EXPERIMENTAL STUDY ON A 508MHZ
SLOT-COUPLED MULTI-CELL MODEL CAVITY

T.Rizawa, K.Satoh, Y.Tanabe and M.Nakano
Toshiba Corporation
2-4 Suehiro-cho, Tsurumi-ku, Yokohama, 230 Japan

Abstract

Experimental and analytical studies on a Slot-Coupled Multi-Cell cavity(SCMC) have been going on and results of 1GHz model cavity were discussed in our previous paper(1). Following it the more actual model has been fabricated and further experiments for r.f. characteristics have been carried out. Referring to analyses with an equivalent circuit and an axially symmetric computational code, dimensions of the model cavity has been determined to obtain the accelerating 'flat-π' mode of 508.58MHz. After that, accelerating and higher order modes' characteristics have been investigated and the experimental results of them are shown here.

## Introduction

According as beam energy of accelerators becomes much higher, a multi-cell cavity is expected to provide higher efficiency for the beam acceleration and to make transmission lines from r.f. power sources simple. A multi-cell cavity consists of cavity arrays (each one is called cell) and an antenna to supply r.f. power to all cells coupled electro-magnetically.

Concerning the type of coupling, multi-cell cavities are distinguished into APS(Alternating Periodic Structure), SCMC(Slot-Coupled Multi-Cell), DAW (Disk And Washer), SCS(Side Coupled Structure) and so on. Each one has its own merits and demerits.

For example, APS has an axially symmetric structure so that dimensions can be numerically determined in detail by axially symmetric computational codes, though SCMC has some coupling slots and its axial asymmetry causes difficulty in determining its dimensions numerically. The APS has large group velocity because it applies the mode confluence at π/2 between the accelerating cell and the coupling cell, but the confluence is not achieved if the resonant frequency of these two cells are not tuned strictly. On the other hand, SCMC uses π mode acceleration whose group velocity is zero and therefore stability against perturbations becomes worse according to greater number of cells. Nevertheless SCMC has no coupling cells, so its structure seems to be rather simple.

For the purpose of studying r.f. characteristics of SCMC, its alumimum model has been fabricated.

## SCMC and its equivalent circuit

An SCMC consists of cells, disks and other parts such as an antenna, tuners and pickup loops. Fig.1 shows a 5-cell SCMC, that is the model fabricated for this study. Its specifications and dimensions are summarized in next chapter.

A cell is axially symmetric except for some ports and has nose cones in order to make shunt impedance ($R_{sh}$) high. A disk is a partition wall with a beam hall and slots to couple adjacent two cells electro-magnetically. A slot has a sectoral shape and the number of slots on a disk is two or four in general. Slot area is one of the most important parameters. The larger slot area is, the more magnetic or electric flux penetrates through slots. Thus the coupling increases and the stability of the accelerating mode against perturbations becomes higher, but $R_{sh}$ reduces oppositely.

By an analysis with an equivalent circuit, it is indicated that modes like TM010 and TM011 on a multi-cell cavity have 'normal' modes and that the number of them is generally equal to the cell number. For N-cell cavity, there ideally exist N+1 normal modes distinguished by the phase shift per cell and called 0 ~ N/Nπ modes. As an actual cavity is not completely periodic due to end walls, the π mode can not exist and N modes of 0 ~ N-1/Nπ exist, if not modifying end cells. In consequence of the modification, the zero mode disappears and the mode called 'flat-π' appears. Assuming that the structure has small wall loss, weak magnetic coupling cell-to-cell and full-length end cells tuned in order to achieve the flat-π mode, the normal mode frequencies are(2)

$$f(m) = \frac{f}{\sqrt{1 - B\cos m\pi/N}} \approx f\ (1 + \frac{B}{2}\cos m\pi/N)\ ,$$

where B is the bandwidth which is a difference of frequencies between 0 mode ($f_0$) and π mode ($f_\pi$) in the ideal infinite structure, f is the average of $f_0$ and $f_\pi$, m is the mode number (m=1,2,~N) and mπ/N is the phase shift per period. From this bandwidth, κ is defined by

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

And the electric field amplitude in the nth cell for the mth normal mode is given by

$$E_n = A_m \sin\,[m\pi(2n-1)/2N]\ .$$

In case of 5 cells, for example, Fig.2 shows the distribution of maximum electric field along the beam axis owing to the phase shift.

Though an equivalent circuit analysis is useful for understanding electro-magnetic phenomena and determining dimensions roughly, the accurate dimensions must be determined by model experiments.

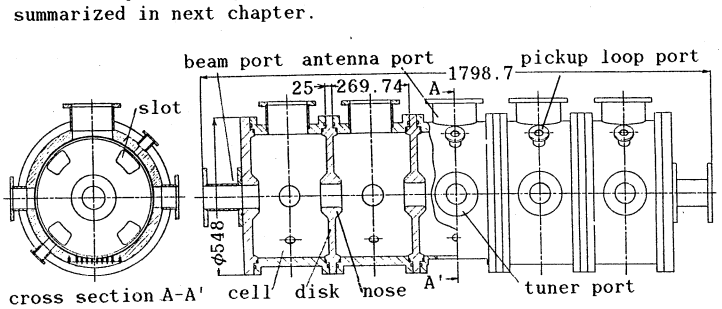


Fig.1 Model of 5-cell SCMC

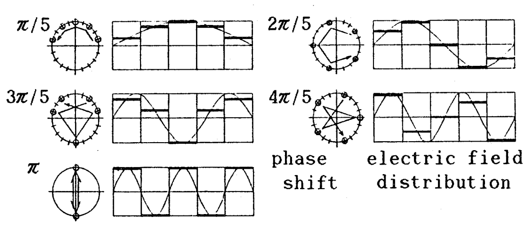


Fig.2 Electric field distributions along the beam axis owing to phase shift

Criteria for designing aluminum model cavity

In order to determine dimensions of an SCMC, it is necessary to fix some specifications. Of course, these parameters have to be changed under requirement from an accelerator.

(1) 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.

(2) Slots: In the $\pi$-mode, cell-to-cell coupling is magnetic. $\kappa$ 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 decided to be four, so as to keep good symmetry and achieve large coupling.

(3) Nose cones: Concerning nose cones, parameters are gap between nose cones, nose configuration and radius of beam hall. These parameters are surveyed using the computational code 'SUPERFISH'.

In order to keep accelerating frequency constant with wider gap, cell radius must be larger. Therefore outer wall loss decreases and $R_{sh}$ increases. On the other hand, transit time factor(T) decreases. So effective shunt impedance($R^*=R_{sh}T^2$) has a maximum value for gap length. In addition, the cooling efficiency and the maximum electric field on the nose must be taken into account.

If radius of a beam hall becomes smaller, $R^*$ grows higher, but its radius is limited by the spread of beam in operation.

(4) 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 r.f. power reflection, an antenna is rotated to make coupling between the cavity and the antenna critical.

(5) Tuners: It is thought to use two kinds of tuners, which are a fixed one and a movable one. A fixed type corrects machining error of each cell and cannot be moved from outside of a cavity. A movable type is, if a cavity is used in an accelerator actually, for feedback control against frequency shift due to temperature and beam loading. It is movable from outside and its stroke can be measured correctly. Each cell has these two tuners.

Experimental investigations

The automatic r.f. characteristics measuring system is employed and the measurements are done by the reflection method with the network analyzer. Electromagnetic field is obtained by metal and dielectric spherical perturbators, which are driven by a PC-controlled pulse motor.

The model experiments include following two main purposes; to obtain the dimensions for the accelerating flat-$\pi$ mode at 508.58MHz and to investigate the r.f. characteristics of this structure. For those purposes, the experiments proceed as follows.

(1) 2-cell structure: A 2-cell structure consists of a center cell and two half cells holding it. (This structure is mentioned as HFH, which is an abridgment of half-full-half.) Because its boundary conditions at both end walls are treated as mirrors, the HFH presents an infinite multi-cell cavity. Study on the infinite structure is important for understanding the fundamental characteristics of SCMC, and it becomes possible to survey the dimensions such as slot angle, radius of a nose cone and so on.

At first, radius of a nose cone is investigated using two types of disks that have a nose cone of $\phi80$ and $\phi100$. For the accelerating flat-$\pi$ mode, it is found that the $R_{sh}$ of the structure with $\phi80$ is 10% larger than that of $\phi100$. Moreover the $\phi80$ structure has higher frequency than $\phi100$ with the same cell radius and slot area. It means that the $\phi100$ structure must have smaller slots, in order to have the same frequency with the same cell radius. Therefore the $\phi80$ structure acts more stably against perturbations because of its larger coupling factor, and the $\phi80$ structure with high $R_{sh}$ and $\kappa$ is adopted in this case.

And next the survey on slot angle is carried out. The r.f. characterisatics are measured repeatedly each time slots are enlarged a little and its results are shown in Fig.3. As slot angle becomes larger, more electric or magnetic flux penetrates through slots and $\kappa$ increases, to the contrary $R_{sh}$ decreases because loss near slots increases. In addition, the frequency of the accelerating $\pi$ mode lowers. From these results, the optimum slot angle is determined as about 35 degrees.

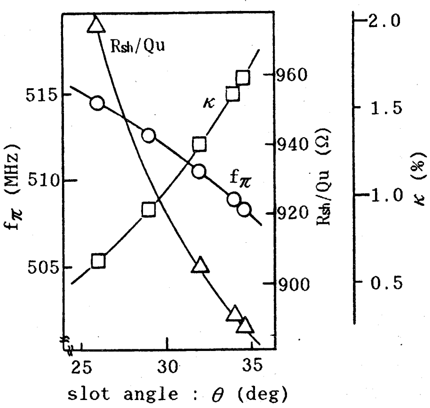



Fig.3 Relation between slot angle and r.f. characteristics (HFH-structure)

(2) 3-cell structure: An actual cavity of SCMC does not have half end cells but full ones in order to reduce wall loss and obtain high $R_{sh}$. Since a structure with full end cells has asymmetry at end walls, end cells must be enlarged to achieve the flat-$\pi$ mode. The radius is roughly determined by the equivalent circuit analysis.

In this step, a 3-cell structure with full end cells is investigated for verifying the equivalent circuit approach. As the results, the accelerating flat-$\pi$ mode at 508.58MHz is obtained with a little adjustment of fixed tuners in order to compensate for machining error of cells.

(3) 5-cell structure: With the same method as the 3-cell case, the 5-cell structure has the accelerating flat-$\pi$ mode at aimed 508.58MHz. Fig.4 represents the electric field distribution on the beam axis of this mode. (The electric field in this figure is shown in arbitrary unit and no polarity.) It is obvious that every cell has the same maximum electric field on the axis. The dip of electric field at the center of each cell is owing to a nose cone, and it is known that the dip becomes shallower if gap between nose cones is wider or radius of a nose cone is larger.

Besides, the measured electric field distributions of the normal modes from $\pi/5$ to $4\pi/5$ have good agreement with ones in Fig.2.

Measured characteristics of the accelerating mode are shown in the following table.

Table 1 Characteristics of the accelerating mode

| | | |
|---|---|---|
| frequency (tuned) | : $f_\pi$ | 508.58 (MHz) |
| unloaded-Q | : Qu | 13700 |
| effective $R_{sh}$ | : $R^*$ | 17.8 (MΩ) |
| $R^*$/Qu | | 1.28 (kΩ) |
| transit time factor | : T | 0.74 |
| coupling factor | : $\kappa$ | 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', R* per meter of SCMC is proved to be over 24(MΩ/m).

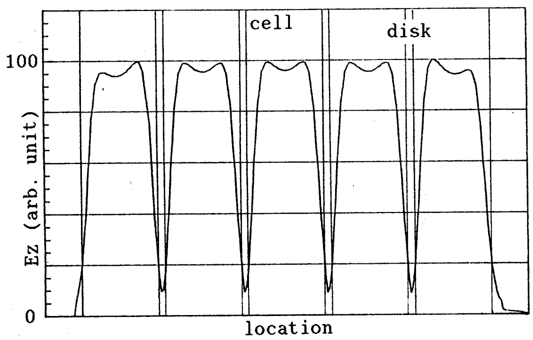



Fig.4 Electric field distribution on the beam axis of the accelerating flat-$\pi$ mode

The dispersion curve of TM010 (including the accelerating mode) is described in Fig.5. The frequency of the zero mode is measured on HFH-structure, $\pi/3$ and $2\pi/3$ modes 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. $\kappa$ is obtained as 1.68(%) and the frequency difference between the accelerating($\pi$) mode and the adjacent($4\pi/5$) mode is 830(kHz).

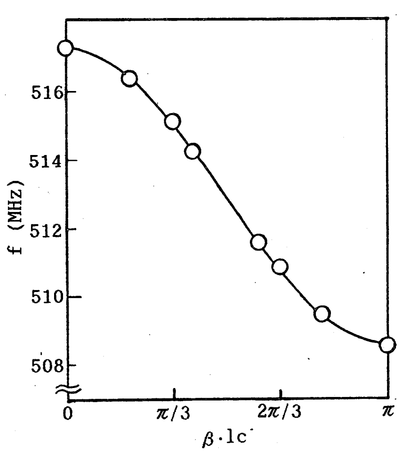
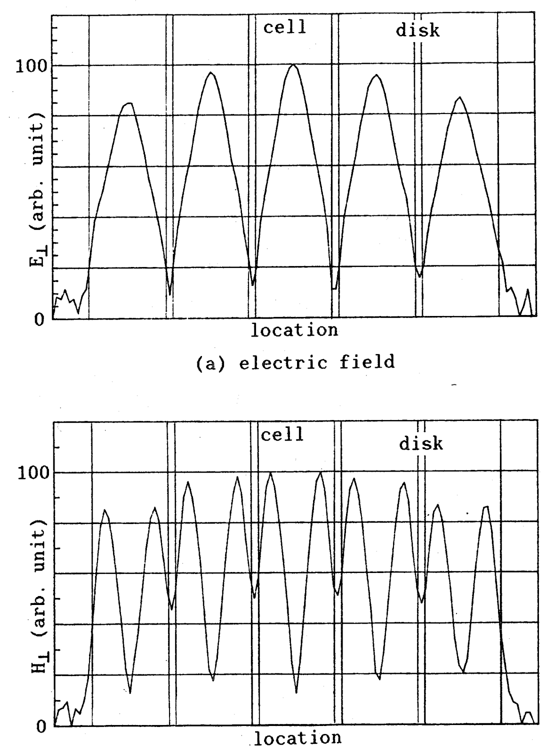



Fig.5 Dispersion curve of TM010 mode

Following it characteristics of HOMs of TM011, TM110 and TM111 are investigated. HOMs have 5 normal modes similar to TM010. Besides, axially asymmetric modes split into two because these have different driver points. So TM110 and TM111 have 10 modes, respectively. The identification for all these modes is completed. For example, electric and magnetic field distributions of the TM111-$\pi$ mode are shown in Fig.6. In this mode, both electric and magnetic field have only the component perpendicular to the beam axis. The distributions are not flat in spite of $\pi$ mode. The reason is considered that the frequency of TM111 mode varies between cells even if that of the accelerating (TM010) mode is adjusted as the same between cells by tuners in order to compensate for machining error of each cell.

It is now going on to estimate the beam instabilities due to HOMs.




(b) magnetic field

Fig.6 Electric and magnetic field distributions on the beam axis of the TM111-$\pi$ mode

## Conclusion

The model cavity of the SCMC type is fabricated and investigated experimentally. The accelerating 'flat-$\pi$' mode at 508.58MHz on the 5-cell structure is achieved on the basis obtained from the 2 or 3-cell structure and from the equivalent circuit and computational code analyses. The experimental results of R* and $\kappa$ seem to be sufficient for the practical use.

The instability of the accelerating mode against perturbations, the impedance of HOMs and the beam instabilities caused by them are now estimated.

## References

(1)T. Rizawa et al.: 'R.F. Characteristics Studies on a Slot-Coupled Multi-Cell Cavity' (in Japanese), Procs. of the 14th linear accelerator meeting in Japan (Sep. 1989) 58.

(2)P. B. Wilson et al.: 'High Energy Electron Linacs; Application to Storage Ring Systems and Linear Colliders', Stanford Linear Accelerator Center, (Copyright 1982 American Institute of Physics)