Study of a magnetic alloy-loaded RF cavity for bunch compression at the CSR*

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Abstract The Heavy Ion Research Facility and Cooling Storage Ring (HIRFL-CSR) accelerator in Lanzhou offers a unique possibility for the generation of high density and short pulse heavy ion beams by non-adiabatic bunch compression longitudinally, which is implemented by a fast jump of the RF-voltage amplitude. For this purpose, an RF cavity with high electric field gradient loaded with Magnetic Alloy cores has been developed. The results show that the resonant frequency range of the single-gap RF cavity is from 1.13 MHz to 1.42 MHz, and a maximum RF voltage of 40 kV with a total length of 100 cm can be obtained, which can be used to compress heavy ion beams of $^{238}U^{72+}$ with 250 MeV/u from the initial bunch length of 200 ns to 50 ns with the coaction of the two single-gap RF cavity mentioned above.

Key words magnetic alloy, high permeability, bunch compression, high gradient, broadband cavity

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1 Introduction

Heavy ion beams, which have a short pulse duration with high intensity can be used to concentrate terawatt power on experimental targets to produce dense plasma matter. This is of great scientific interest and can offer a technical solution in the development of inertial confinement fusion. The CSR [1] accelerator facility offers a unique possibility for the generation of such a solid state density plasma. Effective heating with high intensity beams requires a rather short pulse width of 50 ns [2], since the deposition of ion beam power has to take place before the plasma matter starts to expand effectively. However, at present, high intensity heavy ion beams with the required bunch length of about 50 ns are not available at the CSR. It is at about 200 ns for $^{238}U^{72+}$ with 250 MeV/u, which is too long for optimum target response, so the bunch inevitably requires a strong longitudinal compression. Therefore, an additional RF cavity with an RF amplitude of about 80 kV is needed.

In evaluating the RF cavity performance, it is necessary to consider the RF field gradient defined as the RF voltage per unit length. Since the space for the RF cavity in the ring is normally limited [1], it requires that the RF field gradient is increased as much as possible. The RF field gradient of the conventional ferrite-loaded [3] cavity is limited to less than 15 kV/m because of its large nonlinear hysteresis loss at high RF magnetic field. Recently, a kind of met-glass-like material with high-permeable soft magnetic alloy (MA) [4], such as FINEMET [4], METGLAS and the other amorphous types of soft MA, has become available. Development of this kind of RF cavity using these materials has been carried out for the synchrotron at KEK. Compared with ferrite, this kind of material has some advantages [5], such as high complex permeability, where the imaginary part represents the power loss due to hysteresis and eddy current, it can be required to widen the operation frequency range, the high Curie temperature and high saturation flux density are demanded to obtain a high gap voltage. So the MA material will be a good candidate for the bunch compression RF cavity.

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2 Characteristics of high permeable FINEMET

FINEMET [4] is an Fe-based soft magnetic alloy composed of ultra fine grain structure, which was developed by Hitachi Metals, Ltd. Compared with the ferrite, the FINEMET material has the following characteristics.

1) The μQf-value of the FINEMET core remains constant even at a high RF magnetic field of 0.2 T, and the material is easy to cool even at a relatively high effective RF field gradient of 100 kV/m, since the RF power density of 4 W/cm^3 is low enough, and the more interesting characteristics of the FINEMET cores are that the core is completely stable at the high RF magnetic field and, therefore, a high gradient cavity can be realized with the FINEMET core. However, the μQf-value of the ferrite material decreases enormously with an increase in the RF magnetic field.

2) A high Curie temperature, typically 570 ℃ for FINEMET, allows the cavity to operate at a high effective field gradient.

3) Because the intrinsic Q-value of the FINEMET core is less than 1, the stable operating region of the cavity is very wide, so its resonant frequency does not need to be tuned to the frequency of the supplied RF power, and this makes the RF cavity simple and inexpensive.

Thanks to the advantages mentioned above, we selected one of the FINEMET materials FT-1M as the material for the loaded magnetic cores. Table 1 shows some important RF characteristics of the two kinds of MA FT-1M, FT-3M and Ferrite ST-314.

Table 1. A comparison of the magnetic properties of some MA materials and Ni-Zn Ferrite core.

material type	FINEMET		ferrite(Ni-Zn)
	FT-1M	FT-3M	ST-314
permeability(0.4 MHz)	real 3400	real 3000	real 1000
	image 7200	image 6000	image 100
permeability(1 MHz)	real 1500	real 1200	real 1200
	image 3900	image 3000	image 250
permeability(1.8 MHz)	real 840	real 750	real 900
	image 2260	image 1900	image 400
saturation flux density/T	1.35	1.23	0.28
RF power density/(kW/m^3)	350	300	50
curie temperature/℃	570	570	120

From Table 1, we can clearly see that Type FT-1M core has a relative high complex permeability of (3400, 7200) at 0.4 MHz, (1500, 3900) at 1 MHz and (840, 2260) at 1.8 MHz. The saturation flux density of FT-1M is 1.35 T, and the Curie temperature is 570°. The thickness of the FINEMET ribbon is about 20 μm and its surface is covered with a SiO_2 layer for insulation. The packing factor of the FINEMET is about 0.7.

3 Design of RF cavity of bunch compression

A more effective way to produce a short bunch is non-adiabatic bunch compression [6], and it is implemented by fast bunch compression with a 90° rotation in the longitudinal phase space ellipse. The final bunch pulse length is determined by the relation of $l \propto V_{\rm f}^{1/2}$ [7] So to get the expected bunch pulse length, two RF cavities whose total peak voltage amplitude $V_{\rm f}$ of about 80 kV may be needed, or about 40 kV each in a limited space. Moreover, the voltage rise time must be very fast—several times the synchrotron period. With the existing RF cavity, the maximum available total RF voltage is 7 kV at a frequency of about 1 MHz. For this purpose, a small cavity is preferred, making the high-field FINEMET very appealing. The design specifications are summarized in Table 2. The cavity has a single gap structure, which consists of two quarter-wavelength coaxial resonators loaded FT-1M cores. The length of the cavity is 100 mm. The FT-1M core considered here has inner and outer diameters of 30 and 40 cm, respectively, and the core has a thickness of 2.54 cm. If there was only one core, the flux density [8] would be $B_{\rm rf} = V_{\rm rf}/(\omega_{\rm rf} A_{\rm f})$. To limit the dissipation to below the manageable value, at least 4 FT-1M cores are required per cavity. However, the resonance frequency of the RF cavity is hard to decrease to the required value of about 1 MHz, so the total core number of 10 is necessary. According to the shunt impedance [9] per core, $R_s = \mu_0 w \ln(r_o/r_i)\mu Qf$, where $\mu_0 = 4\pi\cdot 10^{-7}$, w, r_o, r_i is the permeability in vacuum, the width of core, the outer radius and the inner radius, respectively, which is determined mainly by the size of the core for the μQf of FT-1M being nearly constant. The resonant frequency range of 1.13–1.42 MHz is enough for the CSR.

Table 2. Design specification of the bunch compression cavity.

parameter	value
resonant frequency/MHz	1.13–1.42
gap voltage/kV	40
cavity impedance/Ω	780–420
cavity length/m	1
cavity outer conductor diameter/m	0.47
cavity inner conductor diameter/m	0.2
gap width/m	0.03
gap number/m	1
core outer diameter/m	0.45
core inner diameter/m	0.3
core width/m	0.025

The cavity has a single accelerating gap structure that consists of two quarter-wavelength coaxial resonators loaded with FINEMET (FT-1M) cores. The length of the cavity is 1m. The diameters of the inner and outer conductors are 0.200 and 0.47 m, respectively. The length of the gap is 0.03 m, the number of FINEMET cores is 10 and the core has an inner diameter of 0.3 m, an outer diameter of 0.45 m and a width of 0.025 m, and the cores are cooled by air. The cavity is coupled to the feeding lines with magnetic loops by multifeed coupling.

The structure of the RF cavity is characterized as an RLC parallel resonant circuit, in which R, L and C correspond to the shunt resistance to represent the total power loss in the cavity, the total inductance of the loaded magnetic cores and the equivalent capacitance of the gap, respectively. The parameters R, L and C are obtained the size and permeability.

Table 3 lists the designed parameters of the equivalent circuit. Fig. 1 and Fig. 2 show the shunt resistance and total inductance dependence of the RF frequency of RF power, respectively. Fig. 3 shows the equivalent capacitance, which is nearly the same at different RF frequencies. Fig. 4 shows the resonant frequency of the cavity dependence of the RF frequency of RF power.

The required resonant frequency ranges between 1.13 MHz to 1.42 MHz. In order to generate the gap voltage, the amplifier should have a bandwidth of 400 kW output power. The impedance matching between the cavity, the feeding line and the power

Table 3. Designed parameters of the equivalent circuit of the bunch compression cavity.

parameter	value			
frequency/MHz	0.4	0.6	0.7	0.9
permeability	(3400,7200)	(2300,5320)	(2160,5000)	(1630–4100)
R/Ω	780	560	530	420
L/μH	26	21	19	17
C/pF		5.33		
F_r/MHz	1.13	1.28	1.32	1.42

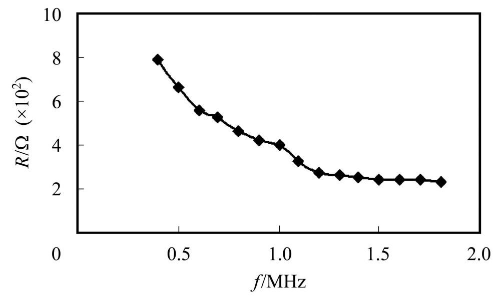

Fig. 1. The shunt impedance dependence of the RF frequency.

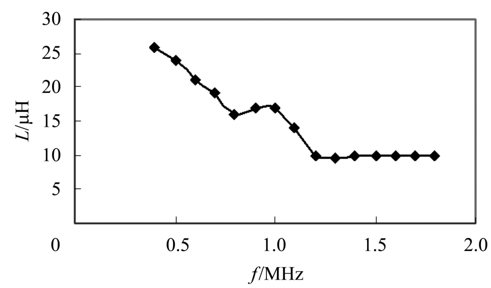

Fig. 2. The total inductance dependence of the RF frequency.

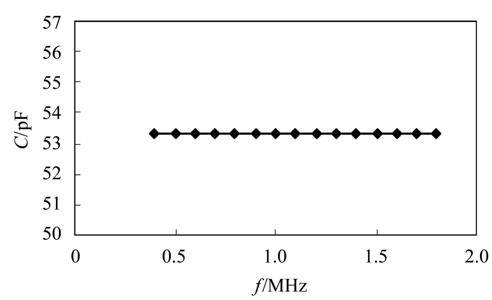

Fig. 3. The capacitance dependence of the RF frequency.

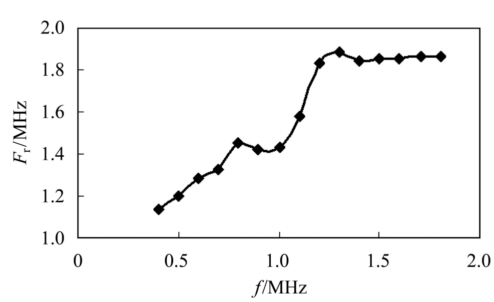

Fig. 4. The resonant frequency dependence of the RF frequency.

source is indispensable to produce a high voltage at the gap. The impedances of the power source and the feeding line are 50 Ω, the cavity impedance to be designed as about 420–780 Ω to moderate the dissipated RF power, 42–78 Ω per core, so multifeed coupling has been adopted to realize the impedance matching between the cavity and the feeding line. Fig. 5 shows the means of multifeed coupling. In mutifeed coupling, the RF power is first split into the same number of loaded FINEMET cores by the power splitter and then each of them is fed into the cavity through the one-turn coil, which is wound on each FINEMET core. Compared with traditional a RF cavity loaded with ferrite, the properties of the RF cavity loaded with FT-1M are listed in Table 4.

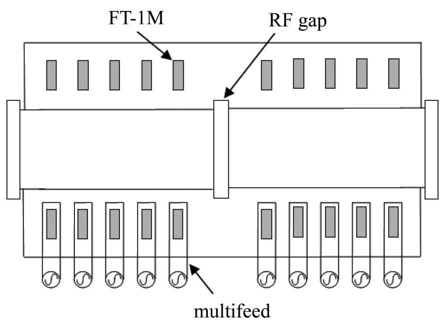

Fig. 5. The means of coupling.

Table 4. Comparison of the bunch compression cavity loaded with FT-1M and the accelerating cavity loaded with ferrite.

parameter	bunch compression	accelerating
cavity length/m	3	1
operation frequency/MHz	0.24–1.81	1.13–1.42
gap peak voltage/kV	7	40
beam pulse duration/ns	CW	50
peak power/kW	20	400
shunt impedance/Ω	2(0.45 MHz)	660(1.13 MHz)

4 Conclusion and perspective

A new type of RF cavity using a highly permeable MA FINEMET (FT-1M) core has been studied and simulated with Computer Simulation Technology (CST). The cavity has many advantages and is suitable for heavy ion bunch compression because of the low Q-value. Moreover, the MA FT-1M core has the maximum allowable RF magnetic flux of more than 2 kG, which can result in a large RF field gradient of more than 40 kV/m, and make the cavity highly stable for the RF voltage. For the compression of 100% of the beam particles down to a pulse duration of 50 ns, a total RF-voltage of 80 kV is required. This voltage must be produced rapidly in about a quarter of the synchrotron period. We expect to achieve the beam and target parameters with the help of the high current injector and the new bunch compressor cavity.

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