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High Power Test of a Proto-Type Tuning-Free Cavity with an All-Pass Network

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Abstract

A new concept of a tuning-free cavity for an ion synchrotron is described, which is based on an idea of applying an all-pass network to a ferrite LC resonator. The new type cavity has a smaller and simpler structure than bias-tuned one. In addition, it is possible to produce far higher rf voltage than a conventional tuning-free cavity. High power tests of newly developed ferrite and a proto-type cavity were performed and all the results confirmed the new concept and its several merits.

1. Introduction

In our previous paper for the last meeting of this symposium[2], a new concept of a tuning-free cavity with a bridged-T type all-pass network was introduced. Equivalent circuit analyses and experimental results of a lumped circuit model predicted the new cavity had several merits. It has a simple structure without bias windings, is easy to operate without feedback control of the bias current and applies new ferrite with lower rf loss, which makes cavity voltage limit higher. Therefore the cavity is considered to be applicable to various kinds of ion synchrotrons, such as compact ion synchrotrons for cancer therapy with both slow and rapid cycling and multi-GeV ones for nuclear physics studies requiring high rf voltage more than several kV.

In order to confirm that the new concept can be realized, a proto-type cavity was constructed while new ferrite with lower rf loss was developed.

2. Concept of a New Type Tuning-Free RF Cavity

A bridged-T type all-pass network is a circuit with impedances 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 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. Inductively, 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

$$C_2 = \frac{2L_1}{R^2}, \quad L_2 = \frac{C_1R^2}{2}, \quad C_3 = \frac{C_1}{4} \text{ and } L_3 = 4L_1. \tag{2}$$

Thus Z_1, Z_2 and Z_3 have a same resonance frequency: ω_0, where Z_1 and Z_3 behave as resistances 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 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.

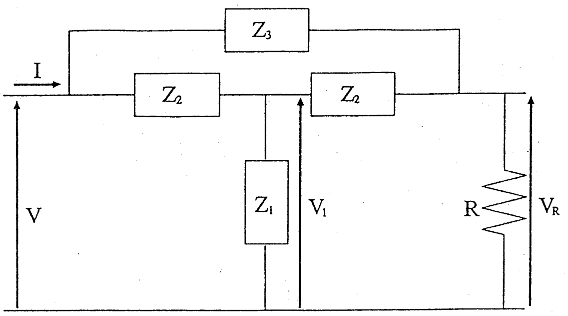


Fig.1(a) A bridged-T type all-pass network (Z expression)

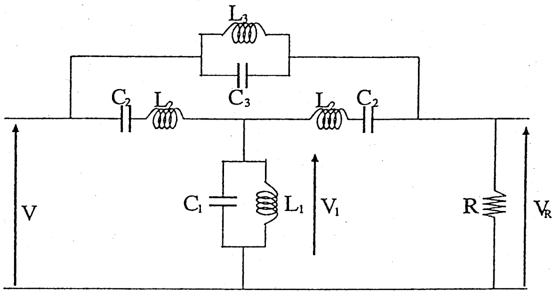


Fig.1(b) A bridged-T type all-pass network (LC expression)

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 parameter,

$$\delta \equiv \frac{\omega_0}{\omega_L} = \frac{\omega_U}{\omega_0}, \tag{3}$$

indicates bandwidth. 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. The circuit can be energized by a commercial transistor rf amplifier of 50Ωoutput through an impedance transformer.

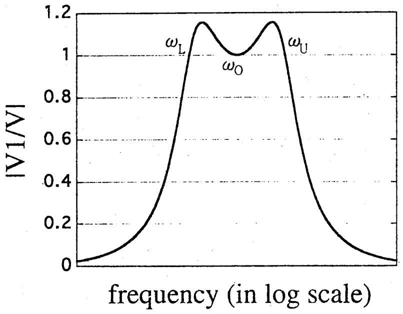


Fig.2 Frequency dependence of $|V_1/V|$

3. Development of New Ferrite Material

The merit of the new cavity that it can generate far higher voltage than a conventional tuning-free cavity is closely related with ferrite characteristics, as noted below.

3.1 New Ferrite for Tuning-Free Cavity; SY-20

In a bias-tuned cavity Ni-Zn ferrite is used due to its quick response to bias field. As it is not needed in a tuning-free type, ferrite containing Co can be used. The Ni-Zn-Co ferrite is poor at bias response but has high μQf product.

For the proto-type tuning-free cavity, new Ni-Zn-Co ferrite SY-20 was developed by TDK co., which has several times larger μQf than conventional ferrite such as SY-2.

By a ferrite test bench at KEK-Tanashi, high power tests of SY-20 were done to measure relative permeability: μ_r, μQf value and so on. While the other features satisfied the requirement for the proto-type, μ_r~200 was rather small. Consequent research of improvement was performed and advanced SY-20, whose μ_r~300, has been developed.

Fig.3 shows SY-20 and its advanced type(Ni-Zn-Co) have several times larger μQf products than conventional SY-2 (Ni-Zn). Outer diameter of all the cores are 500mm.

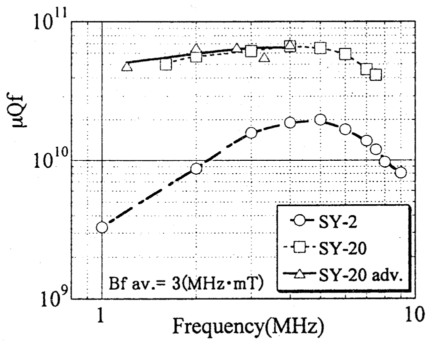


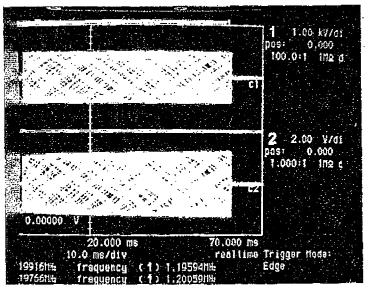
Fig.3 μQf product comparison

About rf loss, as written in the last section, the all pass network can be treated as the simple parallel of R_1(about a few ten kΩ with a ferrite resonator) and R(generally 200, 450, 800Ω or so on). With higher μQf ferrite, R_1 becomes bigger and it can be said that, accordingly, most of the input power is extracted to the external resistance R and only voltage generates on the ferrite resonator. It is why the new cavity can produce far higher voltage than a conventional tuning-free cavity which generates voltage by power dissipation on ferrite cores.

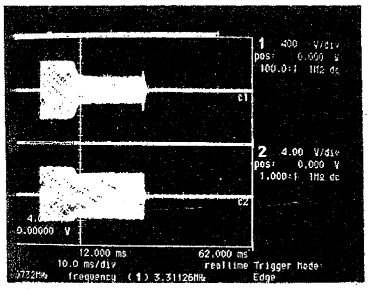
3.2 Q- Loss Effect

The other favorable merit of ferrite without bias field is free from Q-loss effect, which is characterized by a sudden decrease in rf voltage above threshold of input power under bias field. It greatly restricts ferrite voltage in a bias-tuned cavity as Bf product on cores must be below 10MHz•mT.

Fig.4(b) shows the Q-loss effect of an advanced SY-20 core fed by 3.3MHz rf power under 732(A) DC bias current. The voltage on the core is 0.44kV(20.7MHz•mT) at first, but it decreases to 0.18kV(8.4MHz•mT) after about 10ms. On the other hand, as Fig.4(a), the same core with 1.1kV rf voltage (50.6MHz•mT) doesn't suffer from the Q-loss effect without bias field. It shows the new tuning-free cavity can produce higher voltage even more than bias-tuned one.



(a) High power rf input test without bias field



(b) High power rf input test result with Ib=732A

Fig.4 Q-loss effect on an advanced SY-20 core
(by 3.3MHz rf, upper-ferrite voltage, lower-ferrite current)

4. A Proto-Type Tuning-Free Cavity

4.1 Design of a Proto-Type Cavity

A proto-type tuning-free rf cavity, shown in Fig.5 was constructed with its parameters on Table 1. It consists of a cavity resonator and circuit elements to form a bridged-T type all-pass network. The cavity resonator uses 20 cores of the new ferrite SY-20. Its inductance L_1 is 13.5μH and its capacitance C_1 is 235pF with an accelerating gap and an additional capacitor. An external resistance of rather small 200Ω is adopted to realize wide operating frequency range (1~8 MHz). Designed values of the all-pass network circuit elements are shown in Fig.6. The circuit elements of the all-pass network are assembled under the cavity resonator.

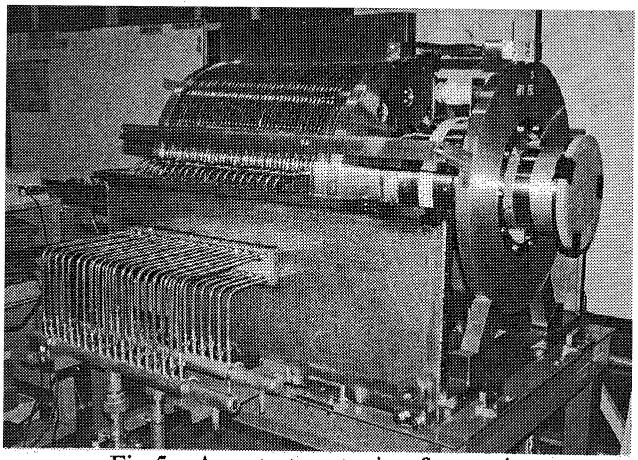


Fig.5 A proto-type tuning-free cavity

Table 1 Parameters of the proto-type tuning-free cavity

Cavity resonator			
Inductance	13.5 μH,	Capacitance	235 pF
Ferrite cores (SY-20:Ni-Zn-Co type)			
Size, number	φ500mm-φ255mm-t25mm × 20P		
μ_i ~200	μQf product ~7 x 10^{10}		
Performance			
Frequency range	1~8 MHz		
rf power input	1 kW,	Cavity voltage	~600 V

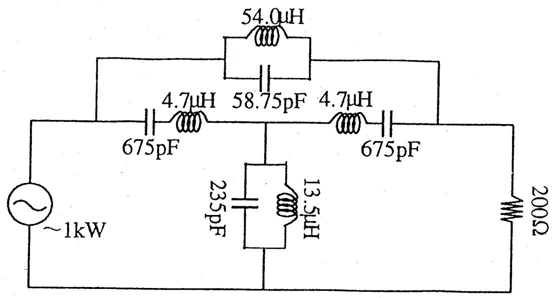


Fig.6 Designed all-pass network

4.2 High power test results

High power performance tests of the proto-type tuning-free cavity were carried out up to 1kW rf input. Sinusoidal wave from a signal generator was amplified by a transistor rf power amplifier, then fed into the cavity. The cavity voltage at the gap was picked up by a high voltage probe.

Fig.7 shows the measured cavity voltages up to 1kW rf power feed at sample frequencies. The voltage over 550V was obtained at 1kW rf power in the frequency range from 1 to 8MHz. These results show that the tuning-free rf cavity can be realized with the bridged-T type all-pass network.

Fig. 8 shows the measured cavity voltage at 1kW rf power feed under rapid cycling frequency sweep. When the frequency was changed from 1 to 8MHz during 25msec, the cavity voltage over 550V was properly obtained as same as Fig.7. It shows that the tuning-free cavity is applicable even to a rapid-cycling synchrotron.

Distortion of the voltage curves on Fig.7 and Fig.8 are thought to be mainly because of the impedance transformer and the external resistance. Especially, ferrite cores in the transformer are rather small and its VSWR characteristics changes according to increase of the input power.

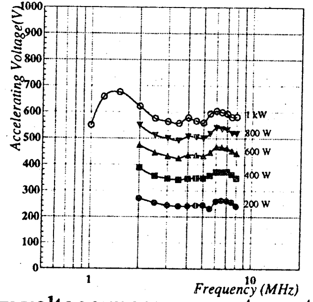


Fig. 7 Cavity voltage measurements up to 1kW input

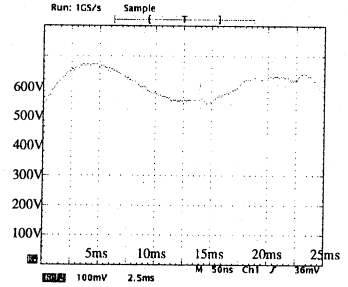


Fig. 8 Cavity voltage at 1kW input under 25ms freq. sweep

6. Discussion and Conclusion

Although the proto-type cavity voltage is slightly lower than the theoretical one, it shows band-pass feature. Thus it is confirmed that the new concept of applying a bridged-T type all-pass network to a ferrite cavity regarded as an LC parallel circuit realizes a new type tuning-free cavity. The voltage feature is expected to be improved by developing the impedance transformer and the external resistance.

Since no bias field is given on ferrite cores, newly developed ferrite with high μQf product can be adopted to the tuning-free cavity in order to decrease ferrite loss.

All those results show that the new tuning-free cavity can produce far higher voltage than conventional one.

The proto-type with a few design changes is planed to be installed into HIMAC(Heavy-Ion Medical Accelerator in Chiba) synchrotron to perform beam acceleration tests.

Acknowledgements

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