{48}Ca, ^{238}U with an energy of 345 MeV/u have been performed with high priorities. The rf frequency of 36.5 MHz for these beam has been mostly used. Designed value of the acceleration voltage is 2 MV/turn.

It was turned out that due to a strong stray field of the K2600 superconducting magnet the rf cavities suffered from very heavy multipactor. In the early stage it took long time, more than a few hours, to recover the rf voltage after breakdown.

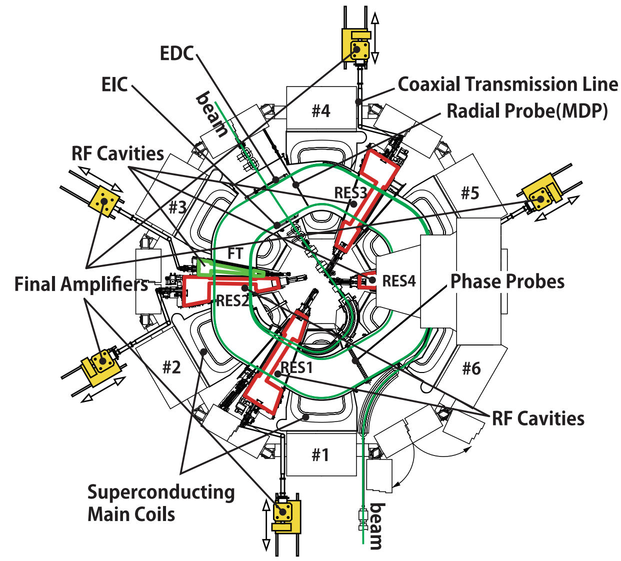

Figure 1: Schematic of the SRC.

This is one of the major problems which reduces the availability of the SRC.

Table 1: Present performance of the rf system.

	Acceleration	Flattop
Frequency [MHz]	36.5	109.5
Number of cavities	4	1
Rs [MΩ]	1.5	1.65
Unloaded Q	30000	29000
Voltage [kV/cavity]	550	-240
$P_{w.l.}$ [kW/cavity]	100	18
Vacuum [Pa]	3×10^{-6}	1×10^{-5}
Voltage Stability	±0.03%	±0.03%
Phase Stability	±0.03°	±0.09°
Availability*	92%	99%

* Here availability is defined as all of the cavities are excited.

Cavities

Design, construction, and commissioning of the rf cavities have been reported at Cyclotrons'98, -'01, and -'07 [4, 5, 6]. A present performance of the rf system is summarized in Table1.

The four acceleration cavities have an acceleration voltage of 2.2 MV/turn in total and the third harmonic cavity has a voltage of -0.24 MV with deceleration phase. The voltage of acceleration cavities were initially restricted to 450 kV, since a trouble with contact fingers which were inserted to the gap of cavity wall and the rotating capacitive tuner occurred. The gap was larger than the designed value, then lack of touching pressure made contact resistance large so that the finger got damaged. Modification of the shape of the contact finger was made to reduce the contact resistance.

Since cooling of RF shield adopted to the window of the cryogenic pump was not enough, temperature rise of cryogenic panel occurred and the vacuum pressure was abnormally raised with the cavity voltage higher than 500 kV. To solve this problem installation of water cooling channel

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directly on the rf shield was done.

After these modification, finally the designed acceleration voltage of 2 MV/turn was obtained.

Amplifier and Low Level Circuit

The main rf amplifier is based on a tetrode THALES/SIEMENS RS2042SK coupled with a tetrode THALES/SIEMENS RS2012CJ with a grounded-grid circuit. This amplifier was originally designed for Riken Ring Cyclotron[7]. The SRC is energy variable machine so that the rf system is frequency tunable with a variable capacitor of input circuit, a stub with short plate, and variable output capacitor(Fig.2). Four power-amplifiers are installed and then the four acceleration cavities were excited by individual amplifiers driven by the same master oscillator. The low level system works very well owing to modifications[8] to stabilize the amplitude and the phase within 0.03% and 0.03°. The rf stability is always measured during operation by newly constructed monitor system based on the commercially available rf lock-in-amplifiers (SR844)[9]. Stabile operation of rf is crucial to realize single-turn extraction. The turn purity of 99.9 % was obtained for polarized deuteron experiment in April 2009.

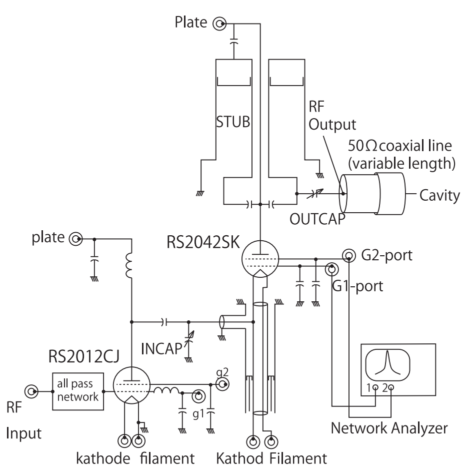

Figure 2: Simplified diagram of the amplifier circuit.

Control of Parasitic Oscillations

S_{21} from the G1-port to the G2-port($S_{21}^{G1\to G2}$) shows a helpful information on parasitic oscillations of our system(3. The setup of the measurement is indicated in Fig.2. Measurement was made using Network Analyzer (Agilent E6061A). Many peaks appear beside the resonance of fundamental mode of cavity and amplifier. The amplifier itself is known to have relatively low frequency parasitic resonances. One is the higher order mode (HOM) of input stub circuit around 55 MHz, denoted by green line in the figure, and the other is the resonance between G1-electrode and G2-electrode of the tetrode RS2042SK. Excitation of these modes causes immense damage to the amplifier.

The coaxial transmission line between the amplifier and the cavity is about 15 m long. A number of HOMs appear according to the length of transmission line as denoted by blue lines in Fig.3. Around 55 MHz, HOM of input circuit, one of the HOM of coaxial line (3) is located in the very close vicinity(yellow circle). The situation possesses considerable risk to excite the parasitic mode. Each coaxial lines is equipped with a sliding mechanism with a stroke of 1 m. By moving amplifier the length of transmission line is changed so as to avoid the coupling oscillation[10]. The measurement was made with a middle position of the stroke. For operation, the amplifier is set to the position closer to cavity by 0.5 m to avoid coupling oscillation.

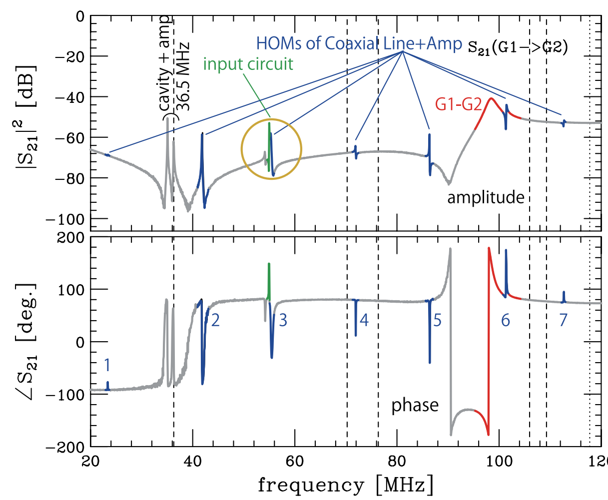

Figure 3: $S_{21}^{G1\to G2}$ measured. Dashed lines are the HOMs of the acceleration cavity.

Magnetic Field Effect to the RF System

The cavities are exposed to a very strong stray field from superconducting sector magnet. The actuators, cryogenic pumps, and turbo molecular pumps are equipped with iron shields. The strong stray field makes the situation of multipactor severe. It becomes difficult to overcome the multipactor levels. As a first step, implementation of an additional cryogenic pump(10000 l/s) to each cavity was made expecting that improvement of the vacuum condition of the cavity will help to moderate the situation of multipactor. The vacuum pressure with rf power 100 kW becomes about 3×10^{-6} Pa. The effect of stray field of 100 Gauss at the position of amplifier to the operation of power tube is negligible small.

OPERATING EXPERIENCES

RF Power Leakage

Asymmetrical excitation of rf in the cavity causes vertical component of the electric field at the median plane which propagates into beam chamber through the beam aperture. Even small portion of rf power leaks, beam probes such as phase probes (PP) which measure the isochronous fields and a main probe and a differential probe (MDP) which measure a beam current and a beam density distribution along radial direction respectively easily malfunction because the signal level induced by circulating beam is very small. The main part of the leaked rf power comes from the flattop cavity because the operation frequency of 109.5 MHz is higher than the cutoff frequency 80 MHz of the beam aperture. To settle the problem with the beam probes, the leaking rf power should be minimized at first and then the improvement of the signal to noise ratio is anticipated to work well.

To detect the rf power leaked from the cavity a sensor which consists of a pair of capacitive pickup electrodes have been installed so as to measure the vertical component of the rf electric field[4]. Though the sensor was too sensitive to handle. On the other hand, a beam loss monitor at the electrostatic deflection channel(EDC) was turned out to be useful. The monitor is a thermometer adopted on the septum electrode of EDC and when the rf power is switched on a rise of temperature is observed according to the leak of rf. The upper and the lower frequency tuners are independently adjusted to the positions where the temperature of the beam loss sensor is minimum.

Countermeasure against RF Noise

Countermeasure against rf noise of the beam probes has been made by trial and error. Observing the noise on MDP, its level varies depending on the position in radial direction. The MDP behaved like an antenna. Therefore an electric contact was attached at the tip of MDP chassis to suppress the TE01 mode on the MDP[11]. To measure the timing of the circulating beams, a pair of electrodes located vertically is used(Fig.4). Because the beam induces monopole component of the electric field while the rf noise have dipole component, if the signals from upper and lower electrodes were combined in the same phase, rf noise is canceled in principle, without affecting the beam signal. To have larger S/N, interference filter which cancels the odd components of the signal is inserted. To measure the zero crossing timing of the beam signal, the second harmonic frequency of beam frequency is employed. Finally the probes work well without disturbance of the rf power leakage.

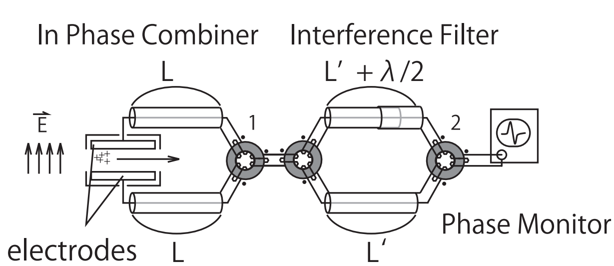

Figure 4: The noise filters for the beam phase probe(PP).

Multipactor

In the initial commissioning of the SRC, conditioning with a pulse rf power with a reputation rate of 100 Hz and the peak power of more than 100 kW was performed to overcome heavy multipactor due to the stray magnetic field. In the method conditioning started with zero magnetic field increasing the coil current step by step observing the situation of multipactor. It worked well but it took a couple of days to overcome.

In order to make the startup time shorter, conditioning with a low cw power of 10∼30 kW was tested instead of pulse and it turned out the new method successfully improved the situation. Coil current is set to the operation current first and by observing the level of the cavity pickup, the reflected power and the vacuum pressure, the rf power is increased step by step overcoming a number of multipactor levels until the cavity voltage becomes around 100 kV. Ordinary it takes only a few hours. After the conditioning with new method performed for 24 hours the recovery time after breakdown becomes as short as 5∼30 minutes during the beam tuning while in the early stage of the commissioning it took 3∼4 hours. The live time of the rf, defined by the ratio of the time when right rf voltages of all the cavity are excited to the scheduled beam bombarding time, is 92 % for the ^{48}Ca experiments in June 2010.

SUMMARY

By improving the vacuum, cooling, and surface cleaning, the designed acceleration voltage of 2 MV/turn has been realized. The beam probes, MDP and PP, work well after some modifications. Multipactor is one of the most important issues which reduce the availability of the SRC. In order to minimize the break time due to the rf breakdown, cw power conditioning has been introduced. Recovery time was 5-30 minutes during the Ca experiment in May this year. Recently conditioning at the cold start takes 1 day. The availability of the rf cavities is now more than 90% but still improvement of this number is required toward 99% which the IRC and the FRC have already achieved.

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