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Simulation of higher order modes and loss factor of a new type of 500-MHz single cell superconducting cavity at SSRF

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Abstract In this paper, higher order modes (HOMs) and loss factor of a new type of 500-MHz superconducting cavity is studied, by simulating its broadband HOMs damping at different positions of the ferrite HOM-absorber and different lengths of the ferrite. The results show that the impedance and *Q* value of the HOMs in transverse and longitudinal modes could be greatly reduced. The HOM longitudinal impedance could be damped to meet the requirement of SSRF beam instability threshold. The calculated loss factor of the new SC cavity was compared with cavities at SSRF. It was estimated that the HOM absorber could absorb a total power of 3.16 kW at 4-mm beam bunch length.

Key words Superconducting RF, HOM absorber, Loss factor

1 Introduction

A new type of 500-MHz single cell superconducting cavity is being designed at SINAP. The cavity has a fluted beam pipe for higher order modes (HOMs) damping, and a coaxial coupler for power input. Specifications of the cavity include: frequency, 499.65 MHz; the ratio of shunt impedance and quality factor r/*Q*, 90.5 Ω; the radio of peak surface electric field and accelerating electric field, Ep/Eacc, 2.35; the radio of peak surface magnetic field and accelerating electric field, Hp/Eacc, 49.5 Oe·MV^{-1}·m, loss factor of fundamental mode of the cavity TM_{010}, 0.071 V/pC; and external *Q*, 1.2×10^5. A fluted beam pipe identical to that of CESR (Cornell Electron Storage Ring) type cavity will be adopted to propagate out almost all the HOMs from the cavity. The HOM absorbers, which are integral parts of the superconducting cavity, are located outside the cryostat and will be equipped at both sides of the cavity to absorb most of the HOMs power at room temperature.

2 Simulations of HOMs damping

Minimizing impedance of a superconducting cavity is a key issue to avoid the beam instabilities. To damp HOMs of the cavity, optimizing the HOM absorber is an effective way. Different simulation codes such as SEAFISH and CST (Computer Simulation Technology) have been adopted to optimize the sizes and locations of the absorbers.

2.1 Optimization of the fluted beam tube HOM absorber

The fluted beam pipe is not of an axi-symmetrical geometry, the 3D computer code of CST is used to calculate the *Q* value of the cavity. TM_{011}, the first monopole higher mode; and TE_{111} mode, the lowest dipole mode, are considered as the most dangerous power generation mode because of their high impedance, and finding their positions of the maximum electromagnetic field is a key task.

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To decide the HOM absorber position at the fluted beam pipe side, the electric fields of the TM_{011} and TE_{111} modes along the beam pipe are calculated by CST. For good damping of HOMs power, the absorber should be placed around where the maximum electric field exits. As shown in Fig.1, where the abscissa is the distance from the cell, the maximum electric field is around 450 mm and 500 mm for the TE_{111} and TM_{011} modes, respectively. For a compromise, the HOM absorber can be 100 mm in length and located 470 mm away from the cell, where a maximum HOMs power absorption shall be the most effective, and where reduction of electromagnetic field for a fundamental mode of the cavity is just 1%, so the absorber effect on the fundamental mode is negligible.

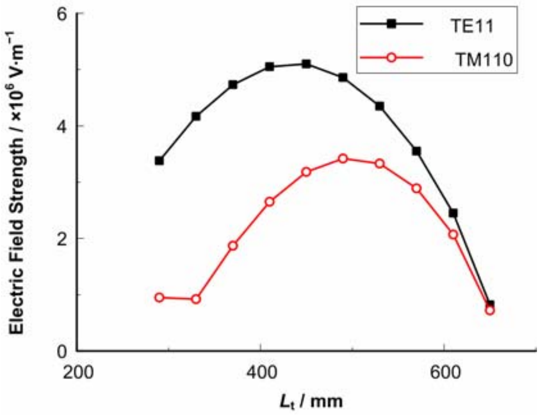

Fig.1 Electric field of the TM_{011} and TE_{111} along the FBT.

2.2 Optimization of the round beam tube HOM absorber

To design the round beam pipe side, the SEAFISH code is adopted to calculate Q value of the higher monopole modes, and to model the cavity with HOM absorber. The ferrites are accommodated in SEAFISH by using a complex of permittivity ε and the permeability μ reported by J.Mouris *et al.*[1] The dependencies of location, ferrite length and thickness on Q value are calculated on the TM_{011} mode, which is the most dangerous mode that can propagate from the cavity. When the cavity without fluted beam pipe is simulated by SEAFISH, the TE_{111} is trapped in the cavity. Fig.2 shows the results.

From Fig.2a, the Q ascend slowly followed by the distance from the HOM absorber to the cell (L_t), and from Fig.2(b) the Q value changes little when ferrite length (L_f) reaches 100 mm. Thus the ferrites length is chosen as 100 mm. And it is decided that the position of the HOM absorber is also 470 mm away from the cell.

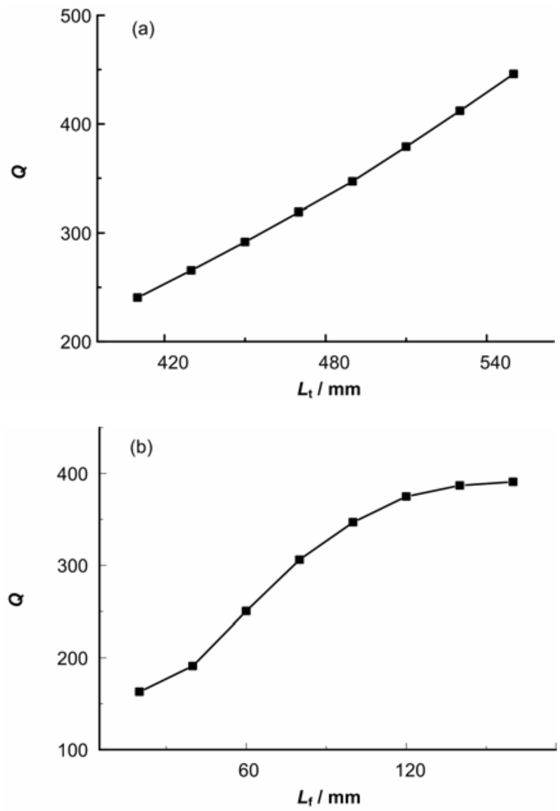

Fig.2 Q as function of the distance from HOM absorber to the cell (L_t) (a) and Q as the function of the ferrite length (L_f) (b).

2.3 Threshold of the multi-bunch instability

To verify the HOM absorber design, impedance and Q value of the HOM from 0. 6 GHz to 1.2 GHz is calculated using the CST code. The results shown in Fig 3 indicate that most of Q values can be damped to 1000 including transverse modes and longitudinal modes. These are well below the threshold of SSRF beam instability[2].

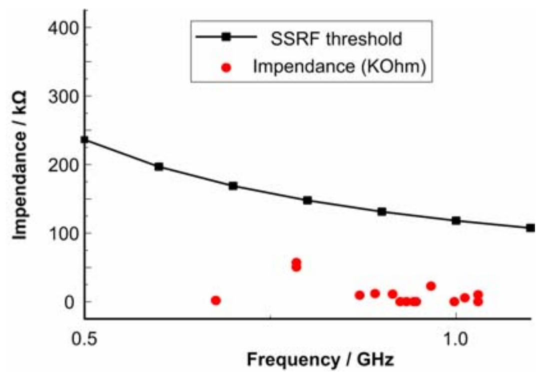

Fig.3 Threshold of longitudinal multi-bunch instability and shunt impedance of the modes for SSRF.

3 Loss factor

Loss factor is the energy lost when a unit charge goes through a structure, which is important in estimating energy lost of the superconducting cavities. Major contributors to the total loss factor of the structure are the cavity cell, the fluted beam pipe, the tapers, and HOM absorbers.

3.1 Cavity cell and Tapers

The loss factor of the new type of SC cavity is calculated by the ABCI code. The coupler, gate valves, fluted beam pipe and HOM absorbers are not taken into account in the calculations, except the tapers. From Ref.[3], the loss factor of coupler and gate valves is negligibly small. The loss factor of the fluted beam pipe and HOM absorbers is calculated separately. The calculated loss factors of the cavity with taper are shown in Fig.4.

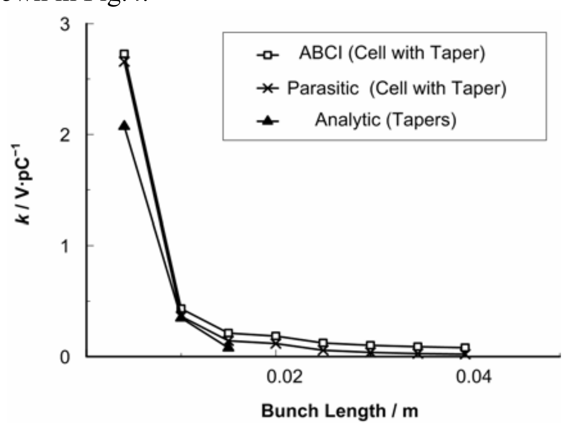

Fig.4 Loss factors of new type of cavity cell with tapers.

For taper contribution to the total loss factor,. Heifets *et al.*[4] derived a formula for two symmetric tapers:

$$k_{\text{tapers}} = \frac{1}{4\pi\sqrt{\pi}\varepsilon_0\sigma}(1-\eta_1)\ln\frac{b}{a}$$

$$\eta_1 = \min(1, \frac{g_1\sigma}{(b-a)^2}) \qquad (1)$$

where, a is the smaller radius, a=30 mm for taper 1, and a=50 mm for taper 2; b is the larger radius, b=120 mm for taper1 and taper 2; and g_1 is the taper length, g_1=450 mm for taper1 and g_1=420 mm for taper2. Eq.(1) is valid for $\sigma<<a<b$. In practice, we can use it for bunches shorter than 16 mm.

From Fig.4, loss factor for the tapers dominates over loss factor of cavity cell for a bunch length of <10 mm. Comparing results of loss factor for the 500-MHz cavity and main cavity transition for a 4-mm bunch length, ion the longitudinal impedance contribution to loss factor of the two tapers of different angles (k_{tapers}=2.07 V/pC) is much larger than cavity itself contributes (k_{cell}=0.97 V/pC) to the longitudinal impedance.

To get parasitic loss factor one can subtract the loss factor of the fundamental mode

$$k_{\text{fund}} = [\omega_{\text{fund}}(R/Q)_{\text{fund}}/4]\ \exp(-\omega^2_{\text{fund}}\sigma^2/c^2) \qquad (2)$$

where ω_{fund}=2π×499.654 MHz is the resonant angular frequency of the fundamental mode, σ is the bunch length, and $(R/Q)_{\text{fund}}$ is the specific impedance of the fundamental mode.

3.2 Fluted beam pipe

A beam tube of special fluted cross-section is used in the new SC cavity to allow the lowest dipole HOMs to propagate toward the ferrite load. Because the fluted beam tube is 3D geometry, a 3D computer code is used to calculate the loss factor. Fig.5 shows the result of the calculation.

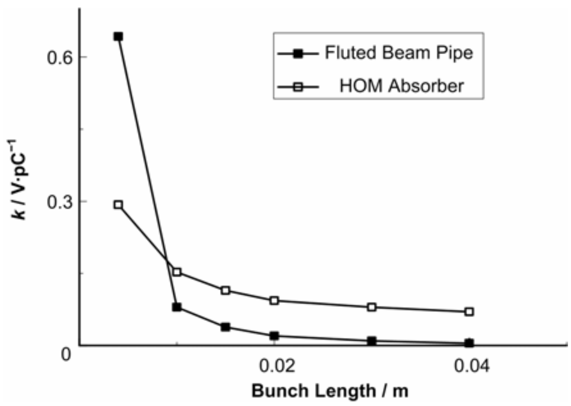

Fig.5 Loss factor of the fluted beam pipe and HOM absorber.

3.3 HOM absorber

Loss factor of the ferrite HOM absorber is calculated with AMOS[6]. An empirical formula for this case is

$$k_{\text{HOMload}} = 0.7834\sigma^{0.7102} \qquad (4)$$

where k_{HOMload} is the loss factor in V/pC, σ is the bunch length in mm. The bunch lengths of the HOM load loss factor are shown in Fig.5.

3.4 Loss factor compared with SSRF cavity

There are three 500 MHz superconducting RF cavities in the SSRF storage ring and the beam tests were carried out. The loss factor was measured by calculating the heat transferred to the cooling water. We measured the temperature of the inlet and outlet cooling water for FBT and RBT HOM absorber along with the water flow rate. The power transferred from the ferrite HOM absorber to the cooling water should be equal to the power lost by the beam due to its interaction with the cavity. The power loss can be expressed by equation (6).

$$P_{\text{loss}} = \sum_{1}^{n} V_f^i C\rho(T_{\text{out}}^i - T_{\text{in}}^i) \qquad (6)$$

where, V_{f} is water flow rate, ρ is water density, T_{out} and T_{in} are exit and entrance temperatures of the cooling water.

The loss factor can be given by

$$k = NP_{\text{loss}}/(I_{\text{beam}}T_{\text{c}}) \qquad (7)$$

where I_{beam} is the beam current, T_{c} is the revolution time, and N is number of beam bunches, P_{loss} is the HOM power.

The loss factors predicted and measured are shown in Fig.6. As one can see, the loss factor measured at a bunch length of 4 mm is 2.08 V/pC, which is a 36.5% reduction to the prediction data. The HOMs with resonant frequencies above the cutoff frequencies of the FBT end beam pipe (2.29 GHz) and the RBT end beam pipe (3.81 GHz) propagate from the cavity structure, so their energy could be dissipated in the FBT and RBT end beam pipe.

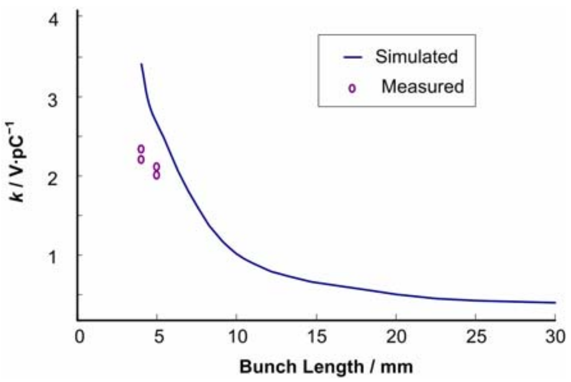

Fig.6 Simulated and measured loss factors of the SSRF cavity.

Comparing the loss factor of the SSRF cavity and the new cavity, which is shown in Fig.7, it can be seen the loss factor the new cavity is close to that of SSRF cavities.

If the new type of cavity is used in SSRF, the HOM power calculated for the structure with ferrite at 4-mm bunch length, 150 bunch number and 300 mA beam current will be 3.16 kW.

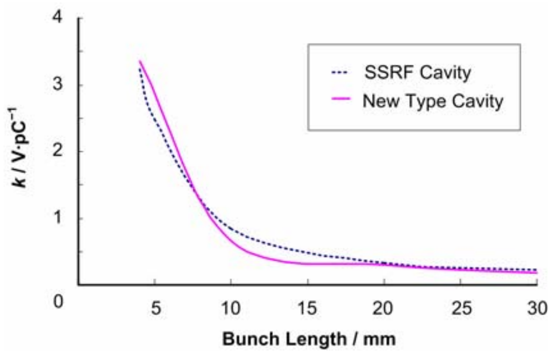

Fig.7 Loss factor of SSRF cavity and the new type of cavity.

4 Conclusion

After the optimization for the HOM damping of the new type of SC cavity, two absorbers, 100 mm in length, 3 mm in thickness and 470 mm away from cavity cell have been considered preliminarily and decided. The loss factor of the new type of SC cavity is estimated numerically using ABCI and CST. And the HOM power need to be absorbed has been estimated.

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