Magnetic alloy cores for the HIRFL-CSRm compressor cavity

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Abstract Four types of magnetic alloy cores, labeled as V1, V2, A1 and A2, were produced by Liyuan Corp. Ltd., for the radio frequency compression cavity of HIRFL-CSRm. In this work, their permeability, quality factor (*Q* value) and shunt impedance were measured before installing them into the cavity. The results show that the V1, V2 and A2 have higher permeability and shunt impedance, and lower *Q* value, and are suitable to the radio frequency compression cavity.

Key words Magnetic alloy cores, Permeability, *Q* value, Shunt impedance

1 Introduction

Heavy Ion Research Facility at Lanzhou (HIRFL) provides high energy heavy ion beams after the heavy ion cooler-storage-ring (HIRFL-CSR) operates. The HIRFL-CSR, including a main ring (CSRm) and an experimental ring (CSRe), can be used to conduct high-energy density and plasma physics research. In order that the short-pulse heavy ion beam of high-intensity current can be effectively deposited in the experiment target, high accelerating voltage is required to compress the longitudinal beam pulse[1].

The radio frequency (RF) cavity with a magnetic alloy (MA) core provides the high accelerating voltage[2] without the tuning loop, thus simplifying the RF control system in the compact accelerators and running the cancer-therapy facility. So the MA core characteristics decide the RF cavity performance.

In this work, four types of MA cores, which are labeled as V1, V2, A1 and A2, and were produced by Liyuan Corp. Ltd., were measured before their installation. The results show that they are of higher permeability, shunt impedance and lower quality factor (*Q* value), and are pertinent to load RF compression cavity.

2 Permeability of the MA cores

In order to provide high accelerating voltage without complicated bias winding loop, and realize the untuned RF cavity, the magnetic cores must have lower Q value, higher permeability, μQf value, and shunt impedance. To cover a wide frequency range[5], an imaginary part of the MA core permeability for an untuned RF cavity needs be larger than or equal to that of the real part, namely $Q\leq1$. The MA cores at the high permeability can have large inductance, and reduce the number of the cores loaded in RF cavity. The higher μQf value and shunt impedance can reduce the power requirements.

The serial complex permeability of MA cores is expressed by Eq.(1).

$$\mu = \mu_s' - j\mu_s'' \quad (1)$$

where μ'_s is the real part representing the reserved energy during magnetization, and μ''_s is the imaginary part representing the dissipation energy. The Q value is given by

$$Q = \mu'_s/\mu''_s \quad (2)$$

The parallel complex permeability of MA cores is determined by

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$$1/\mu = 1/\mu'_p - 1/(i\mu''_p),\ Q = \mu''_p/\mu'_p \tag{3}$$

Eqs.(1)–(3) can be simplified into Eq.(4), which can be used for the serial and parallel permeability[3–7].

$$\mu'_p = (1/Q^2+1)\mu'_s,\ \mu''_p = (1+Q^2)\mu''_s \tag{4}$$

3 MA core measurements

Fig.1 shows a measurement scheme of the MA core performance. The MA cores were wound by coil to form an inductance, and a parallel resonant circuit was formed after a capacitor (C) is parallelly connected to the inductance. The resonant circuit was measured by vector impedance meter. The resonant frequency (f_0) and shunt impedance (R) can be read out directly from the vector impedance meter.

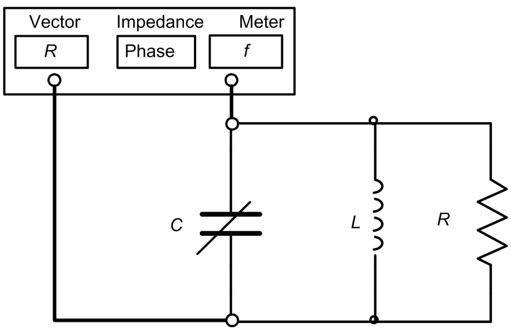

Fig.1 A scheme of the MA core measured.

The inductance (L) of the resonant circuit can be calculated by Eq.(5),

$$L = 1/(4\pi^2 f_0^2 C) \tag{5}$$

The inductance for MA core is calculated by

$$L = \frac{\mu_0 \mu'_p}{2\pi}[\ln\frac{r_2}{r_1}]d \tag{6}$$

From Eqs.(5) and (6), Eq.(7) can be obtained,

$$\mu'_p = \frac{1}{2\pi\mu_0 f_0^2 C[\ln\frac{r_2}{r_1}]d} \tag{7}$$

where r_1, r_2, and d are respectively inner radius, outer radius, and thickness of the MA core, $\mu_0 = 4\pi \times 10^{-7}$ H·m^{-1} is the vacuum permeability, and μ_p' is its real part of the parallel complex permeability.

The Q value for the parallel circuit is calculated by

$$Q = 2\pi f_0 RC \tag{8}$$

The μ_s' and μ_s'' are calculated by Eqs.(2) and (4), and the resonant frequency dependent on the permeability is obtained by changing the C value[8].

4 Results and Discussion

The V1, V2, A1, and A2 are all of Fe-based nanocrystalline and tape-wound cores. Except for the difference of the insulation layer between MA ribbons, the V1 and V2 are 65 mm in outer radius, 35 mm in inner radius and 30 mm thick, and the A1and A2 are of 65-mm outer radius, 35-mm inner radius, and 25 mm thick. One coil was wound on the MA core during the measurement. Fig.2 shows that the R magnitude and phase of MA core at 1.0 MHz vary with the frequency in the range of 0.8 to 1.2 MHz.

The results show that the R is about 70 Ω for V1, 76.3 Ω for V2, about 26 Ω for A1, and 41 Ω for A2; and corresponding phase is 11.1º to –11.1º for V1, 12.3º to –12.5º for V2, 7º to –5.9º for A1, and 6.2º to –7.1º for A2, indicating that the small R changes are good for an untuned RF cavity.

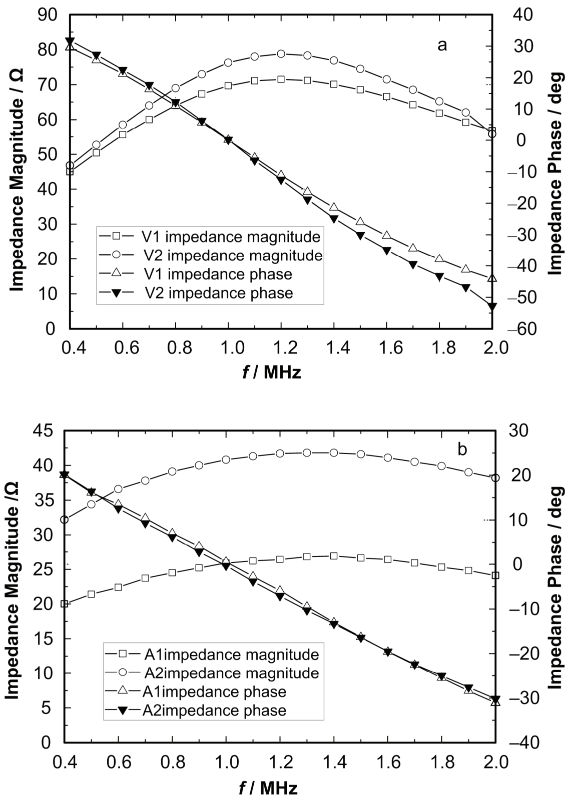

Fig.2 Dependence of R magnitude and phase on frequency.

The frequency error, the Q value, $\mu_p'Qf$, μ_s', and shunt impedance of the cores were measured by changing the capacitor. Fig.3 shows that the frequency error measured by vector impedance meter is in the range of ±0.03 MHz, and is a main parameter measured in the test system.

At 1.0 MHz in the range of 0.8 to 1.2 MHz, the Q values of the V1, V2, A1 and A2 are about 0.67, 0.78, 0.51 and 0.44, respectively, with slight variations (Fig.4a). The μ'_pQf values of the V1, V2, A1 and A2 are, respectively, about 2980, 3260, 1120 and 1750 MHz with variations ranges of 2750–3150, 3000–3460, 1050–1150, and 1670–1820 MHz (Fig.4b). The permeability values of V1, V2, A1 and A2 decrease with increasing operation frequency in the ranges of 1588–1190, 1806–1403, 536–403, and 786–560 MHz, respectively, indicating that the V2 has a higher permeability (Fig.4c). And the R values of V1, V2, A1 and A2 are in the ranges of 64.2–73.7, 70.3–81, 24.6–26.9, and 39– 42.6 Ω, respectively (Fig.4d).

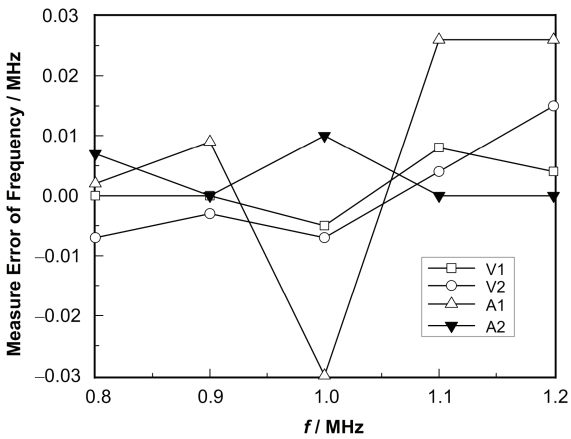

Fig.3 Dependence of measure error on frequency.

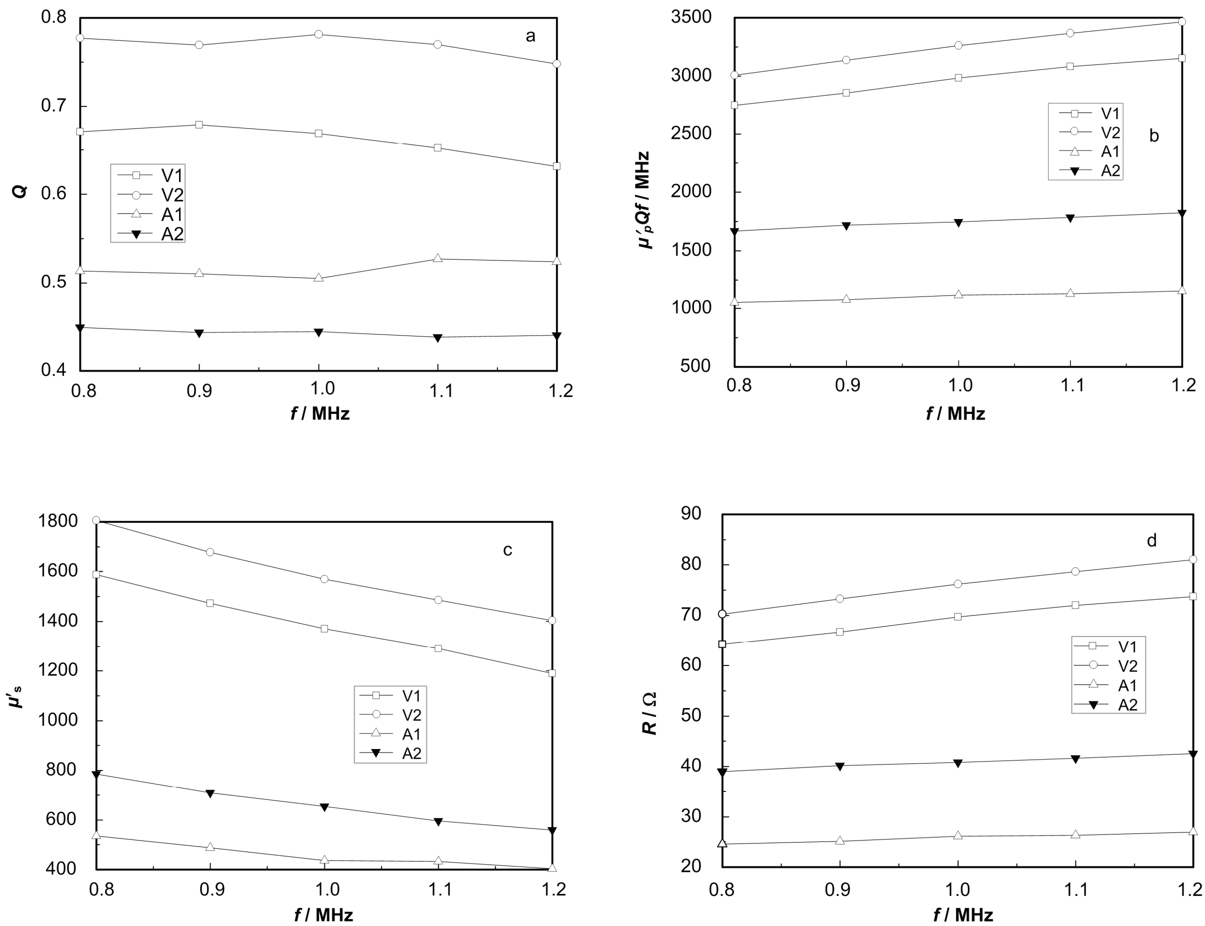

Fig.4 Dependence of Q value (a), μ'_pQf (b), μ'_s (c) and R value (d) on frequency.

Given that the characteristics of a single MA core do not change when scaled up, its shunt *R* can be calculated by its practical dimension, as shown in Fig.5. Finally, we adopted the MA cores with 400 mm outer radius, 170 mm inner radius, and 30 mm thick. Fig.5 shows that V2 is the best to load RF cavity among four kinds of material due to the highest shunt *R*, and V1and V2 has shunt *R* higher than A1and A2.

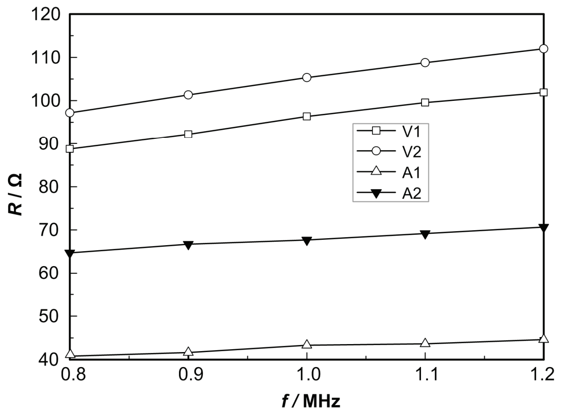

Fig.5 Dependence of *R* values on frequency.

By applying 50 kV accelerating voltage to the MA cores, the power requirement can be calculated when the loaded RF cavity was designed by the fourteen cores[3], as shown in Fig.6. The V2, V1, A2, and A1 require 230, 250, 350, and 550 kW, respectively, for 50-kV accelerating voltage in the range of 0.8 to 1.2 MHz. Therefore, the V2 will be the best for the low power requirement.

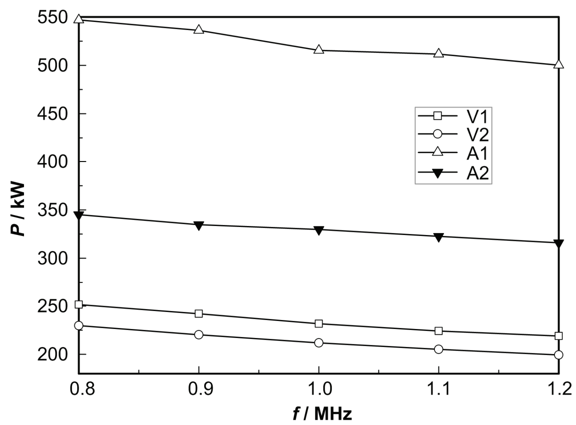

Fig.6 Dependence of power on frequency.

The results show that the V2 performance is the best during the four MA cores in this test system. Briefly, the V and A with Fe-based nanocrystalline tape-wound cores are processed by different techniques, because the V raw cores is from German, and the A tape material is from China. Second, the V and A have the different insulation layer in MA ribbons, the A1 and V1 are SiO_2 of 1.0-μm thickness and silica gel to enhance insulation effect, and the A2 and V2 are just silica gel. Comparatively, the A1 and V1 decrease the filling factor due to increasing thickness, and affect the core performances. As a result, the V2 and A2 have higher Q value, μ'_pQf, and R.

5 Conclusions

The V1, V2, A1 and A2 for loading the RF cavity can be used to get 50-kV accelerating voltage, and the V2 is the best because of the larger shunt *R* and the lower power requirement. Also the A2 can be used only when the V2 is more expensive.

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