CPC(HEP & NP), 2009, **33**(1): 74—76 **Chinese Physics C** Vol. 33, No. 1, Jan., 2009

Study on the RF performance of 2-cell superconducting cavity*

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Abstract The physical design of the 2-cell superconducting cavity is presented. The RF parameters of the cavity and HOMs (high order modes) are reported. In this paper, we put the emphasis on the analysis of the HOMs and interaction between beam and cavity.

Key words 2-cell superconducting cavity, HOM, loss factor, interaction

PACS 29.20.Ej, 29.25.Bx

1 Physical design of the 2-cell cavity

The RF design of a superconducting elliptical cavity requires a trade-off in optimization of the cell shape between the region of high electric field and the region of high magnetic field. There are three main types of elliptical cavity shape for electron acceleration, which are TESLA cavity, low loss cavity and reentrant cavity. Table 1 lists the inner cell parameters for TESLA, the reentrant cavity fabricated at Cornell, and a proposed low loss cavity for the International Linear Collider[1]. It is a challenge to clean the reentrant cavity because the liquids become trapped in reentrant portion when it is vertically hung during high pressure rinsing. The main advantage of the low loss shape is potentially low cryogenic loss and there are still some improvements to do with it[2].

Table 1. Inner cell parameters for three cavity designs.

	TESLA	Cornell reentrant	low loss for ILC
frequency/MHz	1300	1300	1300
$E_{\text{peak}}/E_{\text{acc}}$(-)	2	2.4	2.36
$B_{\text{peak}}/E_{\text{acc}}\left(\frac{\text{mT}}{\text{mV/m}}\right)$	4.26	3.78	3.61
$(R/Q)/\Omega$	115	121	134
$(R/Q)*G/\Omega^2$	31050	33768	37970
k_{cc}(%)	1.87	2.38	1.52

The TESLA cavity[3] is adopted and the 2-cell superconducting cavity consists of two end half cells and two middle cells. In order to reduce the dies in the fabrication with the deep drawing technique, either the long end cup or the short end cup can be used. For this 2-cell cavity there is little difference in performance. Here two long half cells are used, as show in Fig. 1.

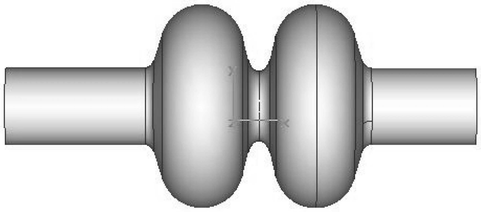

Fig. 1. 2-cell SC cavity.

2 RF parameters of the cavity

The cavity is about half meter including the beam tube whose fundamental TM mode has a frequency of about 1300 MHz. It is bathed-cooled by super fluid helium at 2 K. The important cavity parameters are listed in Table 2.

Among those RF parameters, the total longitudinal loss factor $k_{||}$ and transverse loss factor $k_{\perp}$ are from ABCI[4] simulation, all the others are from Superfish.

Received 14 March 2008

* Supported by National Natural Science Foundation of China (10276001)

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Table 2. Parameters of the 2-cell cavity.

type of accelerating structure	standing wave
accelerating mode	TM_{010}, π-mode
fundamental frequency	1300 MHz
quality factor Q_0	1.63×10^{10}
active length L	229.4 mm
cell-to-cell coupling k_{cc}	1.03%
effective shunt impedance R/Q_0	216 Ω
transit-time factor	0.624
total longitudinal loss factor $k_{\|\|}(\sigma_z^*=3.6$ mm)	1.468 V/pC
transverse loss factor $k_\perp(\sigma_z=3.6$ mm)	0.19 V/pC/cm^2

$*\sigma_z$ is the standard deviation length of the bunch.

3 High order modes

The TM_{010} π-mode can accelerate electron bunches; and the electron bunches passing through the cavity excite the eigenmodes of higher frequency which are HOMs. They should be damped to avoid multibunch instabilities and beam breakup. Especially in superconducting cavity, HOMs also increase the cryogenic losses due to the additional power in the cavity walls[4]. Here Microwave Studio is used to simulation the HOMs, the results of HOMs and fundamental modes below 3 GHz are shown in Table 3.

Table 3. High order modes of the 2-cell cavity.

model	model	$Q_0(10^4)$	$(R/Q_0)/\Omega$	F/GHz
M1	TM_{010}^{+}	2.881	0.010	1.289
M2	TM_{010}	2.881	216	1.302
M3	TE_{111}^{+}	2.184	1.297	1.636
M4	TE_{111}^{+*}	2.203	1.297	1.636
M5	TE_{111}	2.924	2.520	1.724
M6	TE_{111}^{*}	2.906	2.520	1.724
M7	TM_{110}^{+}	2.521	4.159	1.814
M8	TM_{110}^{+*}	2.499	4.159	1.814
M9	TM_{110}	3.373	1.784	1.881
M10	TM_{110}^{*}	3.366	1.784	1.881
M11	TE_{211}^{+}	2.957	0.038	2.284
M12	TE_{211}^{+*}	3.297	0.038	2.285
M13	TE_{211}	3.214	0.018	2.307
M14	TE_{211}^{*}	3.454	0.018	2.308
M15	TM_{011}^{+}	2.964	6.763	2.396
M16	TM_{011}	2.940	58.151	2.441
M17	TM_{210}^{+}	3.104	0.004	2.466
M18	TM_{210}^{+*}	2.963	0.004	2.468
M19	TM_{210}	3.373	0.039	2.479
M20	TM_{210}^{*}	3.273	0.039	2.481
M21	TE_{011}^{+}	5.417	2.377×10^{-12}	2.484
M22	TE_{011}	5.387	9.8×10^{-13}	2.502
M23	TM_{020}^{+}	3.868	0.295	2.680
M24	TM_{020}	3.723	1.490	2.733
M25	TE_{311}^{+}	2.910	1.26×10^{-4}	2.770
M26	TE_{311}^{+*}	2.857	1.28×10^{-4}	2.770
M27	TE_{311}	3.184	4.95×10^{-5}	2.790
M28	TE_{311}^{*}	3.193	5.59×10^{-5}	2.790

Superscript + denotes the π/2 mode in the passband and $*$ means the other polarization of the mode. For some modes, the electric field along the beam centre axis is almost zero, so the voltage is 0. Here we integrate the electric field along the axis 10 mm away from the beam centre and get the accelerating Voltage V_c^*, and the effective shunt impedance is $\left(\dfrac{R}{Q_0}\right)^* = \dfrac{V_c^{*2}}{\omega U}$, where ω is the angular frequency of the mode, U is the stored energy.

3D modeling data for the 2-cell cavity show that there is high R/Q_0 for TE_{111}, TM_{110}, TM_{011} and TM_{020}, which are harmful to the beam. TM_{011} and TM_{020} cause energy spread of the beam, TE_{111} and TM_{110} deflecting the beam cause emittance growth; more details are in the following. In superconducting cavities, the unloaded quality factors of the HOMs are typically 10^9 and must be appropriately damped by HOM couplers.

4 Loss factor

Loss factor of individual modes can be calculated from the individual R/Q_0, and for the total loss factor of an axially symmetric structure ABCI can be used. Table 4 is the results of the 2-cell cavity with ABCI, a bunch of Gaussian profile and length σ_z is used.

Table 4. Loss factor of the 2-cell cavity.

σ_z/mm	$k_{\|\|}$/(V/pC)	$k_\perp$/(V/pC/cm^2)
1	3.39	0.47
2	2.11	0.29
3.6	1.47	0.19
3	1.64	0.22
4	1.38	0.18
5	1.21	0.15
6	1.09	0.13

This 2-cell cavity is used for the beam with the repetition frequency of 54.17 MHz, the average current is 10 mA and the rms bunch length is 3.6 mm. Using these, we make a rough estimation that the HOM-induced power is 1.89 W, which is much higher than the RF dissipation in the fundamental mode 0.82 W. The estimation is coincidental with the result in Ref. [5].

5 Instabilities from beam cavity interaction

Beam-cavity interaction limits the beam quality in linear accelerator. The longitudinal instabilities are induced when the beam interacts with monopole higher-order modes, and the transverse ones are induced when the beam interacts with the deflecting (chiefly dipole) modes[6].

A variation of the longitudinal wakefield across the bunch causes varying energy loss, thereby introducing harmful energy spread. A rough estimation for the wakefields-induced energy spread is[4]

$$\frac{\delta E_{\mathrm{b}}}{E_{\mathrm{b}}}=\frac{2qk_{||}}{E_{\mathrm{acc}}}\ , \tag{1}$$

Here E_{b} is the beam energy, q the total charge of the bunch, $k_{||}$ is the total structure loss factor in V/pC/cm and E_{acc} the average accelerating electric field. For this 2-cell superconducting cavity, $k_{||}$ is 0.064 V/pC/cm.

The transverse wakes deflect the tail of the bunch, causing emittance growth and beam halo. In analogy to the longitudinal loss factor, the total transverse loss factor $k_{\perp}$ is also determined from ABCI. If the head and the tail in a simple two-particle model of the beam are separated by $2\sigma_z$, the relative displacement of the tail with respect to the head is roughly[7]

$$\frac{\Delta x}{x}=\frac{eNk_{\perp}}{2E_{\mathrm{acc}}}\langle\beta\rangle\ln\left(\frac{E_{\mathrm{bf}}}{E_{\mathrm{bo}}}\right), \tag{2}$$

here Δx is the displacement of the tail of the bunch, x is the displacement of the head, N is the number of particles per bunch, $k_{\perp}$ 0.19 V/pC/cm^2 is the total dipole loss factor. E_{b0} is the injection energy, E_{bf} is the final energy, and $\langle\beta\rangle$ is the average focusing strength along the linac.

Both the energy and emittance growth can be substantially improved over the estimation by choosing the proper arrival phase of the bunch as well as by choosing a good focusing lattice for the linac[8].

6 Conclusion

A 2-cell superconducting cavity has been designed in PKU. The RF parameters show that the cavity has a good performance. Identifying the monopole and dipole HOMs and carrying out the field calculation by 3D modeling are essential for the designing of HOMs couplers and the experiment for the couplers, which can be a theoretical guide to the next HOM damping work. The analysis of the interaction between beam and cavity is helpful for the determination of the beam parameters.

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