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An untuned MA-loaded cavity for HIRFL-CSR

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Abstract In order to realize high energy density physics and plasma physics research at HIRFL-CSR, a magnetic alloy (MA)-loaded cavity has been studied. According to the theoretical calculation and simulation for the MA-loaded cavity, we achieved a better result. The MA-loaded cavity had a higher μQf value, with a higher shunt impedance and a higher accelerating gradient. The accelerating gradient was about 95 kV/m at 1.8003 MHz, 130 kV/m at 0.9000 MHz. Compared with the ferrite-loaded cavities that are used at HIRFL-CSR, with about 10 kV/m accelerating gradient, the MA-loaded cavity obviously has an advantage. The results of the theoretical calculation and the simulation, which meet the design requirements are in good agreement.

Key words magnetic alloy material, untuned MA-loaded cavity, accelerating gradient

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1 Introduction

HIRFL can provide high energy heavy ion beams since HIRFL-CSR (heavy ion cooling storage ring) went into operation. In order to realize high energy density physics and plasma physics research at HIRFL-CSR, we need a higher accelerating voltage to compress the beam pulse in the longitudinal direction so that a large amount of energy can be delivered to the experimental target material efficiently with a pulse length as short as possible [1]. A magnetic alloy (MA)-loaded cavity is a device that can provide a higher accelerating voltage to meet this requirement [2]. In addition the MA-loaded cavity does not need the tuning loop, so it simplifies the whole RF control system, and in addition it can be used in the compact accelerator, which will be constructed as a cancer therapy facility in the future. In this paper we mainly focus on the design and simulation of the MA-loaded cavity.

2 MA material and MA-loaded cavity

In order to achieve a wide operation frequency range and high accelerating voltage on the untuned RF cavity, we chose the MA material because of its low Q value (quality factor), high permeability, high μQf value, high Curie temperature and its ability to used in high gradient operation. The low Q value material requires the imaginary part of the permeability to be larger than or equal to the real part, namely $Q \leqslant 1$. So we need the cavity be loaded with MA cores (FINEMET or Vitro VAC). FINEMET is a Fe-based soft MA material composed of an amorphous and ultrafine grain structure. VitroVAC 6030 is a Co-based alloy [3–5]. The MA-loaded cavity can provide a higher accelerating gradient, can be constructed in the limited space and does not need the tuning loop, which sometimes causes parasitic resonance and is usually necessary in the ferrite-loaded cavity. There are many institutes, laboratories and facilities that have been researching and using the MA-loaded cavity in accelerators, such as KEK, JHF, HIMAC, etc. in Japan, GSI in Germany and FNAL in the USA. However, in China there are no MA-loaded cavities being used in accelerators [2–5].

3 MA-loaded cavity design and parameters

In our design, the MA-loaded cavity is a $\lambda/4$ sin-

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gle gap coaxial resonator structure of 700 mm in length without a flange plate, as shown in Fig. 1. The open end of the two half cavities forms the accelerating gap. The MA-loaded cavity induces a voltage at the accelerating gap [5, 6]. The long ion beam, which is captured by the voltage, can be rotated 90 degrees in the longitudinal phase space when the voltage jumps from low to high in a very short pulse. Consequently, the beam compression is completed. Table 1 gives the proposed parameters for the RF system.

For the CSRm compression cavity (MA-loaded cavity), because the required frequency range is 0.9 MHz to 1.8 MHz, we can calculate Q=1.414 according to the equation $Q=f_0/B$, where f_0 is the center frequency and B is the bandwidth. When the material Q value is less than or equal to 1, the bandwidth will be wide, which is better for us. So, we select Q=1 in our calculation and simulation.

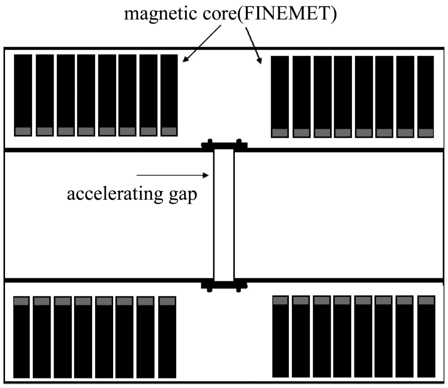

Fig. 1. The MA-loaded cavity structure.

Table 1. The proposed parameters for the RF system.

parameters	CSRm accelerating cavity (Ferrite-loaded)	CSRm compression cavity (MA-loaded)
total length/m	2.60	0.9
frequency range/MHz	0.24−1.81	0.9−1.8
gap voltage/kV	7	50
pulse duration/μs	series	500
duty ratio (%)	23.5	0.05
peak power/kW	20	500
mean power/kW	3.2	0.05
shunt impedance/kΩ	2.0(0.45MHz)	1

Figure 1 showes the MA-loaded cavity structure, it is a $\lambda/4$ single gap coaxial resonator structure of 700 mm in length without a flange plate. The coaxial inductance [7] of the cavity loaded with MA cores is expressed as

$$L_{\mathrm{p}}=\frac{\mu_0\mu}{2\pi}\cdot d_1\cdot\ln\frac{\rho_2}{\rho_1}, \tag{1}$$

where

$$\mu=\left(1+\frac{1}{Q^2}\right)\mu_{\mathrm{s}}', \tag{2}$$

d_1 is the thickness of a single MA core, ρ_1, ρ_2 represent the inner and outer radius of the MA core, Q is the quality factor and μ_{s}' is the real part of relative permeability.

Figure 2 gives the distributed capacitance of the MA loaded coaxial cavity and its equivalent circuit. The distributed capacitance of the coaxial cavity is expressed as

$$C_{\mathrm{coax}}=C_2+C_{\mathrm{e}}, \tag{3}$$

where

$$\frac{1}{C_{\mathrm{e}}}=\frac{1}{C_1}+\frac{1}{C_3}+\frac{1}{C_4}+\frac{1}{C_5}, \tag{4}$$

C_1 is the distributed capacitance between the Teflon and outer radius of the inner conductor, filled with vacuum; C_2 is the distributed capacitance between the inner and outer radius of the cavity, filled with vacuum except for the MA cores; C_3 is the distributed capacitance between the outer radius of the MA cores and the inner radius of the outer conductor, filled with vacuum; C_4 is the distributed capacitance of the Teflon; and C_5 is the distributed capacitance of the MA cores.

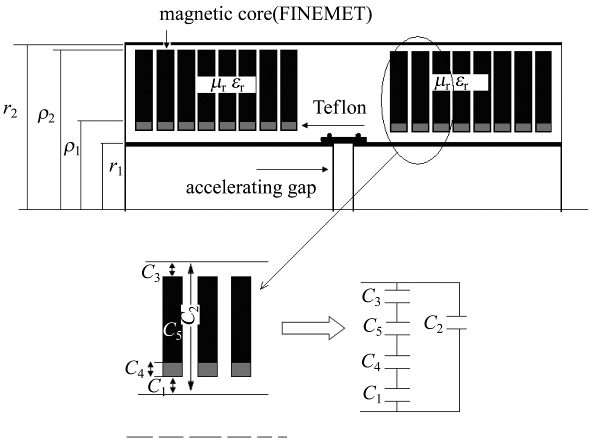

Fig. 2. Distributed capacitance and its equivalent circuit.

We can gain the distributed capacitance of each part from the following equations:

$$C_1 = \frac{2\pi\varepsilon_0}{\ln\dfrac{\rho_1-15}{r_1}}\cdot d_1\cdot n, \tag{5}$$

$$C_2 = \left(\frac{2\pi\varepsilon_0}{\ln\dfrac{r_2}{r_1}}\right)\times l, \tag{6}$$

$$C_3 = \frac{2\pi\varepsilon_0}{\ln\dfrac{r_2}{\rho_2}}\cdot d_1\cdot n, \tag{7}$$

$$C_4 = \frac{2\pi\varepsilon_0\varepsilon_r'}{\ln\dfrac{\rho_1}{\rho_1-15}}\cdot d_1\cdot n, \tag{8}$$

$$C_5 = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\dfrac{\rho_2}{\rho_1}}\cdot d_1\cdot n, \tag{9}$$

where r_1 is the outer radius of the inner conductor, r_2 is the inner radius of the outer conductor, n is the number of loaded MA cores in the half cavity, ε_0 is the permittivity of the vacuum, l is the length of filling with vacuum and $\varepsilon_{\rm r}$ is the permittivity of the MA cores.

The accelerating gap capacitance $C_{\rm g}$ is given by

$$C_{\rm g} = \frac{\varepsilon_0\pi(r_{\rm i}^2-r_{\rm cav}^2)}{d_{\rm gap}}+\frac{\varepsilon_0\varepsilon_{\rm r}'\pi[(r_{\rm i}+0.01)^2-r_{\rm i}^2)]}{d_{\rm gap}+0.01}+ \frac{\varepsilon_0\pi[(r_{\rm i}+0.01+0.005)^2-(r_{\rm i}+0.01)^2)]}{d_{\rm gap}+0.01}, \tag{10}$$

where $r_{\rm vac}$ is the radius of the vacuum tube and $\varepsilon_{\rm r}'$ is the permittivity of the porcelain that is used as insulation. The first term of the equation is the capacitance between the two inner conductors, the second term is the capacitance of the porcelain part and the third term is the capacitance between the two little ring plates that are outside the porcelain.

Figure 3 shows the equivalent circuit of a half cavity.

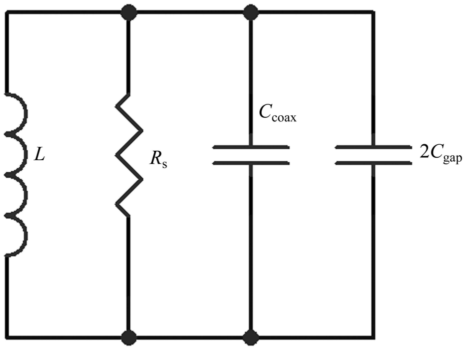

Fig. 3. The equivalent circuit of a half MA-loaded cavity.

where L, $C_{\rm coax}$, $R_{\rm s}$ and $C_{\rm gap}$ are the equivalent inductance, the distributed capacitance of the half cavity, the shunt impedance and the gap capacitance, which includes the external parallel capacitance when there is an external parallel capacitance. So, the resonant frequency of the MA-loaded cavity is given by

$$f=\frac{1}{2\pi\sqrt{LC_{\rm s}}}, \tag{11}$$

where

$$C_{\rm s}=2C_{\rm gap}+C_{\rm coax}. \tag{12}$$

In order to meet the design requirements, we selected the specific parameters and values of the MA-loaded cavity: the length (without a flange plate) of the cavity is 700 mm, and the radius of the inner and outer conductors are 105 mm and 260 mm, respectively. The total number of MA cores is 16, the inner radius of the MA core is 140 mm, the outer radius is 250 mm, the width is 25 mm, the interval of two MA cores is 7 mm and the real part of the permeability of the MA core is 4325. Based on these data, we obtained the following result:

$$L = 200.62\times10^{-6}(\rm H), \tag{13}$$

$$C_{\rm s} = 2C_{\rm gap}+C_{\rm coax}=2C_{\rm g}+C_{\rm coax}=38.959(\rm pF), \tag{14}$$

where $C_{\rm g}=C_{\rm gap}$ because there is no external parallel capacitance. So,

$$f=\frac{1}{2\pi\sqrt{LC_{\rm s}}}\approx1.8003(\rm MHz). \tag{15}$$

According to f=1.8003 MHz, the μQf value is 15.0213 GHz, and the shunt impedance is 4.379 kΩ. From the equation $V^2=2R_{\rm s}P$, the calculated accelerating voltage V=66 kV, where $R_{\rm s}$ is the shunt impedance and P is the power of the RF generator. For the frequency of 0.9000 MHz, the accelerating voltage is about 92 kV, which can meet the design requirements. The accelerating gradient, which is defined as the accelerating voltage per cavity length, is about 95 kV/m at 1.8003 MHz, 130 kV/m at 0.9000 MHz. Compared with the ferrite-loaded cavities that are used at HIRFL-CSR with about 10 kV/m accelerating gradient, we could clearly see the advantage of the MA-loaded cavity.

4 Simulation of the MA-loaded cavity and the result

We use the code of MICROWAVE STUDIO to simulate the MA-loaded cavity. MICROWAVE

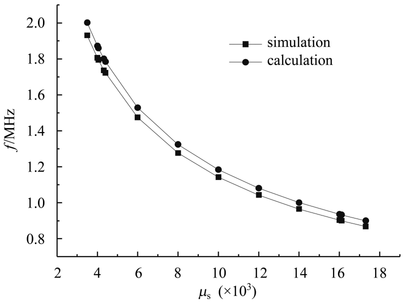

Fig. 4. The resonant frequency of simulation and theoretical calculation dependence of permeability.

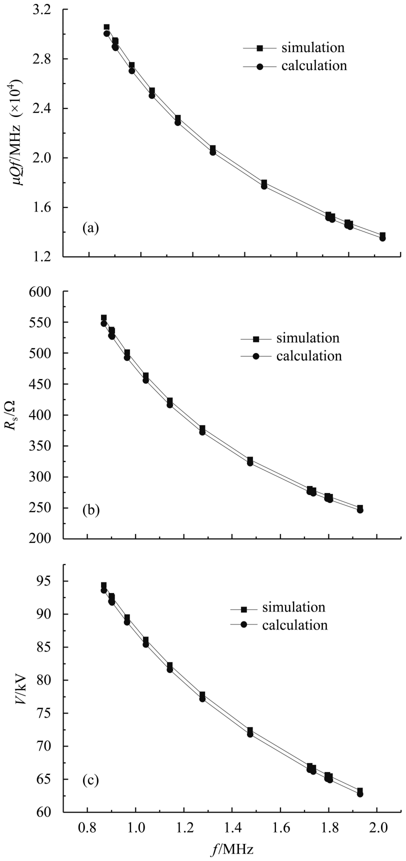

Fig. 5. The μQf value (a), shunt impedance (b) of a MA core and accelerating voltage of cavity (c) dependence of frequency.

STUDIO can be used to simulate the complex 3-dimensional cavity structure and to calculate the cavity resonant modes with high accuracy. Fig. 4 shows the resonant frequency results obtained by simulation and theoretical calculation. From the curve we can see that the resonant frequency of simulation is 1.7366 MHz when the real part of the permeability of the MA core is 4325. Compared with the resonant frequency of 1.8003 MHz from the theoretical calculation, the difference is very small. Meanwhile, the variation in the μQf value, the shunt impedance and the accelerating voltage with the frequency from the theoretical calculation and simulation are shown in Fig. 5.

From Fig. 5 we can see that the MA-loaded cavity has higher a μQf value and a higher shunt impedance, and the accelerating voltage can meet the design requirements well. The results of the simulation and the theoretical calculation are consistent with each other, too. The reason for the very small difference between the simulation and the theoretical calculation is that the Q value is different. This is about 1.2 in the simulation and 1 in the theoretical calculation.

5 Conclusions

From the theoretical calculation and the simulation for the MA-loaded cavity, we got a better result. The MA-loaded cavity had a higher μQf value, a higher shunt impedance and a higher accelerating voltage. The accelerating gradient was about 95 kV/m at 1.8003 MHz and 130 kV/m at 0.9 MHz. Compared with the ferrite-loaded cavities that are used at HIRFL-CSR with about 10 kV/m accelerating gradient, the MA-loaded cavity obviously has an advantage. The results of the theoretical calculation and the simulation are coincident with each other. The calculation results show that the parameters can meet the design requirements.

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