

THE MEASUREMENT OF THE FERRITE RINGS FOR THE MASS PRODUCTION RF CAVITY OF CSNS RCS

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Abstract

The Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS) will install 8 ferrite-loaded coaxial resonant cavities. The construction and measurement of prototype cavity have been finished. Based on the existing experiences, the small inner diameter (ID) rings T500/250/25-4M2 (mm) have been adopted for the mass production RF cavity, and the test results have shown that such rings can bear more RF magnetic flux density and have lower power loss. The characteristics of 60 small ID rings have been measured with two-ring test system, and we figured out that the rings have good consistence and the shunt impedance of all rings is above 100 Ω .

INTRODUCTION

CSNS RCS is a high intensity proton accelerator with 8 accelerating cavities, each containing 56 ferrite rings. The frequency range of the cavity is 1.022 to 2.444 MHz and the total accelerating voltage is from 21 to 165 kV in the 20 ms accelerating period of 40 ms cycle. Ferroxcube (former Philips) soft ferrite material 4M2 has been chosen, the demerits of which are the shunt impedance (R_{sh}) decreasing quickly and serious nonlinear effect appearing above certain peak RF magnetic flux density (B_{rf}). So, the T500/250/25-4M2 (mm) rather than T500/300/25-4M2 (mm) is chosen to improve the cavity operation because the small inner diameter (ID) rings can bear more B_{rf} and have higher R_{sh} . The 60 small ID rings were measured by a two-ring test system. The merits of small ID ring and the test results of 60 rings are described in this paper.

TEST SYSTEM

The test system consists of 5 components of two-ring test cavity, low-level radio frequency (LLRF) control system, bias power supply (0~3000 A), valve RF power amplifier (up to 3000 W) and some test facilities^[1-2], as shown in Fig. 1. Two 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 resonant RF current (I_{rf}) is sampled by a Pearson model 411 current transformer, and then the sampled current is demodulated in LLRF system to get fundamental waveform. The resonant RF voltage (U_{rf}) is sampled separately by Tektronix probe P5100 (sending to Oscilloscope) and a 110:1 capacitive voltage divider (sending to LLRF). Then their values and phase error between the two waveforms can be given in LLRF

system, and automatic measurement can be realized by amplitude and tuning feedback loops. We detect the temperature ($T_{ferrite}$) of ferrite by the probe PT100, and the bias current (I_b) by DCCT, each sends to one digital multimeter (DMM). The oscilloscope is used to check resonant condition.

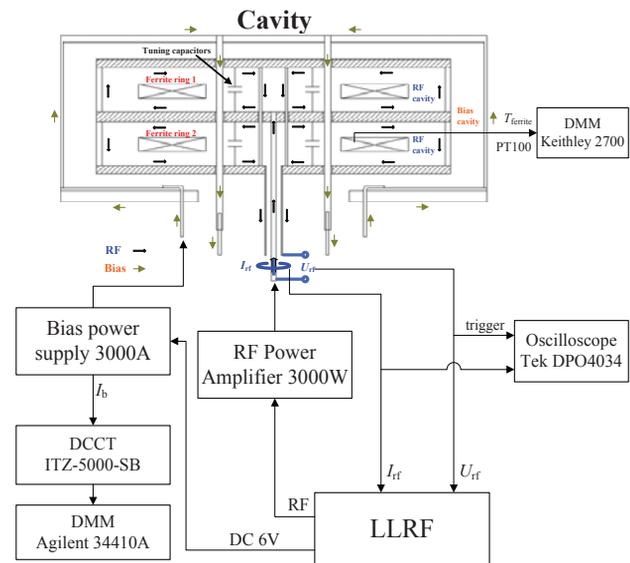


Figure 1: Diagram of two-ring test system.

MERITS OF SMALL ID RINGS

Small Maximum Bias Current

The resonant RF frequency (f_{rf}) of the ferrite ring is approximately decided by the bias magnetic field strength (H_b) when the resonant capacitors are fixed. Based on Ampere's circuital law

$$H_b = I_b / L_e \quad (1)$$

where L_e is the effective magnetic path length, small L_e requires less I_b . The L_e decreases about 10% when the ID of the ring decreases from 300 mm to 250 mm, so the requiring maximum bias current lessens 10%. The result has been verified in actual test.

Small Maximum RF Magnetic Flux Density

The characteristics of 4M2 deteriorate quickly when the B_{rf} increases towards the saturation value^[3], so it will be stable for rings to operate in low B_{rf} . The maximum B_{rf} of the cores can be given by

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$$B_{rf\max} = \frac{U_{rf}}{2\pi f_{rf} d r_1 \ln(r_2/r_1)} \quad (2)$$

where r_2 , r_1 and d are outer radius, inner radius and thickness of the cores, so $B_{rf\max}$ will lessens 13% as r_1 decreases 1/6.

Less Power Loss

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

$$R_{sh} = \mu_0 d \ln\left(\frac{r_2}{r_1}\right) (\mu' Q f_{rf}) \quad (3)$$

where μ_0 is the vacuum permeability, μ' the relative permeability, and Q the quality factor. $\mu' Q f_{rf}$ is nearly same for different-size cores, so only r_1 decides the power loss (R_{sh}). We measured separately ten large and ten small ID rings in 200 V@2.24 MHz and 100 V@2.44 MHz, and the test results show that compared with large ID rings, $\mu' Q f_{rf}$ of small ID rings decreases only 5%, but the R_{sh} increases almost 30%.

60 SMALL ID RINGS TESTING

Relations

The RF characteristics of two cores rather than one would be achieved by the two-ring test cavity. We would get one core's data in two steps, firstly one known core (sample core) should be tested, and then other cores' data would be calculated based on the test results and sample core's data. Some relations would be given as followed.

• Sample ring's relations

3 cores are chosen randomly, and the number is proposed as i, j and k . We will finish 3 groups of testing for each of the two cores, and get 3 angular frequencies of $\omega_{i,j}$, $\omega_{i,k}$ and $\omega_{j,k}$. The inductance of these 3 cores is

$$\left. \begin{aligned} \frac{1}{L_i} &= \frac{C_g}{2} (\omega_{i,j}^2 + \omega_{i,k}^2 - \omega_{j,k}^2) \\ \frac{1}{L_j} &= \frac{C_g}{2} (\omega_{i,j}^2 + \omega_{j,k}^2 - \omega_{i,k}^2) \\ \frac{1}{L_k} &= \frac{C_g}{2} (\omega_{i,k}^2 + \omega_{j,k}^2 - \omega_{i,j}^2) \end{aligned} \right\} \quad (4)$$

where C_g is the resonant gap capacitance. Then μ' is

$$\mu' = (L - L_s) / \left(\frac{\mu_0}{2\pi} d \ln \frac{r_2}{r_1} \right) \quad (5)$$

where L represents one core's inductance randomly, L_s is the straying inductance.

We also get 3 shunt impedance of $R_{i,j}$, $R_{i,k}$ and $R_{j,k}$ for each two paralleled cores, and the value of one core is

$$\left. \begin{aligned} \frac{2}{R_i} &= \frac{1}{R_{i,j}} + \frac{1}{R_{i,k}} - \frac{1}{R_{j,k}} \\ \frac{2}{R_j} &= \frac{1}{R_{i,j}} + \frac{1}{R_{j,k}} - \frac{1}{R_{i,k}} \\ \frac{2}{R_k} &= \frac{1}{R_{i,k}} + \frac{1}{R_{j,k}} - \frac{1}{R_{i,j}} \end{aligned} \right\} \quad (6)$$

• Other ring's relations

No. i core is proposed as sample, and x as other core. No. i and x lay in two RF cavities, and inductance $L_{i,x}$ and shunt impedance $R_{i,x}$ are tested. So the values of other ring are

$$L_x = \frac{L_i}{L_i/L_{i,x} - 1} \quad (7)$$

$$R_x = \frac{R_i}{R_i/R_{i,x} - 1} \quad (8)$$

Relative Permeability

The bias current dependence of the μ' was measured. We fixed 5 bias currents and changed RF frequency for cavity to obtain resonance in the low peak RF field ($B_{rf\max} < 15$ Gauss).

Fig. 2 shows the μ' distribution of 60 cores in 5 bias currents, and there is no obvious dispersion. The corresponding frequency ranges to the bias currents are about 1.022 MHz@153 A, 1.548 MHz@755 A, 2.088 MHz@1724 A, 2.243 MHz@2122 A, and 2.444 MHz@2777 A.

The relative deviation of μ' in 5 bias currents is about -8%~+15% (Fig. 3), which is better than the product specification $\pm 20\%$. The sample core (No. 55) has the largest deviation above 500 A, and the reason might be the accumulated error.

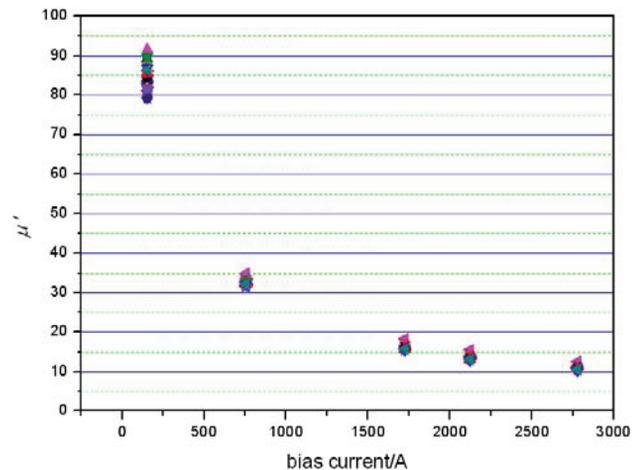


Figure 2: μ' vs. bias current of 60 cores.

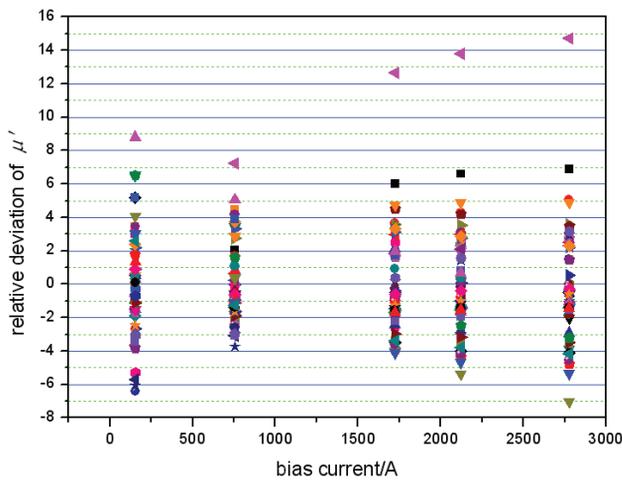


Figure 3: Relative deviation of μ' vs. bias current of 60 cores.

Shunt Impedance

The measurements of shunt impedance (power loss) of 60 cores are performed in the fixed RF frequencies and RF voltages, and we tune the bias current to gain resonance. Because the characteristics of ferrite become worse in high frequency, we mainly choose 3 frequencies above 2 MHz (2.088, 2.243 and 2.444 MHz), each contains two B_{rf} and the higher B_{rf} is almost same as the actual operation of the CSNS RCS RF cavity. The RF signal duty is 10%.

Fig. 4 shows peak RF magnetic flux density dependence of the shunt impedance. In 2.088 and 2.243 MHz, R_{sh} decreases with B_{rf} increasing, and average R_{sh} changes from 152 Ω @70.38 Gauss to 137 Ω @127.39 Gauss in 2.088 MHz, and from 134 Ω @65.52 Gauss to 118 Ω @118.58 Gauss in 2.243 MHz. However, average R_{sh} (118 Ω approx.) almost doesn't change in 2.444 MHz because of the low peak RF magnetic field (60 Gauss approx.). R_{sh} is over 100 Ω above 2 MHz, and based on testing experience, there will be higher value below 2 MHz, so R_{sh} of all cores will be over 100 Ω in the frequency range 1.022~2.444 MHz.

The relative deviation of R_{sh} of 60 cores is about in $\pm 15\%$, and also that of 85% cores is in $\pm 10\%$ (Fig. 5). There is no cooling facility in the test system, so the operating temperature of cores will be different which will affect the consistency of R_{sh} to some extent, and all tests were performed in lower temperature 15~20 $^{\circ}\text{C}$. We believe that the R_{sh} deviation of the cores will be lessen in the same temp. range, and the characteristics of ferrite will be more stable in higher temp. 25~35 $^{\circ}\text{C}$ [4].

CONCLUSION

We have studied the characteristics of small inner diameter rings. Compared with T500/300/25-4M2 (adopted by R&D stage), theoretical calculation and testing results have proved that T500/250/25-4M2 (adopted by CSNS RCS formal RF cavities) have such merits: the requiring maximum bias current lessening

10%, the maximum peak RF magnetic flux density decreasing 13%, and shunt impedance increasing almost 30%.

The RF characteristics of 60 cores have been compared. The maximum relative deviation of μ' is about -8%~+15%, superior to the product specification $\pm 20\%$. The shunt impedance is above 100 Ω in the operating frequency 1.022~2.444 MHz, the deviation of 60 cores is approximately in $\pm 15\%$, and 85% cores in $\pm 10\%$.

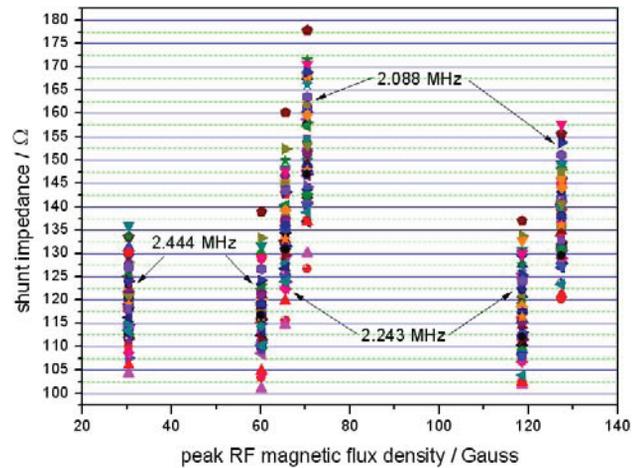


Figure 4: R_{sh} vs. B_{rf} of 60 cores.

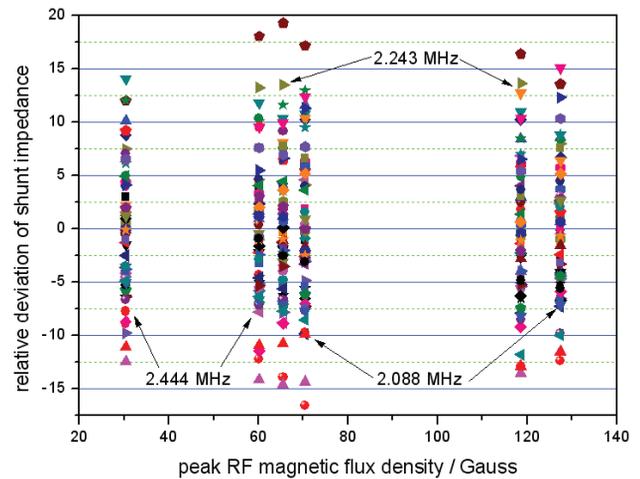


Figure 5: Relative deviation of R_{sh} vs. B_{rf} of 60 cores.

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