Design of large aperture 500 MHz 5-cell superconducting cavity

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Abstract With the potential application of Energy Recovery Linac (ERL), the superconducting (SC) cavities were developed to deliver much higher current than before. Nowadays, the current of the international SC accelerator designed has already exceeded 100 mA. This paper presents the design of a new 500 MHz 5-cell SC cavity (SINAP 5-cell cavity), in which the parameters r/Q= 515.5 Ω of the fundamental mode and the geometry factor G=275.8 are under an acceptable Radio Frequency (RF) field level (B_{peak}/E_{acc}=4.31 mT/MV/m and E_{peak}/E_{acc}=2.48). This design employs a larger beam pipe to propagate the Higher Order Modes (HOMs) out of the cavity and increases the damping efficiently for the dangerous HOMs. By simulation technique, it has been found that almost all the dangerous HOMs (including TE_{111}, TM_{110}, and TM_{011}) can be propagated into the beam pipe and are absorbed by ferrite absorbers, when the beam pile is enlarged. Finally, the loss factor for the new 5-cell cavity is also calculated.

Key words High current, Superconducting cavity (SC), HOMs, Loss factor

1 Introduction

In recent years, Superconducting (SC) Radio Frequency (RF) technology is becoming popular for high average current Energy Recovery Linac (ERL). The multi-cell SC cavity has advantage to damp the strong HOMs in high current ERL except achieving higher accelerating fields in a single module as well as reducing the construction space of accelerator. Therefore, it is a potential candidate to deliver much higher current than before, even in ampere class in ERL. Nowadays there are some existing multi-cell SC cavities for high current ERL. For example: with the simulated beam of 1.3 GHz, 9-cell SC cavity designed by KEK can achieve current of 600mA in the 5 GeV ERL model[1]. With the beam of 748.5 MHz, 5-cell JLab SC cavity can reach ampere class in the 60 MeV ERL model[2].

With the physics point of view, the longitudinal HOMs loss factor and the resonance frequency is inversely proportional to the size of the aperture of beam pipe. It indicates that a lower frequency can allow a possibility of a large aperture, which can not only reduce the HOMs power deposited by the beam, but, can also raise the threshold current for the onset of multi-bunch instabilities. Therefore, frequency of 500 MHz was chosen to be the fundamental resonance frequency instead of L-band or 700 MHz frequency.

Owing to large HOMs power and multi-bunch effects that limited the maximum achievable current, high current multi-cell cavity should have strong HOMs damping. The problem is that, with increase in the number of cells, the electromagnetic fields in the end cells and beam pipe gradually decrease, which make the HOMs unable to extract and damp[3]. Therefore, five cells were chosen to be an optimum number to achieve effective HOMs damping.

Hence the larger aperture 500 MHz 5-cell SC cavity would be a strong potential candidate in the near future to achieve higher current ERL.

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2 Cavity Design

The SINAP 500 MHz 5-cell cavity was optimized to minimize the B_{peak}/E_{acc} and E_{peak}/E_{acc} and to maximize the $(r/Q)*G$ for the fundamental mode. The parameters for optimizing the cavity geometry are listed in Table 1. The equator outline of inner cell is started with a vertical wall joining an arc towards a "low loss" concept (higher $r/Q*G$)[4] , as shown in Fig.1. The half length of the cavity gap was usually $L = \beta\lambda/4=\beta c/4f$ =150 mm (where λ is the fundamental wavelength, f is fundamental resonance frequency, β is electron beam velocity and c is the speed of light in vacuum). A large iris radius of R_{iris}=105 mm was chosen to increase the cell-to-cell coupling factor[5] (k_{cc}=3.18%) and to keep the r/Q in an acceptable level. The beam tube radius was selected 160 mm to allow propagation of dangerous HOMs out of the enlarged beam tube. Meanwhile, the end-cell shape was exactly same as that of the inner-cell. However, the end-cells were trimmed at equator (shorter by 2.1% of the fundamental wavelength) to attain a flat field profile along the cavity, which was calculated to be 98.8%, as shown in Figs.3 and 4. Therefore, the SINAP 5-cell cavity could be formed only using one set of dies to reduce the mechanical complexity. In addition, the transition between the end cell and beam pipe was also schematically shown in Fig.2.

In Table 2, the fundamental mode RF parameters of new 5-cell cavity are compared with BNLIII and JLab. It is evident that the new 5-cell cavity is showing great performance in both B_{peak}/E_{acc} or E_{peak}/E_{acc} and $(r/Q)*G$.

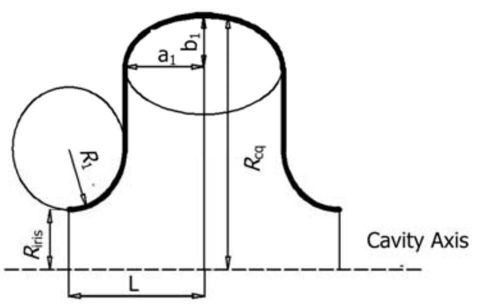

Fig.1 Inner cell shape for the SINAP 500 MHz 5-cell cavity.

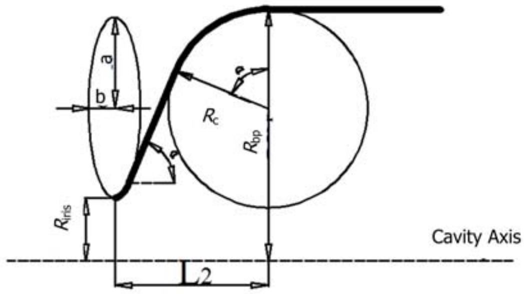

Fig.2 Transition shape for the SINAP 500 MHz 5-cell cavity.

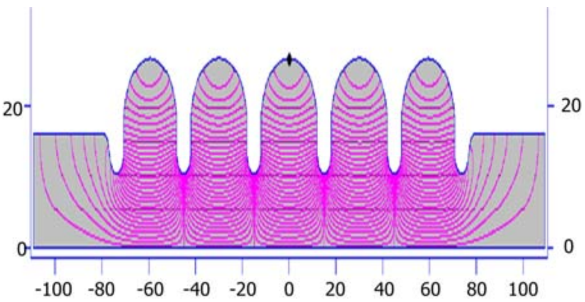

Fig.3 The model of SINAP 500 MHz 5-cell cavity by Superfish.

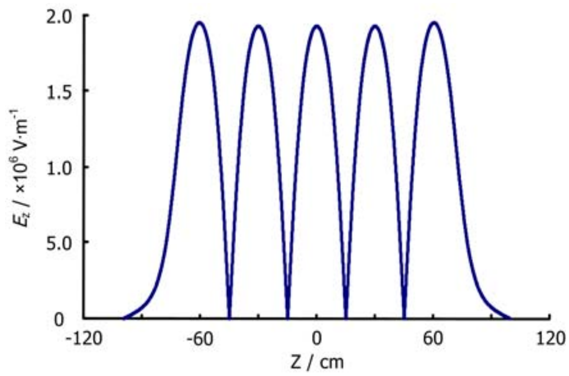

Fig.4 Field flatness of the SINAP 500 MHz 5-cell cavity by Superfish 98.8% at low Loss Superconducting Cavity.

Table 1 Final optimized geometry parameters of the SINAP 500 MHz 5-cell cavity (units: mm)

Inner cell	Transition
a_1=120	a=30
b_1=89.30	b=30
R_1=30	angle α=700
L_1=a_1+R_1=150	Rc=25.35
R_{iris}=105	R_{iris}=105
R_{eq}=264.26	R_{bp}=160

Table 2 Compares RF parameters of the SINAP 500 MHz 5-cell cavity with BNLⅢ and JLab

Parameters	BNLⅢ	JLab	SINAP 5-cell cavity
Frequency[MHz]	703.79	748.5	499.65
beta	1	1	1
Cells number	5	5	5
Geometry factor *G*	283	276	275.8
r/Q*[Ω]	506.3	525	515.5
E_{peak}/E_{acc}*(void)(**)	2.46	2.50	2.48
B_{peak}/E_{acc}*[$mT/MV/m$]	4.27	4.27	4.31
Longitudinal Loss Factor***[V/pC]	3.60	4.82	3.48
Coupling factor[%]	3.02	3.26	3.18
R_{iris}	72/78	70	105
R_{bp}	110	70	160

*Calculated using SUPERFISH. Here r/Q is effective characteristic impedance and E_{acc} is the average effective accelerating field.

**The value of E_{peak}/E_{acc}, B_{peak}/E_{acc} is calculated with c-length (cavity length for normalization, which is 1474.8 mm in SUPERFISH).

***Calculated by ASCI with σ_z=2 mm.

3 Higher Order Modes

The complex structures of 5-cell cavities could often lead to large power loss into the HOMs excited by the beam and in some cases can break-up the beam[6]. Hence, it is essential to study the behavior of HOMs during their transportation out of the cavity and further, ensure that they are damped sufficiently.

Mainly, the two schemes[7] were applied in transporting and damping HOMs. Firstly, a larger beam pipe is employed to transport the HOMs out of the cavity, which would be absorbed completely by RF absorbers on the enlarged beam pipe. Secondly, HOMs can also be transported out of cavity by using electric field probes through coaxial transmission line or waveguide and finally, they can be damped at room temperature. In this work, the former scheme is adopted to damp HOMs by keeping the r/Q of fundamental mode in an acceptable level. In fact, the beam pipe could be seen as a high pass filter and HOMs can be propagated to a load outside the cryogenic environment. Ferrite absorbers are used to absorb large HOMs power and to reach effective broadband damping. At room temperature (300 K), these absorbers were placed on the end of beam pipe to minimize cryogenic losses. Further the study will be carried out on the design of HOMs absorbers. This will help to decide the various parameters for absorbers such as the location, and the size etc.

Using Computer Simulation Technology (CST), the frequency was set from 0.5 GHz to 1.2 GHz. The three modes TE_{111}, TM_{110} and TM_{011} were found the main dangerous HOMs in the cavity with reference to their cutoff frequencies. The detail is shown in Tables 3 and 4. Because of the beam hole, the TM_{110} cavity mode is partially like TE_{111}. For that reason, both the trapped modes (TM_{110} and TE_{111}) are coupled to the beam pipe via the TE_{11} waveguide mode. This will help them to propagate into the beam pipe including TM_{011} mode. Finally, they are absorbed completely by RF absorbers on the enlarged beam pipe. Further, from the Tables3 and 4, it is clear that TE_{011} and TE_{211} need not to be transported into the beam pipe,, because of their small r/Q. Even if they propagate, they seldom have an influence on the current of electron beam.

Therefore, damping the most harmful HOMs (TE_{111}, TM_{110} and TM_{011}) was got by using the larger beam pipe and ferrite absorbers on the enlarged beam pipe.

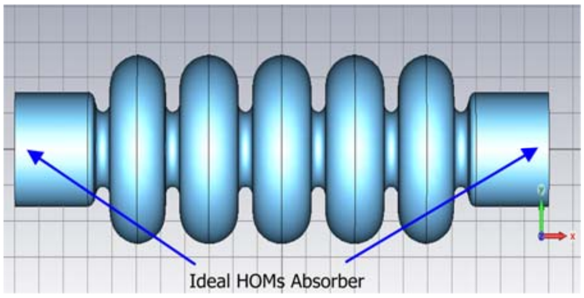

Fig.5 The 3D model for HOMs calculation.

Table 3 Parameters of some lowest harmful modes

Modes (lowest)	Frequency / MHz	r/Q* / Ω
TE111	582.748	0.088
TM110	718.611	39.809
TM011	858.23	0.091
TE011	933.125	1.008e-9
TE211	845.456	4.625e-6

*Calculated by CST when deviate from the axis of 10 mm

Table 4 Cutoff frequency for TE_{11}, TM_{11} TM_{01}, TE_{01} and TE_{21} mode in the beam pipe (R_{bp}=160 mm).

Modes (lowest)	Cutoff frequency / MHz
TE11	549.383
TM11	1143.528
TM01	717.689
TE01	1143.528
TE21	911.361

4 Longitudinal loss factor

When an electron bunch passed through a cavity structure, the energy change ($\triangle\varepsilon$) was found the function of its charge q and of the induced voltage V=-$Z_{//}I_b$. The voltage was proportional to the current I_b=$q\omega_0/2\pi$. The relation can be expressed as:

$$\Delta\varepsilon = -k_{//}q^2 \tag{4}$$

where $k_{//}$ is called the longitudinal loss factor. In this frequency domain, the loss factor is given by the integral over the product of the impedance $Z_{//}(\omega)$ and the power density of the particle distribution $h(\omega)=\lambda(\omega)\lambda^*(\omega)$.The loss factor could be given as[8]

$$k_{//}(\sigma) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} dw Z_{//}(w)h(w,\sigma) \tag{5}$$

In Fig.6 the integrated loss factor for SINAP 5-cell cavity is displayed as a function of frequency for a Gaussian bunch of 2 mm length. The integrated loss factor is calculated by ABCI code[8], which is found to be $k_{//}$= 3.48 V/pC.

$$P_{\mathrm{loss}} = \frac{I_{\mathrm{beam}}{}^2 \times t_{\mathrm{c}} \times k_{//}}{N} \tag{6}$$

where, I_{beam} is the beam current, t_c is the revolution time, N is number of the beam bunches. The P_{loss} is the HOMs power loss, which from the simulation results is found to be less for the SINAP 5-cell cavity.

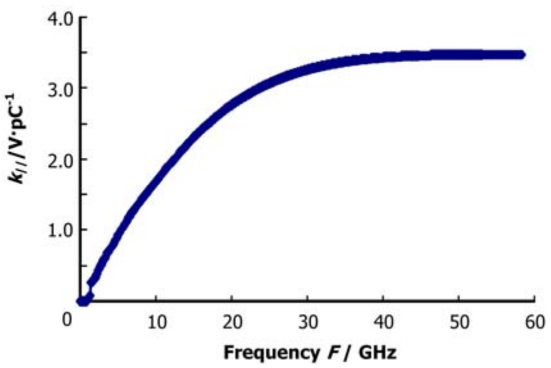

Fig.6 Integrated loss factor for Dipole modes of the SINAP 500 MHz 5-cell cavity (σ_z=2 mm).

5 Conclusion

Based on the simulation results in SINAP 500 MHz 5-cell cavity, it is found that it can meet the requirements of a higher accelerating current gradient, low surface field ($B_{\mathrm{peak}}/E_{\mathrm{acc}}$ and $E_{\mathrm{peak}}/E_{\mathrm{acc}}$), but, high $(r/Q)G$. A large iris radius of R_{iris}=105 mm was chosen to increase the cell-to-cell coupling. The r/Q is being kept in an acceptable level. The most harmful HOMs, such as TE_{111}, TM_{110} and TM_{011} are propagated out of the cavity through the enlarged beam pipe. The study also shows that all the simulations results are in good agreement with the required specifications.

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