R.F. CHARACTERISTICS OF 508MHz
SLOT-COUPLED MULTI-CELL CAVITY

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Abstract

For the development of a Slot-Coupled Multi-Cell cavity(SCMC) experimental approaches with an aluminum model have been performed, which were discussed in our previous paper.(1) With the model cavity that provides the accelerating 'flat-π' mode at 508.58MHz, r.f. characteristics of accelerating mode and higher order modes(HOMs) have been investigated. The results are discussed here.

Introduction

According to the increase in beam energy, multi-cell cavities are expected to provide higher accelerating efficiency and simpler phase adjustment of each cavity. In terms of electro-magnetic coupling between cells, multi-cell cavities are distinguished into several types, such as SCMC(Slot-Coupled Multi-Cell), APS(Alternating Periodic Structure) and so on.

APS has an axially symmetric structure thus its dimensions can be numerically determined in detail by axially symmetric computational codes. But SCMC has coupling slots and its axial asymmetry causes difficulty in determining its dimensions numerically. APS has large group velocity because it applies mode confluence at $\pi/2$ between accelerating cells and coupling cells. If the resonant frequency of these cells are not tuned strictly, however, the confluence is not achieved. On the other hand, SCMC uses π mode acceleration whose group velocity is zero and stability against perturbations becomes worse with larger cell number. Nevertheless SCMC has no coupling cells, so its structure seems to be rather simple.

SCMC consists of cells, disks and auxiliary parts such as an antenna, tuners and pickup loops. Fig.1 shows 5-cell SCMC, that is the aluminum model fabricated for this study. Summary of its specification is stated in next chapter. On a disk as a partition wall, there exist slots to couple adjacent two cells electro-magnetically. A slot has a sectoral shape whose number is in general two or four on a disk. Slot area is one of the most important parameters for coupling. The coupling factor κ is defined by

$$\kappa = \frac{f_0 - f_\pi}{(f_0 + f_\pi)/2}$$

where f_0 and f_π are resonant frequencies of 0 and π mode, respectively. Larger κ means higher stability of the accelerating mode against perturbations.

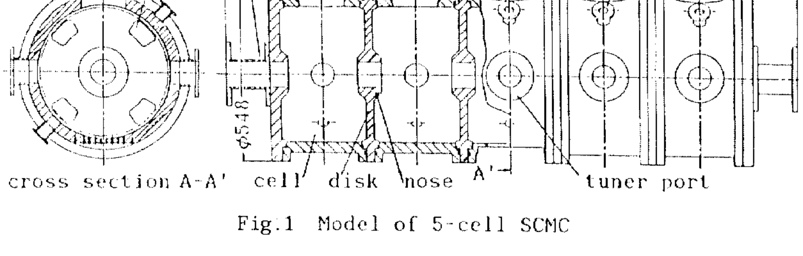


Fig.1 Model of 5-cell SCMC

Model cavity

The model SCMC was made of aluminum alloy (A5052) for easiness in assembly. Some design considerations were taken into as follows;

(1) cells: A cell is axially symmetric except for some ports and has nose cones in order to make shunt impedance (R_{sh}) higher. The configuration of cell including nose cones has been surveyed for one cell structure with the computational code SUPERFISH. The radius of each cell has been determined roughly by analyses, but strict dimensions must be obtained by experiments for the accelerating 'flat-π' mode at the required frequency.

In order to survey the important parameters for SCMC, such as slot angle, radius of a nose cone and so on, a 2-cell structure called HFH is necessary. This structure consists of a center cell and two half length cells holding it. ('HFH' is an abridgment of half-full-half.) Because its boundary conditions at both end walls behave as mirrors, the HFH presents an infinite multi-cell cavity, which helps to understand the fundamental characteristics of SCMC.

In order to select the cell number N, coupling factor κ must be considered. κ and N determine the frequency spacing, which indicates the mode stability against perturbations, between the π mode and its neighboring $(N-1)\pi/N$ mode. The frequency spacing is proportional to κ and it becomes small with the increase in N. Judging from κ of our model SCMC, the mode stability seems to be allowable up to 5-cell structure, which has been investigated in detail.

(2) slots: As for the π-mode, cell-to-cell coupling is magnetic. κ depends on slot area and magnetic field strength at slots. For large coupling and high stability against perturbation, slots have to be large and come near to outer wall.

The number of slots on a disk is fixed at four so as to keep good symmetry and achieve large coupling. Slot angle have been determined by HFH experiments.

(3) antenna: This model has a coupler antenna ordinarily located at a center cell. In order to measure r.f. characteristics accurately without the influence of power reflection, an antenna is rotated to make critical coupling between the cavity and the antenna.

Modes such as $2\pi/5$ and $4\pi/5$ are excited by the pickup probes inserted in each cell because the antenna at the center cell doesn't drive these modes.

(4) tuners: Two kinds of tuners, a fixed one and a movable one, are used. A fixed tuner corrects machining error of each cell and is immovable from outside of a cavity. The other tuner is movable from outside by feedback controller for frequency shift due to beam loading and temperature rise. Each cell has these two tuners at the right angle with the antenna.

(5) frequency: The high power 508MHz klystron (e.g. E3786 508.58MHz - 1.2MW C.W.) is available from Toshiba corp. Considering high power required at high beam energy, it is advantageous to fix the frequency upon 508.58MHz.

Experimental investigations

The automatic r.f. characteristics measuring system is employed, applying the reflection method with the network analyzer. Metal and dielectric spherical perturbators driven by a PC-controlled pulse motor are used in order to obtain electro-magnetic field.

By this method, however, perturbators provide only absolute field values. Field sign +- at all points in a cavity must be decided theoretically by mode assignments.

The model experiments include following two main purposes; to obtain the dimensions for the accelerating flat-π mode at 508.58MHz and to investigate the r.f. characteristics of this structure. The former is stated in our previous paper(1) in detail. In this paper the latter; the r.f. characteristics of the structure, in particular 5-cell, are shown mainly.

(1) dimension survey for the flat-π mode: One of our final purposes is to survey the dimensions providing the flat-π mode at 508.58MHz for 5-cell structure. The dimension survey has proceeded with the increase in cell number. This process is important because it is very difficult to obtain the flat-π mode at the required frequency.

The fundamental parameters, such as cell radius, slot angle, radius of beam hole and so on, have been determined experimentally with a 2-cell HFH structure that has the same characteristics as an infinite one.

Actually, however, a cavity of SCMC does not have half end cells but full ones in order to reduce wall loss and to obtain high R_{sh}. Since periodicity breaks at end cells due to the lack of slots on end walls, end cells must be enlarged in order to achieve the flat-π mode. Though the radius is roughly determined by the equivalent circuit analysis, the accurate radius of end cells must be obtained by experiments with the 3-cell structure.

With the dimensions from these processes, the accelerating flat-π mode at 508.58MHz has been obtained for the 5-cell structure with a little adjustment of fixed tuners for machining errors of cells.

(2) investigation of 5-cell structure: With the final configuration of the 5-cell structure, the accelerating mode (TM010) and the higher order modes (HOMs) are investigated.

Fig.2 represents the electric field distribution on the beam axis of the TM010 mode. (The electric field is shown in arbitrary unit and the polarity is given theoretically in this figure.) It is obvious that all the cells have the same maximum electric field. The dip of the electric field at the center of each cell is owing to a nose cone.

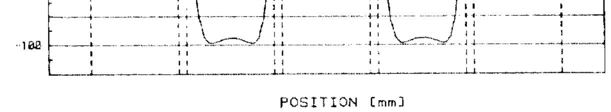


Fig.2 Electric field distribution on the beam axis of the accelerating flat-π mode

The experimental dispersion curve of the TM010 (including the accelerating mode) is described in Fig.3. The value of the zero mode is measured on HFH-structure, $\pi/3$ and $2\pi/3$ mode are on 3-cell and the others are on 5-cell. The line in the figure is the cosine curve and traces the experimental results exactly. κ is obtained as 1.68(%) and the frequency difference between the accelerating(π) mode and the adjacent($4\pi/5$) mode is 830(kHz).

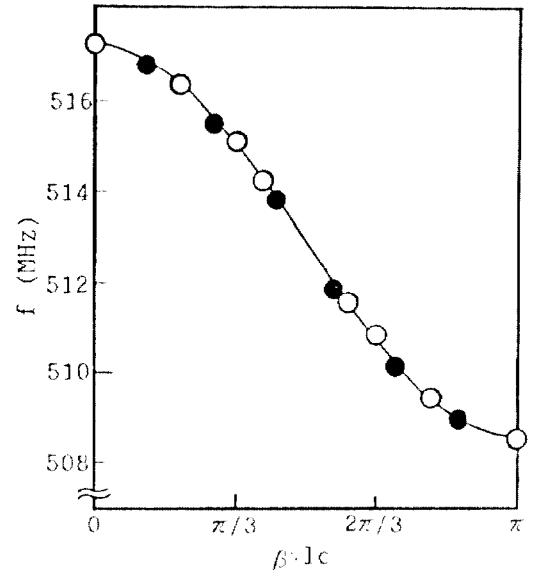


Fig.3 Dispersion curve of TM010 mode

The effective shunt impedance(R_{sh}) is given by the following equation;

$$R_{sh} = \frac{2Q_u}{\omega\varepsilon_0}\left|\int_{-d/2}^{d/2} sE_a(\cos kz + j\sin kz)\,dz\right|^2 .$$

where ω is the angular frequency($=2\pi f$), k is the wave number($=\omega/c$, c is the speed of light). E_a is the normalized electric field without polarity and s is the theoretically decided field sign of +1, -1 or 0.

Measured characteristics of the accelerating mode are as follows;

Table 1 Characteristics of the accelerating mode

frequency (tuned)	: f_π	508.58	(MHz)
unloaded-Q	: Q_u	13700	
shunt impedance	: R_{sh}	17.8	(MΩ)
R_{sh}/Qu		1.28	(kΩ)
transit time factor	: T	0.74	
coupling factor	: κ	1.68	(%)
length (5-cell)	: l	1.4737	(m)

Since the model is made of aluminum, the value of Qu indicates rather low. Simply converted with the resistivity of copper, Qu becomes about 21000. Considering insufficient smoothness of machined surface, oxidation of aluminum and imperfect r.f. contacts, Qu of the actual cavity will grow higher. Assuming that Qu is 28000, which is reasonable with the results of the analysis by 'SUPERFISH' for one cell structure, R_{sh} per meter of SCMC is proved to be over 24(MΩ/m).

HOMs of TM011, TM110 and TM111 have been investigated. All these modes have been identified and the results are summarized in Table 2, including TM010. TM010 and TM011 have 5 normal modes from $\pi/5$ to π. Every dipole mode splits into 2, since its degeneracy is incomplete due to axial assymmetry caused by some ports. In result both TM110 and TM111 modes split into 10.

Coupling impedances are calculated by (2)(3)

<longitudinal coupling impedance> (for TM010, TM011)

$$R_{/\!/} = \frac{2Q_{11}}{\omega\varepsilon_0}\left|\int_{-d/2}^{d/2} sE_a(\cos kz + j\sin kz)\,dz\right|^2 ,$$

<transverse coupling impedance> (for TM110, TM111)

$$R_{\perp} = Q_{11}z_0\left|\int_{-d/2}^{d/2} (s_h H_a - j s_e E_a)(\cos kz + j\sin kz)\,dz\right|^2 ,$$

where $z_0 = \sqrt{\mu_0/\varepsilon_0}$, s, s_h and s_e are field signs.

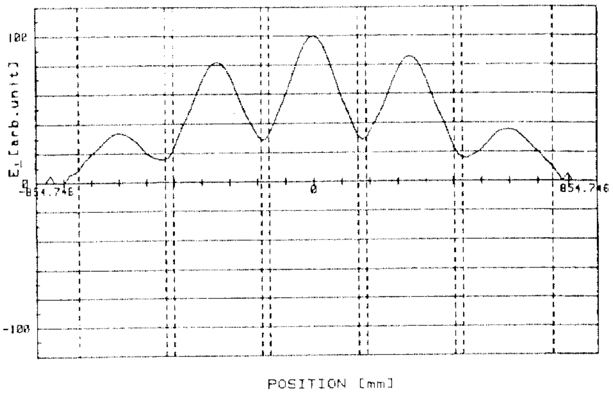
If cell length equals to half of wave length, it is theoretically proved that coupling impedances of all nomal modes except π are zero. The TM010 mode frequencies nearly equal to that of the π mode, whose half wave length is designed as the cell length. Therefore $R_{/\!/}$ of the $\pi/5 \sim 4\pi/5$ modes are almost zero.

Table 2 shows that some modes have large $R_\perp$. In particular $R_\perp$ of TM111-π/5(b) is extremely large, whose electric and magnetic field distributions are shown in Fig.4. With Fig.4(b), it is obvious that the magnetic field of this mode alternates every half cell length. Because the resonant frequency is nearly twice as much as that of the accelerating mode, the deflecting force on the beam is superposed in only one direction. For a mode like TM111-π/5(b) may induce a beam instability, some cures will be taken if necessary.

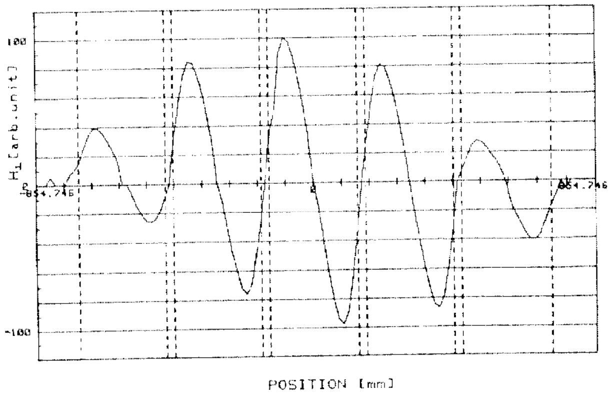
Table.2 R.F. Characteristics of Each Mode

Mode		Frequency :f (MHz)	unloaded -Q :Q_{11}	Field distr.	R/Q(Ω)
TM010 like	1π/5	516.339	15599	-+++-	*
	2π/5	514.204	14866	-+0--	*
	3π/5	511.514	14597	-+-++	*
	4π/5	509.420	14129	+-0+-	*
	5π/5	508.587	13728	+-+-+	1281
TM011 like	1π/5	718.487	10567	+++++	*
	2π/5	725.460	11378	++0--	47.5
	3π/5	734.908	11183	++-++	159.1
	4π/5	742.322	13382	+-0+-	70.1
	5π/5	744.432	13332	+-+-+	17.1
TM110 like (a)	1π/5	850.638	16670	+++++	254.5
	2π/5	846.615	17177	++0--	674.9
	3π/5	842.239	16535	++-++	390.7
	4π/5	838.668	16249	+-0+-	5.7
	5π/5	837.394	15044	+-+-+	87.6
TM110 like (b)	1π/5	861.559	17580	+-+++	274.0
	2π/5	857.616	17051	++0--	669.4
	3π/5	852.471	16614	++-++	407.1
	4π/5	848.872	16340	+-0+-	11.1
	5π/5	847.157	12749	+-+-+	56.5
TM111 like (a)	1π/5	998.247	12409	+++++	5868
	2π/5	1005.970	13594	++0--	45.9
	3π/5	1018.432	14080	++-++	769.8
	4π/5	1029.052	14823	+-0+-	3.1
	5π/5	1032.859	13538	+-+-+	139.2
TM111 like (b)	1π/5	999.212	12545	+++++	6122
	2π/5	1006.940	12554	++0--	49.9
	3π/5	1018.771	15471	++-++	913.0
	4π/5	1030.565	16103	--0+-	5.8
	5π/5	1036.899	16695	+-+-+	172.0

* -- negligible small



(a) Electric field



(b) Magnetic field

Fig.4 Electric and magnetic field distributions on the beam axis of TM111-π/5(b) mode

Conclusion

The model cavity of SCMC type has been fabricated and studied experimentally. The accelerating 'flat-π' mode at 508.58MHz on a 5-cell structure has been obtained. The measured R_{sh} and κ are considered to be sufficient for the practical use.

The mode assignment for TM010, TM011, TM110 and TM111 has been completed through electro-magnetic field distributions as well as their polarity.

The investigation of the important modes shows some modes have rather large coupling impedances. If accelerator ring parameters are given, threshold current will be calculated.

<references>

(1)T. Rizawa et al.: 'Experimental Study on a 508MHz Slot-Coupled Multi-Cell Model Cavity', Procs. of the 7th Symposium on Accelerator Science and Technology (Dec. 1989).

(2)J. Jacob: 'Measurement of the Higher Order Mode Impedances', ESRF-RF/88-02 (Jan.1988).

(3)Y. Yamazaki et al.: 'Measurement of the Longitudinal and Transverse Coupling Impedances of the Higher-Order Modes of the Re-entrant accelerating cavity', KEK 80-8 (Aug. 1980).