TEST SYSTEM AND CHARACTERISTICS STUDIES OF FERRITE CORES FOR THE CSNS RCS RF SYSTEM*

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Abstract

A two-ring ferrite test system for ferrite-loaded cavities of Rapid Cycling Synchrotron (RCS) of China Spallation Neutron Source (CSNS) has been developed. By this system, the RF characteristics of full-sized ferrite cores of RCS cavities have been studied. On dc bias current, the swept frequency range and thresholds of High Loss Effect (HLE) have been presented. On ac bias current of 25 Hz, although the shunt impedance of the cores satisfies the CSNS cavity, comparing with the dc bias, more power dissipation and more required bias current have been observed because the induced magnetic anisotropy of the ferrite cores disappears. Consequently, it is important to evaluate the dynamic features of the cores with 25 Hz bias current for designing the cavities, the power supplies and the bias current sources.

INTRODUCTION

The Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS) is a high intensity proton accelerator, and the RF system will have 8 ferrite-loaded coaxial resonant cavities. The gap voltage and RF frequency vary according to the beam dynamic designing parameters in the 20 ms accelerating period of 40 ms cycle. The frequency is from 1.02 to 2.44 MHz and the total voltage is from 21 to 165 kV. Each cavity includes two very similar resonators and each resonator is loaded by 28 pieces of ferrite rings, and the two accelerating gaps are parallel-connected. The shunt impedance of the cavity in 25 Hz repetition frequency is required about 400~1500 Ω, so 30~110 Ω per core is required. In order to acquire the characteristics of the cores on ac bias current with full RF power, a two-ring ferrite test cavity [1] has been developed by the CSNS RCS RF system and the LLRF control system has also been included for precise and efficient test. In this paper, the test system has been introduced, and the ac bias test results are presented and compared with the dc bias test results.

MEASUREMENT APPARATUS

The Ferroxcube T500/250/25-4M2 has been adopted by CSNS, which is one of soft ferrite and has the feature of fast recovery after magnetic bias. 3 kW valve power supply could drive the two cores far above the realistic magnetic flux densities.

Two-ring Test Cavity

Figure 1 shows the diagram of the two-ring test cavity. Full sized rings lay in separate annular RF cavities, electrically in parallel; bias current counter-couples so as to cancel induction between the bias and RF current paths. The cavity was resonant over the frequency range of 1.02~2.44 MHz by the use of two rings of capacitors one in each RF cavity, together with permeability (μ') tuning of the ferrite. Temex Ceramics RF power capacitors of 1000 volt peak RF voltage rating were used and the total value is 171 nF. The resonant RF current I_{rf} was sampled by a Pearson model 411 current transformer, and RF voltage U_{rf} was sampled by a Tektronix P5100 probe in the coaxial RF feed line.

Figure 2 is a photograph of the test system. The RF power was supplied to the cavity through the coaxial RF feeder, and no matching circuit was needed because of the impedance transformer connecting between 3 kW valve power supply and test cavity, which could satisfy 30~200 Ω variable load. A bias power supply provided the direct current and 0~25 Hz alternating current up to 3200A. The test system also included the LLRF control box and some test instruments.

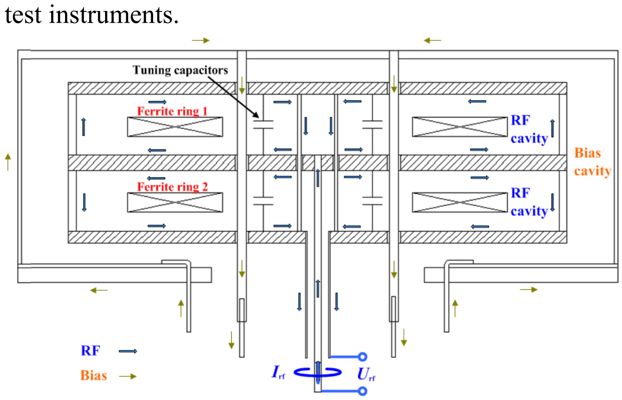

Figure 1: Diagram of two-ring test cavity.

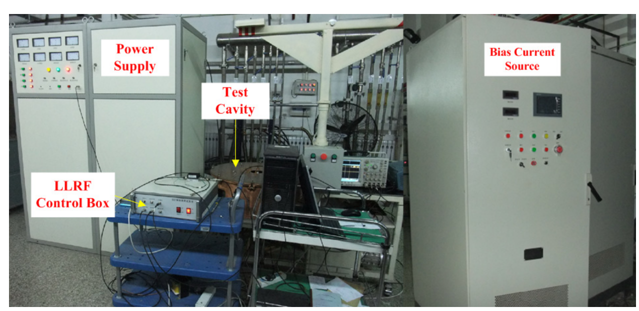

Figure 2: Photograph of the test system.

Equivalent Circuit

Figure 3 shows the equivalent circuit of the test system, where, C_g is the total resonant capacitor, L_1 and L_2 are the inductance of two cores in the RF cavities.

In resonance, the shunt impedance of the cavity can be expressed as

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$$R_{\mathrm{sh}} = \frac{U_{\mathrm{rf}}}{I_{\mathrm{rf}}} = \mu_0 d \ln\left(\frac{r_2}{r_1}\right)(\mu' Q f)\cdot \qquad (1)$$

where r_2、r_1 and d are outer radius, inner radius and thickness of cores, μ_0 is the vacuum permeability, Q is the quality factor, and f is the resonant frequency respectively. The $\mu'Qf$ factor is independent of the core size which can represent the R_{sh}, and usually is used to evaluate the core merit.

The power dissipation and maximum RF magnetic field in core are given by

$$P = \frac{U_{\mathrm{rf}}^{\ 2}}{2R_{\mathrm{sh}}}\cdot \qquad (2)$$

$$B_{\mathrm{rf}} = \frac{U_{\mathrm{rf}}}{(2\pi f)\, d r_1 \ln\frac{r_2}{r_1}}\cdot \qquad (3)$$

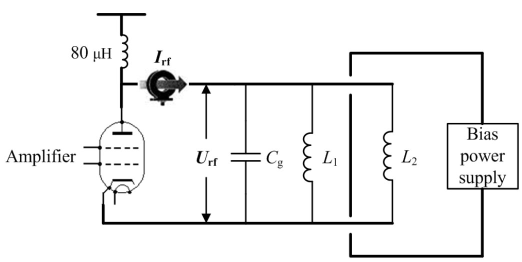

Figure 3: Equivalent circuit of the test system.

MEASUREMENT RESULTS

RF Characteristics with dc Bias Current

The dc bias current dependence of the RF characteristics is shown in Fig. 4. As the bias current increases from 160 to 2820 A, the μ' decreases from 111.2~19.4, and accordingly, the resonant frequency varies from 1.02~2.44 MHz which satisfies the RCS cavity requirement.

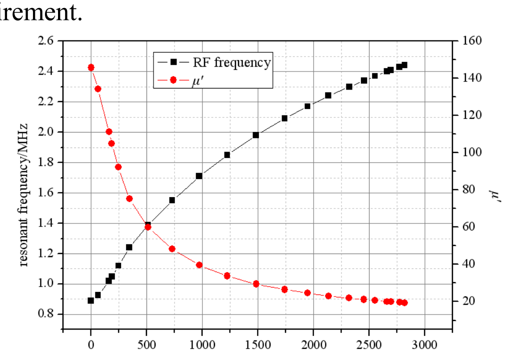

Figure 4: DC bias current versus μ' and frequency.

On dc bias current, there had been two test modes, that is, continue wave and burst mode according to the different RF signal, and the features had been studied in two modes. Figure 5 shows the obvious High Loss Effect (HLE) [2] in continue wave test mode, that is, the power dissipation increases ($\mu'Qf$ decreases) suddenly as the peak RF field (maximum magnetic flux density B_{rf}) is above some value (threshold), and in the same time, with the increase of RF frequency, the thresholds of HLE lessen. In the burst mode of 0.3 duty, as shown in Fig. 6, no obvious HLE is observed as it does in the continue wave mode (Fig. 5), and in the high RF frequency, the shunt impedance almost doesn't change with B_{rf} because of the unchanged Q. But in each RF frequency in burst mode, when B_{rf} is above some value (threshold), the RF voltage envelope displayed in the oscillograph will show obvious HLE.

The thresholds of the two static test modes are completely different. In continue wave mode, when the power density is above 32 mW/cm^3, the HLE begins to occur; while, in the burst mode, the value is over 300 mW/cm^3. The main reason is that the magnetic stored energy in ferrite rings is far higher in continue wave mode than it is in burst mode.

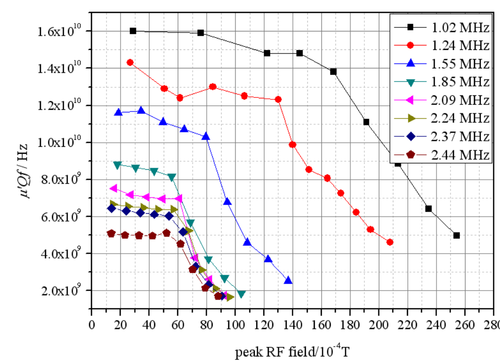

Figure 5: $\mu'Qf$ versus B_{rf} in continue wave mode (DC).

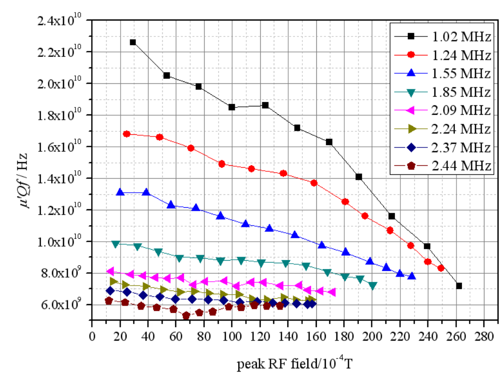

Figure 6: $\mu'Qf$ versus B_{rf} in burst mode (DC).

RF Characteristics with AC Bias Current

The form of the ac bias current is a sine wave from 60 to 3200 A with a maximum frequency of 25 Hz, and the RF signal is the burst signal of low duty (below 2%). Figure 7 shows the dynamic loss in 25 Hz, and the feature lines of 8 frequencies overlap each other in some range of peak RF field, such as in 12~14 mT, the $\mu'Qf$ values in the whole frequency range of 1.02 to 2.44 MHz are all in 4.5~5 GHz. However, the feature lines separate each other in static modes as shown in Figs. 5 and 6. The main

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reason is that Q value of the rings in ac mode will increase with RF frequencies increasing, as shown in Fig. 8, such as, in 1.02 MHz, Q value is below 30 as B_{rf} being above 22 mT; whereas the 4 frequencies above 2 MHz, Q value is always above 80 till B_{rf} reaches 14~16 mT. However, in DC mode, Q value will decreases with RF frequencies increasing.

According to the shunt impedance in realistic magnetic flux density of each frequency in CSNS cavities (● line in Fig. 9), we measured the shunt impedance of the core in the same conditions by the test system. The results (■ line in Fig. 9) proved that the shunt impedance of the ferrite cores completely satisfy the CSNS RCS design.

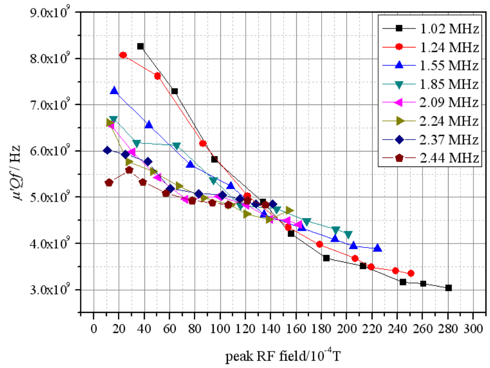

Figure 7: $\mu'Qf$ versus B_{rf} (25 Hz).

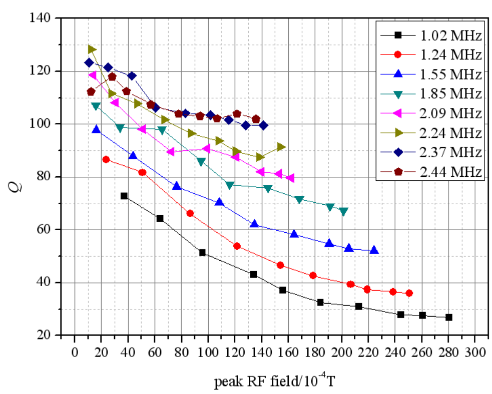

Figure 8: Q versus B_{rf} (25 Hz).

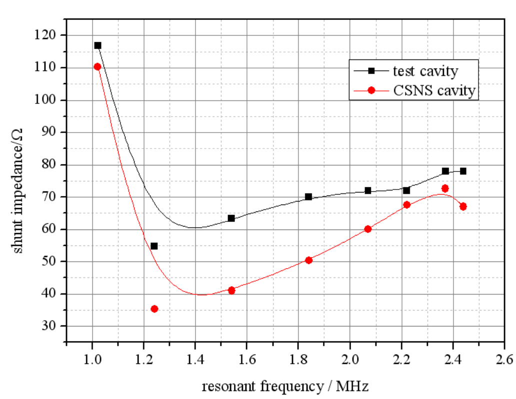

Figure 9: Comparison of R_{sh} versus frequency in CSNS cavity and test cavity in the same peak RF field.

Comparison of RF Characteristics with dc and ac Bias Current

Comparison with dc bias current, ferrites will show following special features on ac bias current.

When the frequency of the bias current is high enough (such as above 15 Hz), the HLE won't occur. The reason might be that the induced small tune spread (Landau damping) in ac mode destroys the coherence while on dc or ac bias current of low frequency, ferrite would store energy in the highly coherent wave above the threshold of HLE [2].

The power dissipation increases ($\mu'Qf$ becomes low) with the frequency of ac bias rising and this change is large from dc to 5 Hz, but becomes small above 5 Hz, as shown in Fig. 10. It becomes impossible to induce high voltages with high B_{rf} because $\mu'Qf$ becomes low on ac bias current of high frequency. For example, when the RF voltage is 300 V at 10 mT and 1.24 MHz, the required RF power can be calculated from Fig. 10 using Eqs. 1 and 2. R_{sh} and P are 101.4 Ω and 55 W (17.5 mW/cm^3) with dc bias of continue wave, but 45.7 Ω and 126 W (40 mW/cm^3) with an ac bias of 25 Hz, so the required RF power on an ac bias of 25 Hz is more than twice that with dc bias. The reason might be that when the repetition rate of ac current is higher than the relaxation time, the induced magnetic anisotropy disappears and the magnetic loss increases highly [3].

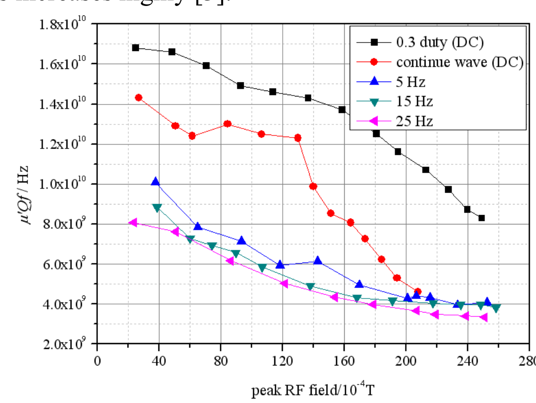

Figure 10: Comparison of RF characteristics in dc and ac bias current (1.24 MHz).

In the same RF frequency, the required bias current is higher in ac mode than in dc mode, for example, in 2.44 MHz, the current is 2800 A with dc bias, but 3100 A with ac bias of 25 Hz. The reason for this increase might be an increase in μ' due to the disappearance of the induced magnetic anisotropy [3].

CONCLUSION

The RF characteristics of ferrite rings of CSNS RCS have been studied with dc and ac bias current, in the whole frequency of 1.02~2.44 MHz and even in the over-realistic magnetic flux density.

On dc bias current, obvious HLE will occur when the power density is above 32 mW/cm^3 in continue wave

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mode and above 300 mW/cm^3 in burst mode of 0.3 duty in the whole working frequency range.

On ac bias current of 25 Hz, the shunt impedance of the cores satisfies the CSNS cavity. At the same time, the cores have following features.

- The HLE won't occur for the tune spread destroying the coherence in the excitation frequency.
- Power dissipation on ac bias current might be more than twice over dc bias current for the rapidly changing bias magnetic field breaks down the low loss mechanism.
- Much bias current is required in ac mode compared with dc mode for the increase in μ'. In maximum frequency (2.44 MHz), the ac bias current increases almost 300 A.

Present results have given some good advices for proposing the whole RCS RF system, and have turn out that the design of power supplies and bias current sources for RCS RF system should consider the RF characteristics of the ferrite cores with ac bias current and should have comfortable margin.

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