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題目 (TITLE) A New Annular-Coupled Structure Suppressing Higher Order Modes' Mixing with π/2 Coupling Mode

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概要 (ABSTRACT)

A new annular-coupled structure (ACS) operated in the π/2 mode has been developed for the high-β coupled-cavity accelerating structure (1296MHz) of the Japanese Hadron Project (JHP) 1-GeV proton linac. An annular-ring coupling cavity has higher order modes of TM-dipole and TM-quadrupole in the neighborhood above a TM-monopole mode which is the π/2 coupling mode of ACS. The ACS cavity was designed to keep the TM-dipole mode away from the passband of the π/2 accelerating mode. It was also designed to suppress excitation of the TM-quadrupole mode in the annular coupling cavity, which decreases the Q value of the accelerating mode. The configuration (including number, size, shape and cell-to-cell relative orientation) of coupling slots, through which adjacent accelerating and coupling cells are magnetically coupled, is the most important factor to put ACS to practical use for accelerators.

KEY WORDS:

Ion source, RFQ, DTL, CCL, Magnet, Monitor, Beam Dynamics, Transport, Vacuum, Cooling
Klystron, Low level rf, High power rf, Modulator
Control, Operation, Radiation, Others

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A NEW ANNULAR-COUPLED STRUCTURE SUPPRESSING HIGHER ORDER MODES' MIXING WITH THE π/2 COUPLING MODE

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Abstract A new annular-coupled structure (ACS) operated in the π/2 mode has been developed for the high-β coupled-cavity accelerating structure (1296MHz) of the Japanese Hadron Project (JHP)[1] 1-GeV proton linac[2]. An annular-ring coupling cavity has higher order modes of TM-dipole and TM-quadrupole in the neighborhood above a TM-monopole mode which is the π/2 coupling mode of ACS. The ACS cavity was designed to keep the TM-dipole mode away from the passband of the π/2 accelerating mode. It was also designed to suppress excitation of the TM-quadrupole mode in the annular coupling cavity, which decreases the Q value of the accelerating mode. The configuration (including number, size, shape and cell-to-cell relative orientation) of coupling slots, through which adjacent accelerating and coupling cells are magnetically coupled, is the most important factor to put ACS to practical use for accelerators.

INTRODUCTION

It has been well known that standing wave coupled-cavity accelerating structures operated in the π/2 mode have a high degree of stability and uniformity of the accelerating field against turbulence by beam loading, and perturbative effects such as cell-to-cell frequency variation arising from errors in machining and assembling of cavity segments.

For the π/2-mode coupled-cavity structure, two adjacent accelerating cells are electromagnetically coupled via a coupling cell between them. There are three well-known types of π/2-mode coupled-cavity structures (shown in Fig. 1): Alternating Periodic Structure (APS)[3] or On-axis Coupled Structure (OCS), Side-Coupled Structure (SCS)[4] and Annular-Coupled Structure (ACS)[5,6]. For the OCS, accelerating and coupling cells are arranged alternately along the beam axis. For the SCS, coupling cells of pillbox type are located off the beam axis. The ACS has coupling cells of annular-ring cavity structure around the beam axis. Machining and assembling of axially symmetric OCS are easier and more accurate than those of asymmetric structures such as the SCS. However, the shunt impedance of the OCS is lower than that of the SCS because the OCS has coupling cells, which make no contribution to the beam acceleration, on the beam axis. This problem becomes more serious at the lower velocity region of $0.4 < \beta < 0.5$, where the length along the beam axis occupied by one coupling cell is not negligible compared with one periodic length of accelerating structure. From the view point of geometrical structure, the ACS is axially symmetric like the OCS, and has no dead space for acceleration on the beam axis like the SCS. In other words, the ACS has both merits of the OCS and SCS. From the view point of electromagnetism, however, an annular-ring cavity has quite different properties compared with a pillbox-type cavity. This is the major difficulty for the development of ACS cavities.

In the following sections, we will summarize problems with 2-slot ACS cavities, and report how to overcome these difficulties in the recent studies at KEK, including numerical calculations and measurements of model cavities.

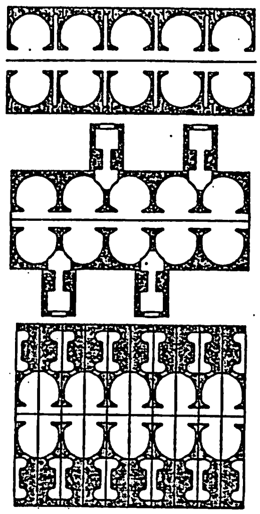

FIGURE 1. Accelerating structures operated in the $\pi/2$ mode.

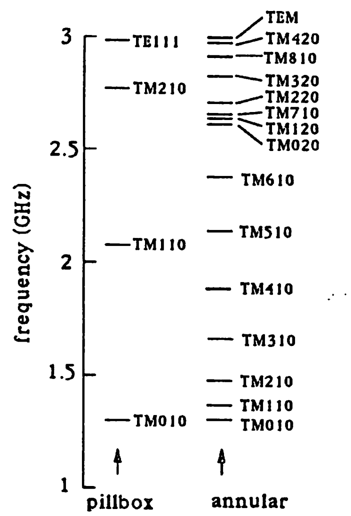

FIGURE 2. Frequency spectra of a pillbox and an annular cavity.

PROBLEMS WITH 2-SLOT ACS CAVITIES

In Fig. 2, the mode spectrum of an annular cavity is shown compared with that of a pillbox cavity. For the annular cavity, there are higher order modes of TM_{110} and TM_{210} in the neighborhood above the lowest TM_{010} mode, which is the $\pi/2$ coupling mode of the ACS. Several studies[6,7] have been made on ACS cavities with two coupling slots between accelerating and coupling cells. Summarizing the results of these studies, the ACS with two slots has the following problems:

(1) When the relative orientation of slots on opposite faces of the coupling cavity (cell-to-cell orientation) is 0°, the TM_{110} mode becomes closer in frequency to the TM_{010} mode as the slot arc-length increases.

(2) When the cell-to-cell orientation is chosen at 90° in order to reduce the second nearest neighbor coupling between the accelerating cells, the $\pi/2$

accelerating mode excites a TM_{210}-like mode in the coupling cells, which causes degradation in both Q and shunt impedance of the accelerating mode. Using the three-dimensional numerical solution codes of MAFIA[8] for Maxwell's equations, we have confirmed these problem. Figure 3 is a result of MAFIA calculations on 2-slot ACS at S band, which shows how the TM_{010}, TM_{110} and TM_{210} modes vary in frequency as the coupling increases. If the coupling is larger than 0.035, the TM_{110} mode crosses the TM_{010} pass band. (Here, the coupling coefficient is simply defined by the TM_{010} passband width.) Figure 4 shows electromagnetic field patterns in the coupling cell excited by the $\pi/2$ accelerating mode. The pattern has a feature similar to that of the TM_{210} mode.

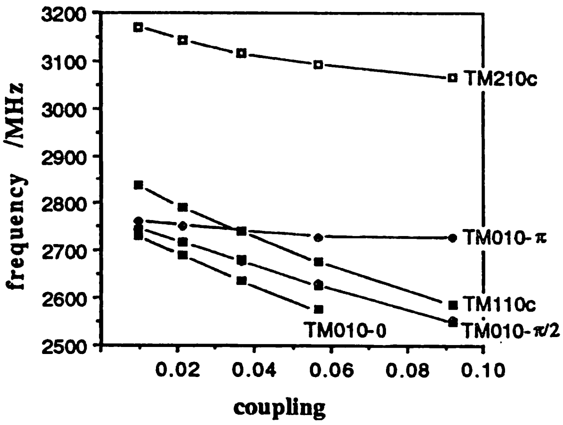

FIGURE 3. Calculated frequency spectrum of a 2-slot ACS with the slot configuration of cell-to-cell orientation = 0°.

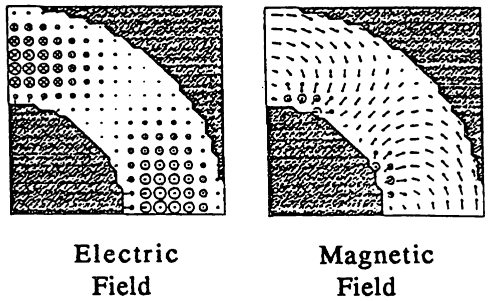

FIGURE 4. The patterns of electromagnetic fields excited by the $\pi/2$ accelerating mode in the annular coupling cell of a 2-slot ACS with the slot configuration of cell-to-cell orientation = 90°.

From the above results based on other experiments and our MAFIA calculations, we concluded as follows:

(1) These difficulties with 2-slot ACS are attributed to the fact that a degree of axial-symmetry breakdown in 2-slot ACS configuration, which introduces perturbative effects such as mode mixing, is not small compared with the mode spacings between the TM_{110} and TM_{010} modes and between the TM_{210} and TM_{010} modes of the annular coupling cell.

(2) These difficulties can be cured by recovering the axial-symmetry of the annular coupling cell of the ACS by multi-slot (more than two slots) ACS configurations.

If the number of slots is larger than two, higher order modes to be excited in coupling cells will have multi-fold symmetry (sextupole, octupole, etc.) depending on the slot configuration. Since the coupling strength between two modes is inversely proportional to the difference between the squares of the frequencies, the excited electromagnetic fields will be smaller in strength than those of the TM_{210} mode excited in the coupling cell of the 2-slot ACS.

MULTI-SLOT ACS

We have performed MAFIA calculations on multi-slot ACS cavities and measurements of 4-slot and 8-slot ACS cold model cavities with half scale.

MAFIA Calculations

MAFIA calculations were made on the 4-slot ACS with half of L- band scale in order to design S-band model cavities. Fig. 5 shows a three-dimensional view of a 4-slot ACS cavity generated by MAFIA, which represents a quarter part of a half segment. For the slot configuration of cell-to-cell orientation = 0°, the quarter part in Fig. 5 is enough for the input of MAFIA calculation on account of mirror symmetry. The mesh size was $0.25\times 0.25\times 0.125$ cm^3, and the number of mesh points was about 20000. In Fig. 6, the TM_{010} coupling coefficient is plotted as a function of the slot arc-length. The coupling coefficient is proportional to the cube of the slot arc-length. Figure 7 shows how the TM_{010}, TM_{110} and TM_{210} modes vary in frequency as the coupling coefficient increases. The TM_{110} mode is kept away from the TM_{010} passband even at a coupling coefficient larger than 0.05 for the 4-slot ACS in contrast to Fig. 3 for the 2-slot ACS.

The slot configuration of cell-to-cell orientation = 45° will reduce the second nearest neighbor coupling between the accelerating cells of the 4-slot ACS. Thus, we have investigated, through MAFIA calculations on a simple model of the 4-slot ACS, what mode is excited in the annular coupling cell by the $\pi/2$ accelerating mode. Although a TM_{410}-like mode is excited in the coupling cell of the 4-slot ACS, the stored energy of the TM_{410}-like mode in the annular coupling cell was reduced to about 10% of that of the TM_{210}-like mode for the 2-slot ACS, and probably will make no harm for its practical use. This is because the TM_{410} mode is far above the TM_{010} mode in frequency compared with the TM_{210} mode as shown in Fig. 2.

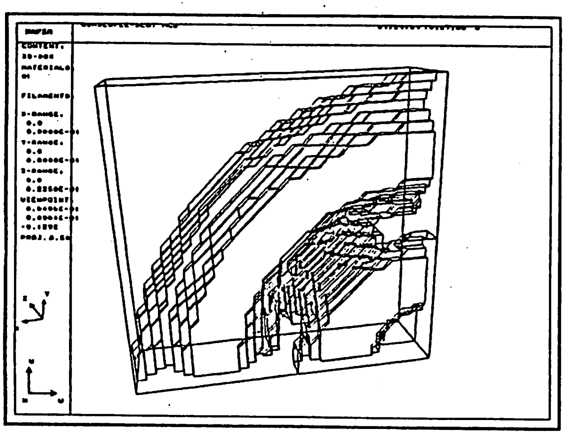

FIGURE 5. A three dimensional view of a 4-slot ACS cavity generated by MAFIA.

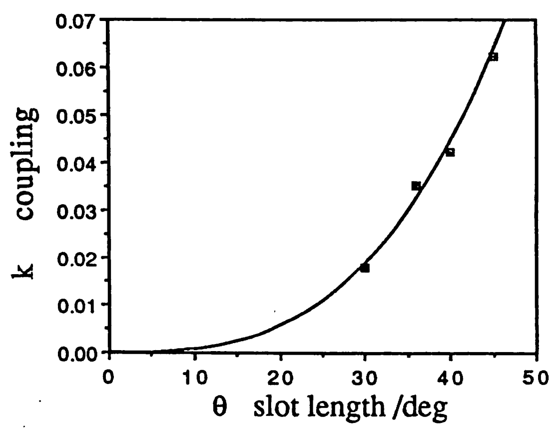

FIGURE 6. Calculated coupling coefficients of the 4-slot ACS are shown as a function of the slot arc-length.

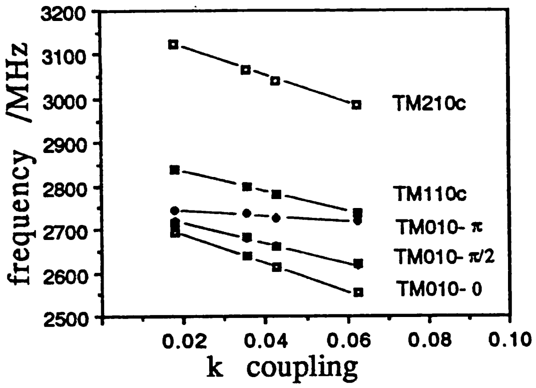

FIGURE 7. Calculated frequency spectra of the 4-slot ACS are shown as a function of the coupling coefficient.

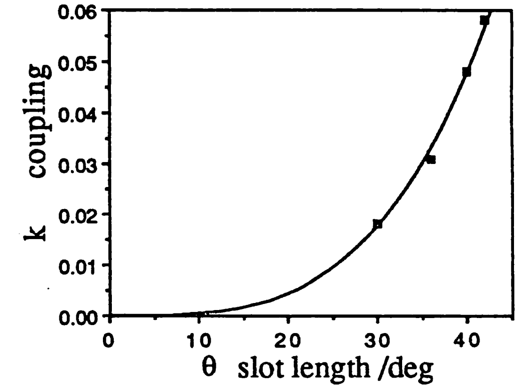

FIGURE 8. Measured coupling coefficients of 4-slot ACS models are shown as a function of the slot arc-length.

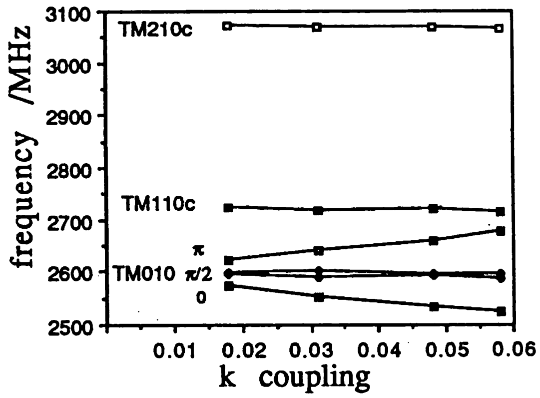

FIGURE 9. Measured frequency spectra of 4-slot ACS models are shown as a function of the coupling coefficient.

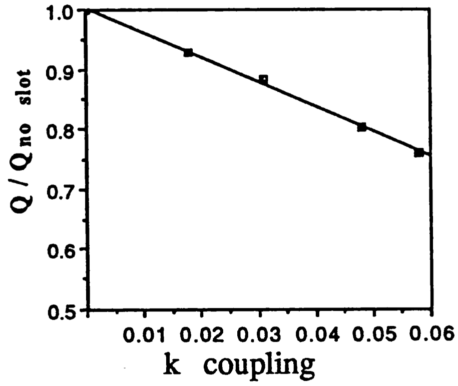

FIGURE 10. Measured Q values of 4-slot ACS models are divided by the Q value of a single cell without slots, and plotted as a function of the coupling coefficient.

Measurements of Cold Model Cavities

Both of 4-slot and 8-slot ACS model cavities with half scale (S-band scale) were made of vacuum-melted oxygen-free copper (OFC). We have measured four 4-slot models with slot sizes of 30°, 36°, 40° and 42° in arc length, and three 8-slot models with slot sizes of 20°, 25° and 30°. The inner copper surfaces of model cavities were chemically polished by the solution of sulfuric acid (44%), nitric acid (22%) and water (33%). By this process, the degradation of Q value due to the surface-finish by cutting tools was reduced to 5% compared with the Q value calculated by SUPERFISH[9].

The results of measurements of the 4-slot model cavities with the slot configuration of cell-to-cell orientation = 45° are as follows. Measured coupling coefficients are shown in Fig. 8 as a function of the slot arc-length θ. It is seen that the coupling coefficient is proportional to $\theta^{3.5}$, and 0.048 at $\theta = 40°$. Measured frequencies of the TM_{010}, TM_{110} and TM_{210} modes are shown in Fig. 9 as a function of the coupling coefficient k. At k = 0.048, the TM_{110}

mode is kept away from the TM_{010} passband. Furthermore, it is seen that the frequency difference between the TM_{110} mode and the TM_{010} $\pi/2$ coupling mode is almost independent of the coupling coefficient (or the slot arc-length). Measured Q values are shown in Fig. 10 as divided by that of a single cell without coupling slots. The reduction of the Q value is found to be proportional to the coupling coefficient k, and about 20% for k = 0.048. This reduction is 5 ~ 10% larger than that (10 ~ 15%) of the SCS with a coupling coefficient of 0.05.

In measurements of the 8-slot models, no significant improvement by 8-slot configuration in the mode spectrum or in the Q value was observed. The more coupling slots the ACS has, the poor become the mechanical strength and thermal conductivity of the wall between the accelerating and coupling cells. Therefore, the 4-slot ACS is a practical solution for the difficulties with the 2-slot ACS.

CONCLUDING REMARKS

The present study indicates that the difficulties with the 2-slot ACS can be cured by recovering the axial-symmetry of the annular coupling cell by a multi-slot (4-slot or 8-slot) configuration. The potential advantage of the axially symmetric structure of the ACS will compensate only 5 ~ 10 % inferiority of the quality factor of the ACS to that of the SCS. For a further step in the study on the ACS at KEK, we are planning to test performance of the multi-slot ACS at high-power operation.

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