Super Wide Band Cavity With an All-Pass Network

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Abstract

A new type of a tuning-free cavity with an all-pass network has been developed for an ion synchrotron. We have improved the prototype tuning-free cavity reported elsewhere[1] into a super wide-band tuning-free cavity. An acceleration voltage of the cavity was found out to be generated in the rf frequency range of 0.1-8 MHz. The cavity was installed at a HIMAC synchrotron ring to make a beam acceleration test. We succeeded to accelerate 6 MeV/u He^{2+} ions up to 40 MeV/u. It was found that the cavity works quite well in the rf frequency range of 0.2615-2.62729 MHz.

1 Introduction

A study on the tuning-free cavity used a bridged-T type all-pass network has been carried out and it has been found out that basic concept is clearly appropriate through the test using the prototype tuning-free cavity[1].In other words, we can realize the bridged-T type circuit as a hardware and can experimentally confirm to generate the gap voltage in a wide range of the rf frequency without any tuning. This type of cavity have another merit, that is, the limit of a gap voltage should be higher than that of the normal type of cavity, because most of input electric power is consumed by a terminating resistor. When larger value of the terminating resistor is selected, the gap voltage is larger and, therefore, the acceleration efficiency increases and is almost the same of the normal bias-controlled cavity. In this time, we remodeled the prototype tuning-free cavity, that is, the value of the terminating resistor decreases to 22.2 ohm in order that the band width of the cavity is wider. The gap voltage of this cavity can be generated with a rf frequency range of 1:80, which is very difficult in other types of cavity. Although the remodeled cavity can not generate a very high gap voltage, we can accelerate both low-energy super-heavy ions and low-energy molecular ions by a synchrotron. It may be possible to construct the tuning-free cavity both with a high gap voltage and with a wide rf frequency band because we can choose other sets of parameters.

2 Basic Concept

A bridged-T type all-pass network is a circuit with impedance Z_1, Z_2, Z_3 and a terminating resistor R connected as shown in Fig.1(a). The all-pass conditions,

$$Z_2 = \frac{R^2}{2Z_1}, \quad Z_3 = 4Z_1, \tag{1}$$

keep the whole circuit impedance V/I=R at any frequency,

where V and I are the input voltage and current.

It was known that the circuit works as a low-pass filter if Z_1 is a capacitance and that as a high-pass filter with Z_1 as an inductance. It should be a band-pass filter with Z_1 as an LC parallel circuit. In this case, Z_2 and Z_3 should be an LC series and an LC parallel, respectively, to fulfill the eqs.(1). The all-pass network is rewritten as Fig.1(b) and the all-pass conditions are as

$$C_2 = \frac{2L_1}{R^2}, L_2 = \frac{C_1 R^2}{2}, C_3 = \frac{C_1}{4} \text{ and } L_3 = 4L_1 \tag{2}$$

Thus Z_1, Z_2 and Z_3 have a same resonance frequency: ω_0, where Z_1 and Z_3 behave as resistors and Z_2 is a short. So the all-pass circuit turns to be a simple parallel of R_1 (parallel resistance of Z_1) and R at ω_0.

From circuit analyses, V_1 (Z_1 voltage) normalized by V (source voltage) has a band-pass feature as Fig.2, while the circuit has a constant impedance without tuning. Therefore a new type of a tuning-free cavity can be realized with Z_1 as a ferrite LC resonator with an accelerating gap.

The curve on Fig.2 is symmetric at ω_0, where $|V_1/V|=1$, with the log scale horizontal axis. If the other frequencies where $|V_1/V|=1$ are called ω_L and ω_U, a bandwidth parameter δ is as;

$$\delta \equiv \frac{\omega_0}{\omega_L} = \frac{\omega_U}{\omega_0} = \sqrt{1 + \alpha^2} + \alpha, \tag{3}$$

where the parameter α is decided by L_1, C_1, R or ω_0 as;

$$\alpha = \frac{\omega_0 L_1}{R} = \frac{1}{R}\sqrt{\frac{L_1}{C_1}}. \tag{4}$$

δ is larger with larger L_1 and smaller R, though smaller R obtains lower source voltage V with same input power and accordingly lower cavity voltage V_1. Thus the value of R is decided by requirement from synchrotrons, e.g. wide bandwidth or high voltage.

It should be noted that using a larger L_1 and a moderate R is one solution for a super-wide frequency-range cavity with a sufficient cavity voltage for synchrotron operation, and, therefore, the larger ferrite inductor need be developed.

The gap voltage V_1 exceeds the source voltage; $V = \sqrt{2PR}$, where P is input rf. power, at the frequency region $\omega_L < \omega < \omega_U$.

It is a unique merit of the new type tuning-free cavity that the external resistor R can be arbitrarily selected according to the users' option. Furthermore, as the relation between Z_1 and Z_3 is independent of the resistor, it is quite easy to modify R only by changing the R, the impedance transformer for input matching and the Z_2's.

Since the inductor L_1 is generally constituted by ferrite cores,

it is not easy to construct the L_1. The capacitor C_2 and the inductor L_2 are, however, rather easy to be constructed.
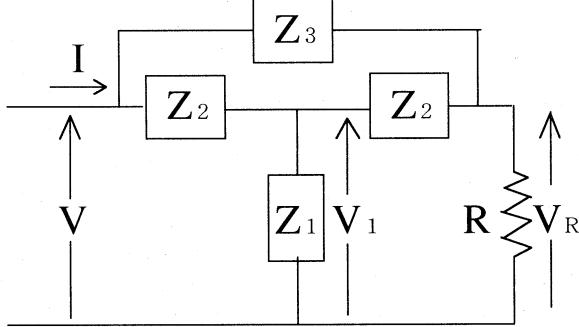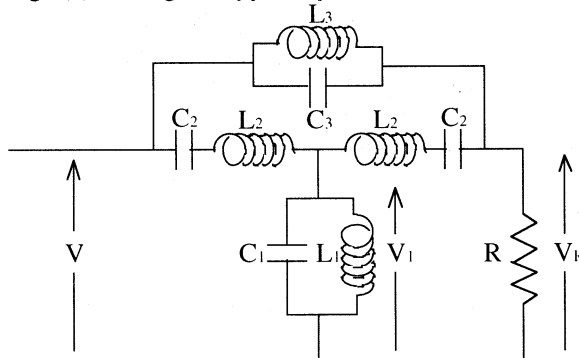

Fig.1(a) A bridged-T type all-pass network (Z)

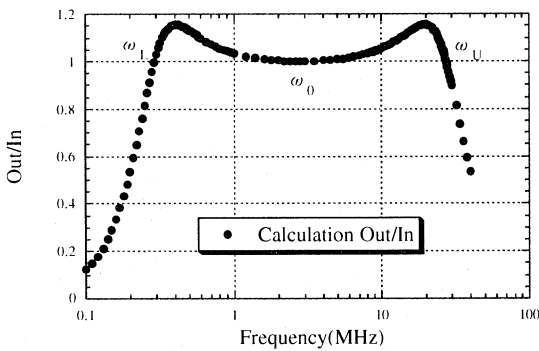Fig.1(b) A bridged-T type all-pass network (LC expression)

Fig.2 The Frequency dependence of $|V_1/V|$

3 Experimental Study

3.1 Improvement of the Tuning Free Cavity

We modified two capacitors C_2, two inductors L_2, the capacitor C_3, the inductor L_3, the register R and the impedance transformer to widen the frequency range of the tuning-free cavity. It should be noted that, in order to facilitate to exchange the circuit elements, each element was designed to be easily removed and attached. Fig. 3 shows a schematic drawing of a new all-pass circuit. The parameter sets were selected as the lowest frequency level of the cavity becomes 0.1 MHz. The frequency range is theoretically expected to be 0.1-67 MHz. Fig. 4 shows the experimentally-obtained relation between an gap voltage of the cavity and a given frequency of rf with the same rf low-

level input. Slight decrease in a high frequency region(>1MHz) is partly due to decrease of the gain property of the used 2kW rf amplifier shown in Fig. 5.
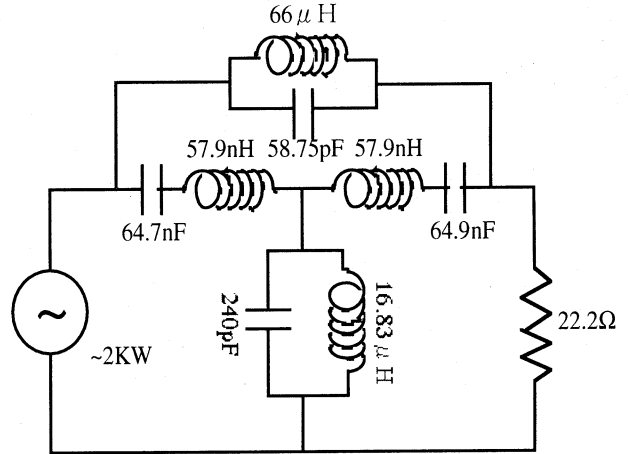

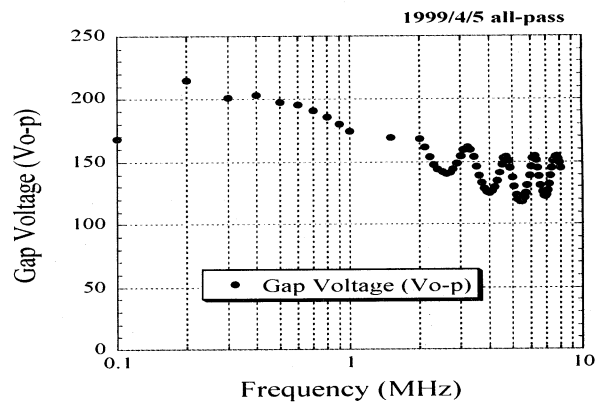Fig.3. Designed all-pass network

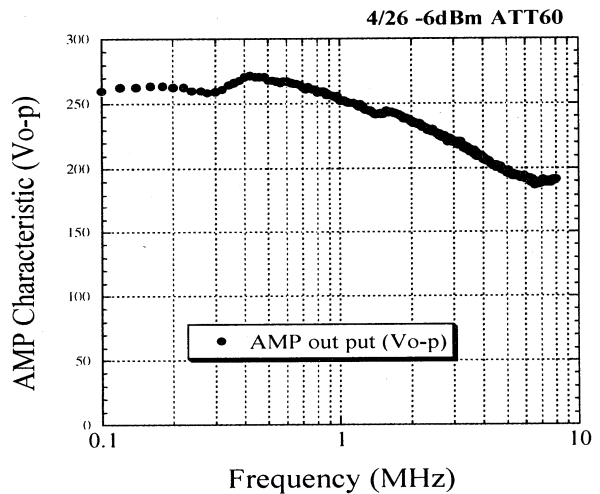Fig.4. A change of the gap voltage as a function of the given rf frequency

Fig.5. Gain property of the used 2kW rf amplifier as a function of the given rf frequency

3.2 Experimental Results

The super wide-band tuning-free cavity was installed at a HIMAC synchrotron ring to make a beam acceleration test.

Fig. 6 shows the used operation pattern for the synchrotron. The period of the HIMAC operation pattern is fixed to be 3.3 seconds. We selected He^{2+} ions as test particles and operated the synchrotron with harmonic number h = 1, 2 and 4. An incident energy of He^{2+} was 6 MeV/u and the ion was accelerated up to 40 MeV/u after 1.8 second acceleration. The ranges of the rf frequency are 0.2615-0.65682 MHz for h=1, 0.522872-1.31364 MHz for h=2 and 1.0460-2.62729 MHz for h=4, respectively. Acceleration of the He ions was found to be succeeded in each case. For synchrotron acceleration, the following condition is required:

$$Ve * Sin\Phi s = 2\pi R * \rho * \dot{B} ,\qquad(5)$$

From the limit of the used rf amplifier, the maximum gap voltage Ve is limited to be about 230 V for h=1, 205 V for h=2 and 170 V for h=4, respectively (average value).

more input power to the cavity is needed.

4 Discussion

In this experiment, it is confirmed that the new super wide-band tuning-free cavity works quite well in the rf frequency range of 0.2615-2.62729 MHz from the beam acceleration test. In other words, we have succeeded to construct the cavity which the frequency ratio of the upper band to the lower one of is more than 10 times. The frequency ratio is considered to be 1:670 theoretically and was measured as, at least,1:80(see fig. 4). However, the experimental limitation, that is, the rf input power and the synchrotron operation pattern, made impossible a beam test with higher frequency operation of the cavity. One solution is to prepare another 2 kW rf amplifier, which will make the maximum gap voltage Ve 1.4 times larger and make Φs an adequate value(see eq.5).In this way, the frequency ratio of this cavity should increase through particle acceleration tests.

5 Conclusion

It is our great pleasure to achieve the initial purpose in this modification, that is, to modify the cavity due to the frequency ratio of which is more than 10 times. We would like to thank the HIMAC staffs and operators for their fruitful cooperation. In order to utilize the super wide-range tuning-free cavity, we plan to improve the cavity especially in point of a higher gap voltage which is required to be more than 2 kV.
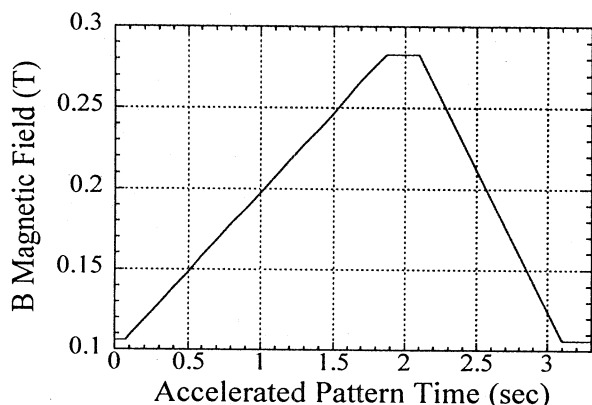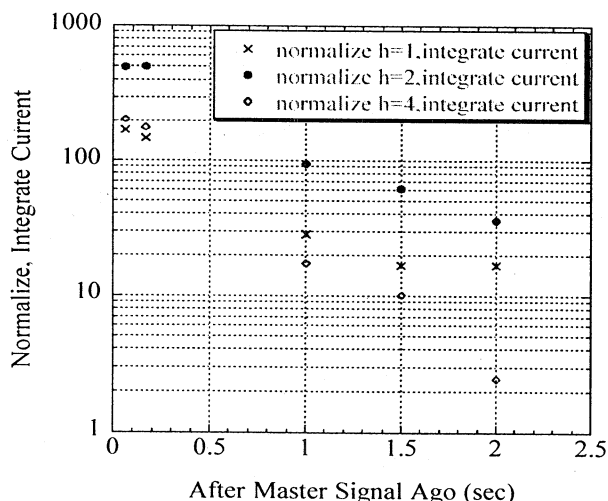

Fig.6. A synchrotron operation pattern

Fig.7. A change of the beam current

Fig. 7 shows relative beam current of one beam bunch as a function of the time for acceleration. Slight decreases after 1 second acceleration in all cases may be due to the shortage of the accelerator voltage especially for h=2 and 4. Clearly,

Reference

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