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Cold Model Test of Slot Coupling between RFQ and DTL Cavities

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A cold model test has been carried out using a constant-velocity model for the investigation of slot coupling between a four vane RFQ and an Alvarez DTL cavity. The RFQ model cavity is the existing one which has unmodulated vanes. The DTL model cavity consists of six 4π-mode cells which are fabricated to be resonant at 403.5 MHz and correspond to a proton energy of about 1 MeV. These two cavities are aligned close each other and separated by a common end plate. The RFQ cavity is coupled to the DTL cavity through two slots provided in the end plate. The maximum coupoing obtained in this test is 1.15%. Distributions of the magnetic and electric field through the coupled cavities were measured using the Bead Perturbation Method. These measurements indicate that good field distributions in the cavities can be obtained by the π-mode coupling if the coupling is less than 0.75%.

KEY WORDS: Proton Linac / Four Vane RFQ / Alvarez DTL / 4π-mode Acceleration / Slot Coupling / Field Distribution

1. INTRODUCTION

A design study of a proton linac for multi-purpose use has been carried out since April 1990, in cooperation of the Institute for Chemical Research of Kyoto Univ. and Mitsubishi Atomic Power Industries, Inc. It is intended in this study to investigate an optimum combination of a four vane RFQ and Alvarez DTLs for 4π and 2π-mode acceleration of proton beams from 50 KeV to 10 MeV. The average beam current is aimed to be 1 mA and the operating frequency is selected to be about 400 MHz because of the requirement for the neutron yield and transportability of the linac respectively. The transition energy from the RFQ to the DTL of 4π-mode acceleration is tentatively fixed at 1 MeV so that the fabrication and adjustment of the RFQ may be facilitated. A cold model test of the RFQ indicated that good field distributions would be achieved[1].

The transition energy from 4π to 2π-mode acceleration in the DTL is tentatively fixed at 2 MeV. The DTL is designed to be a single-tank structure because of the simplicity. A cold model test was carried out for the investigation of the DTL with transition from 4π to 2π-mode acceleration[2]. The average electric field difference of about 5% was observed between the 4π and 2π-mode cell, which agreed satisfactorily with the SUPERFISH calculation. The effect of post coupler and double stem on the field stability were also investigated.

The RFQ and DTL cavity are usually constructed as separate tanks which are connected with a beam transport line. It is planned to couple the RFQ cavity with the DTL cavity so that

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the rf power for the RFQ cavity can be fed from the DTL cavity, because this scheme eliminates the necessity for a separate rf power source and a drive line for the RFQ. In the design of PIGMI (Pion Generator for Medical Irradiation), the RFQ cavity was coupled through slots to the RFQ manifold, which in turn was resonantly coupled to the DTL structure3). A simpler and more effective configuration is desirable. Therefore, it was decided to carry out a cold model test of coupling between the RFQ and DTL. Although loops may be applicable to the coupling device, the slot coupling seems simpler than the loop coupling. The RFQ model to be used in this test is the existing one which has unmodulated vanes1). A DTL model is newly fabricated.

2. CONFIGURATION OF MODEL CAVITIES

The configuration of the DTL model cavity together with the RFQ model cavity is shown in Fig. 1. The DTL cavity consists of six cells of 4π-mode acceleration which are 68.5 mm long each and correspond to the proton energy of about 1 MeV. The cavity wall is hexa-decagonal because of the fabrication easiness. The equivalent inner diameter of the cavity and the diameter of the drift tube (DT) are 460.0 and 80.0 mm respectively. The bore radius is 5.0 mm. The DTL model cavity is made of aluminum alloy (5052). The gap length between the DTs is determined by the SUPERFISH calculation to bring the resonant frequency for the TM010 mode at 403.5 MHz. A side tuner and fixed tuners are provided to adjust the resonant frequency.

The equivalent inner diameter and length of the RFQ model cavity are 154.5 and 1220.0 mm respectively. The bore radius is 3.0 mm. The cavity-wall and vane are made of aluminum alloy (5052). Opposing to the each vane end, eight end tuners are provided. The tuner is a copper rod of 12 mm diameter and the tuner-to-vane gap is adjustable from 10.0 to 0 mm. As seen in Fig. 1, four tuners at the outlet is mounted in the first half DT of the DTL model.

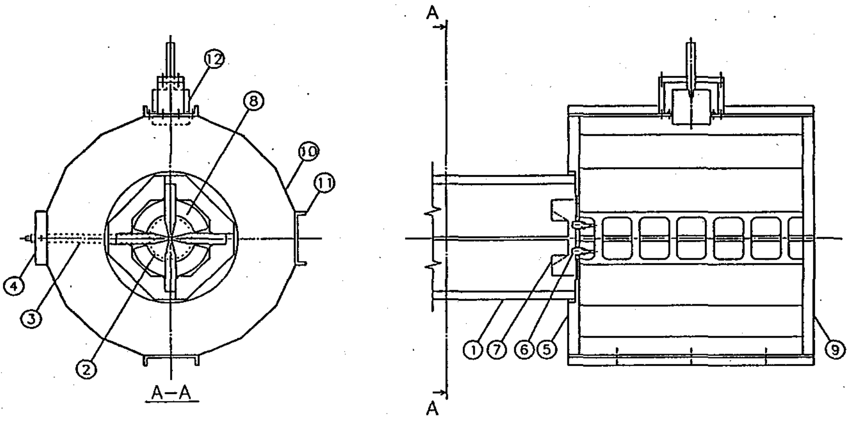

Fig. 1. Structure of the model cavities

1 RFQ (existing) 4 Garter 7 Cutback-block 10 Cavity wall
2 Drift tube 5 End plate (inlet) 8 Slot plate 11 Channel
3 Stem 6 End tuner 9 End plate (outlet) 12 Side tuner

There is a cutback of $30.0 \times 39.8\ \mathrm{mm}^2$ at the each end of the each vane. The cutback-blocks of five different sizes are provided which reduce the cutback space by 12.6, 25.1, 37.7, 50.0 and 63.3% respectively.

The distance, L, from the exit of the RFQ vane to the center of the first gap of the DTL should satisfy the following relation for synchronization when "half end cell" scheme of the RFQ is used:

$$L = (\Phi_{\mathrm{SDTL}} - \Phi_{\mathrm{SRFQ}})\,\beta\lambda/2\pi + n\beta\lambda/2 \quad (n = 1,\ 2,\ \cdots) \tag{1}$$

where Φ_{SDTL} and Φ_{SRFQ} are the synchronous phase of the proton beam in the DTL and RFQ respectively. By rotating the RFQ 90°, the second term can have the factor 1/2. As seen in Fig. 1, the RFQ and DTL cavity are close each other and separated by a common end plate. Two end plates (A and B) are provided whose thickness are 7.1 and 24.3 mm, assuming Φ_{SDTL} is equal to Φ_{SRFQ}. The end plate A provided for non-resonant slots was mainly used in the test. The end plate B is provided especially for a resonant slot and allows a margin in installing elements for transverse matching between the RFQ and DTL.

In order to find out whether the magnetic field around the end plate of the RFQ side can couple with that of the DTL side through the slots provided in the end plate or not, we carried out a preliminary test and calculations as follows: The distribution of the magnetic field along by the vane of the RFQ model was measured using the Bead Perturbation Method. A typical result of the $\Delta f/f$ distribution is shown in Fig. 2, which indicates that a peak of about three-fold exsists in the end region. Using the result obtained by the perturbation measurement and the magnetic field on the vane calculated with SUPERFISH, the magnetic field around the end plate was estimated. On the other hand, the magnetic field on the end plate of the DTL model was calculated with SUPERFISH. These results indicate that the magnetic fields to be coupled are almost equal each other. Therefore, the RFQ cavity can derive its power from the DTL cavity, if appropriate slots are provided in the end plate.

The shape of the slot used in the test is fundamentally a curved racetrack. For the non-

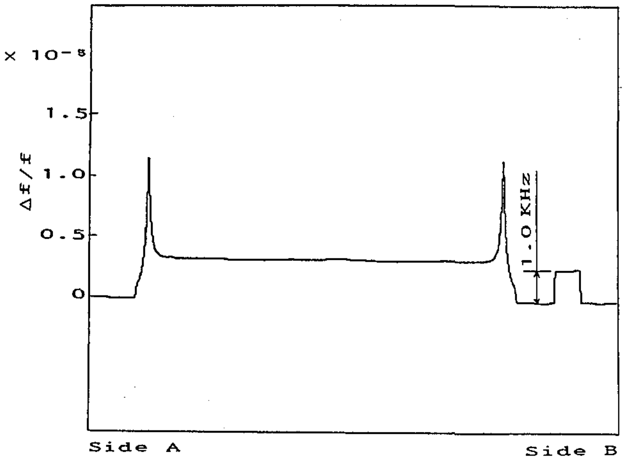

Fig. 2. $\Delta f/f$ distribution along by the vane of the RFQ cavity ($f = 404.23$ MHz)

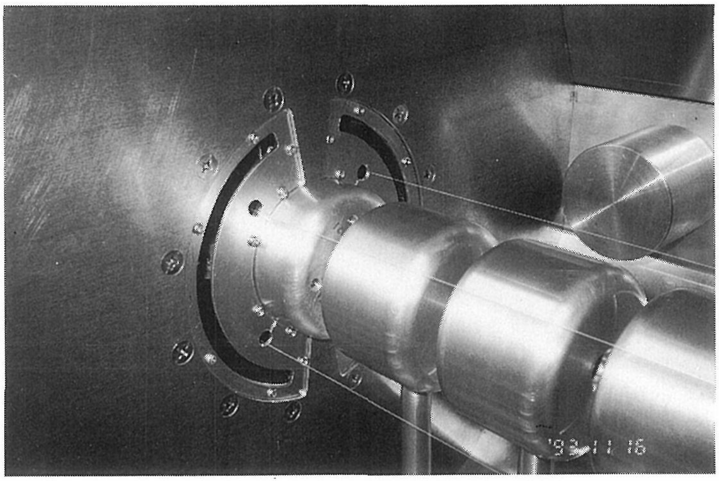

Photo. 1. The slot-plates installed in the end plate and the inside of the DTL cavity

resonant coupling, two slots with the same shape are used at the opposite positions facing to the vane ends. Photo. 1 shows the slot-plates installed in the end plate and the inside of the DTL cavity. Replacing the slot-plates, the shape of the slot can be changed for the comparison of the coupling characteristics.

3. COUPLING CHARACTERISTICS

3.1 Resonant Frequency and Coupling

The resonant frequencies of the RFQ and DTL cavity were measured separately. The resonant frequencies of the RFQ cavity measured before the field tunings were 402.96 MHz for the TE210 mode, and 397.48 and 398.28 MHz for the TE110 modes. The measured resonant frequency of the DTL cavity was 402.18 MHz for the TM010 mode. Fig. 3 shows the effect of the side tuner on the resonant frequency for the TM010 mode in the DTL cavity.

The arc-angle of the slot initially used in the test was limited to 90° keeping the same polarity of the magnetic flux in the end region of the RFQ cavity. The resonant frequency of the slot itself was measured with a network analyzer. The measurement indicated that the resonant frequencies of these slots were higher than 1 GHz.

Two resonant frequencies appear in the cavities coupled through non-resonant slots. The coupled frequencies given in Table 1 are those measured in the following way: Firstly, the resonant frequency fot the TE210 mode is measured in the RFQ cavity while the DTL cavity is detuned. Secondly, the resonant frequency for the TM010 mode in the DTL cavity is equalized to the above uncoupled RFQ (detuned DTL) frequency using the side tuner and fixed tuners while the RFQ cavity is detuned by shorting the vanes. Then, the detuning is removed and the two coupled frequencies, f_π and f_0, are measured which correspond to the π and 0-mode coupling respectively.

Using the coupling cavity theory and assuming the coupling between similar cavities, the coupling constant, k, is given as:

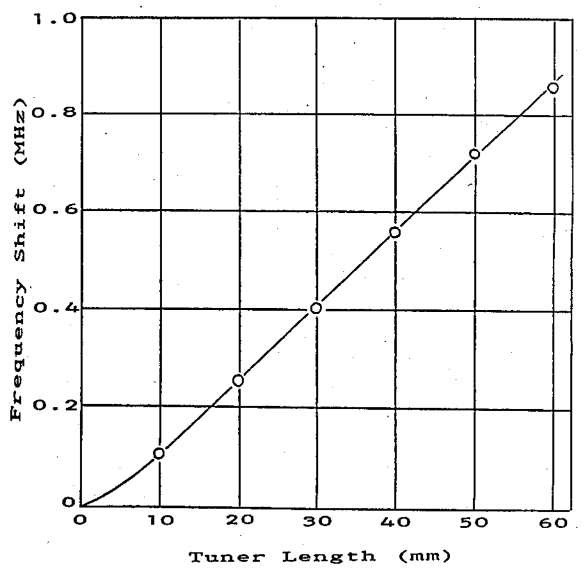

Fig. 3. Effect of the side tuner on the resonant frequency for the TM010 mode in the DTL cavity

Table 1. Summary of the coupling obtained in the test

Slot	Arc-angle (°)	Width (mm)	f_π (MHz)	f_0 (MHz)	$f_\pi - f_0$ (MHz)	k (%)
A-1	90	9.0	404.36	403.50	0.86	0.21
A-2	90	18.0	404.47	403.33	1.14	0.28
A-3	90	27.0	404.45	403.09	1.36	0.34
A-4	120	9.0	405.36	403.80	1.56	0.39
A-5	150	9.0	404.95	401.93	3.02	0.75
A-6	150	18.0	405.25	400.94	4.31	1.07
A-7	150	27.0	405.30	400.65	4.65	1.15

$$k = (f_\pi{}^2 - f_0{}^2) \,/\, (f_\pi{}^2 + f_0{}^2) \tag{2}$$

Although k increases as the width of the slot increases from 9.0 to 27.0 mm, the maximum coupling obtained is only 0.34% when the arc-angle is limited to 90°. If the arc-angle is expanded beyond 90°, k increases largely as seen in the table.

Fig. 4 shows the resonant frequencies for the π and 0-mode coupling in the cavities with slot A-5, which are observed as the uncoupled DTL (detuned RFQ) frequency is changed using the side tuner and adding the fixed tuners. The π-mode frequency is asymptotic to the uncoupled RFQ frequency and the line of 45° as the uncoupled DTL frequency becomes small and large enough respectively. On the other hand, the 0-mode frequency is asymptotic to the line of 45° and the uncoupled RFQ frequency. The values of f_π and f_0 seen in this figure are different from those in Table 1 because the two cutback-blocks on the slot-sides are replaced

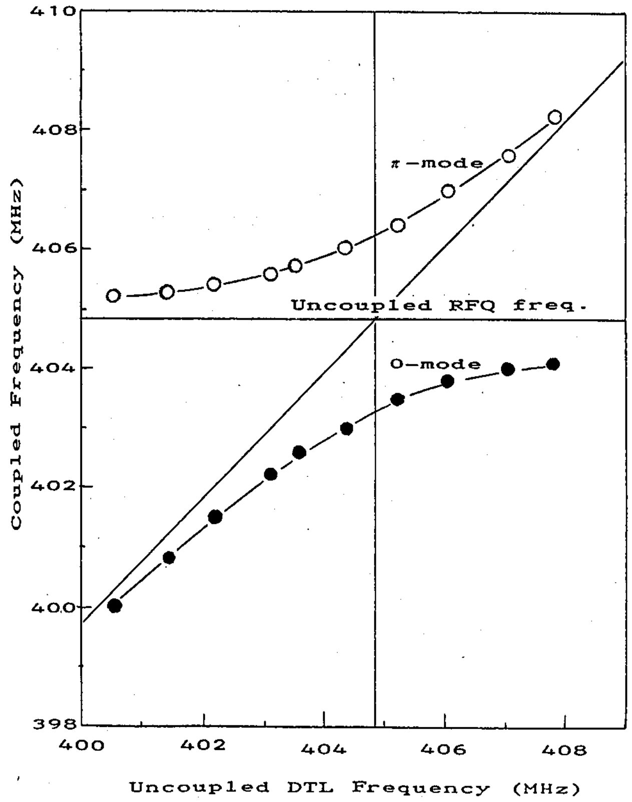

Fig. 4. Coupled frequency in the RFQ and DTL cavity with slot A-5

Table 2. Experimental and calculated values of the equalized frequency

Slot	Experimental f (MHz)	Calculated f (MHz)
A-4	404.67	404.58
A-5	403.55	403.43
A-6	403.29	403.08
A-7	403.22	402.96

with the largest ones in the measurement.

The equalized frequency, f, is given as:

$$f = f_\pi \cdot f_0 \cdot \sqrt{2/(f_\pi^2 + f_0^2)} \tag{3}$$

Table 2 gives the comparison between the experimental and calculated values of f. These values agree well, which may imply the coupling cavity theory is applicable to this test.

3.2 Field Distribution

Distributions of the magnetic and electric field in the RFQ and DTL cavity were measured using the Bead Perturbation Method. An aluminum cylinder of 4.5 mm diameter and 9.0 mm length is inserted through holes in the end plates at 50 mm off axis for the measurement of the magnetic field distribution in the RFQ cavity. An aluminum cylinder of 3.0 mm diameter and 3.0 mm length is inserted along the axis for the measurement of the distribution of the electric field. The model cavities equipped with the bead drive mechanism is shown in Photo. 2.

Preliminary measurements of the distribution of the magnetic field in the RFQ cavity indicated that the field decreased exponentially from the outlet when the 0-mode coupling was used. Therefore, the π-mode coupling has been investigated since then. Fig. 5 shows the distributions of the magnetic fields in the four quardrants of the RFQ cavity coupled to the DTL cavity through slot A-5. The fields declined towards the outlet, resulting in the lower fields in the outlet region. The tilt of the field from the inlet to outlet is up to −15%.

When slot A-6 was used, the tilt increased intolerably. When the operating frequency was decreased, the tilt was reduced to some extent. The distributions of the magnetic field shown in Fig. 6 are those obtained at 404.72 MHz which is lower by 0.55 MHz than f_π. It can be seen that the tilts of the field are even smaller than those shown in Fig. 5.

The azimuthal symmetry of the magnetic field shown in Fig. 5 and 6 are poor, although the end tuner gaps are set at the optimum values selected for the RFQ cavity with the blind slot. Therefore, the end tuner gaps have been readjusted for improving the azimuthal field symmetry as well as the longitudinal field uniformity in the RFQ cavity with slot A-5. The result is shown in Fig. 7. These distributions are pretty good; both the azimuthal field symmetry and the longitudinal field uniformity are within ±2.3%.

Fig. 8 shows the distributions of the average electric field strength on the axis of the DTL cavity with slot A-6 ($f_\pi = 404.72$ MHz) and A-5 ($f_\pi = 404.88$ MHz). This figure reveals that the field declines towards the outlet, resulting in the lower field in the cell-6 of the DTL with slot A-6; the longitudinal field uniformity is within ±4.1%. On the other hand, the longitudi-

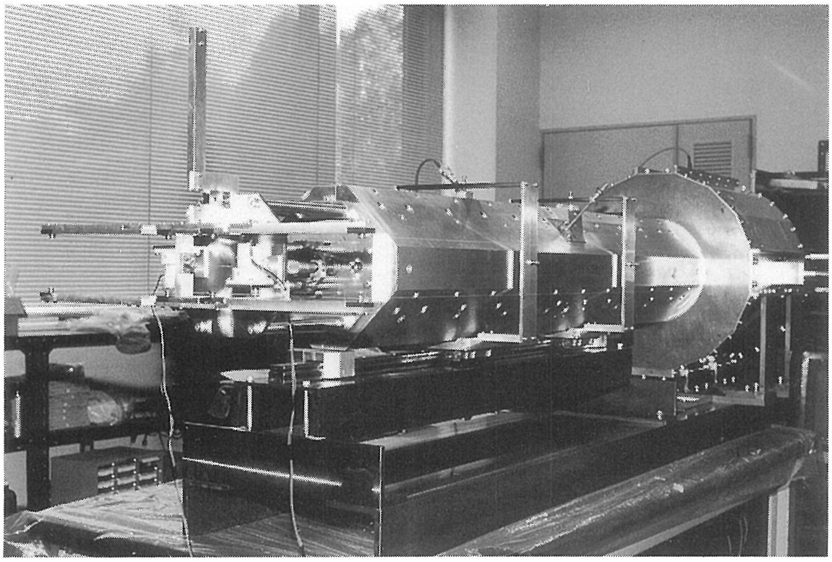

Photo. 2. The model cavities equipped with the bead drive mechanism

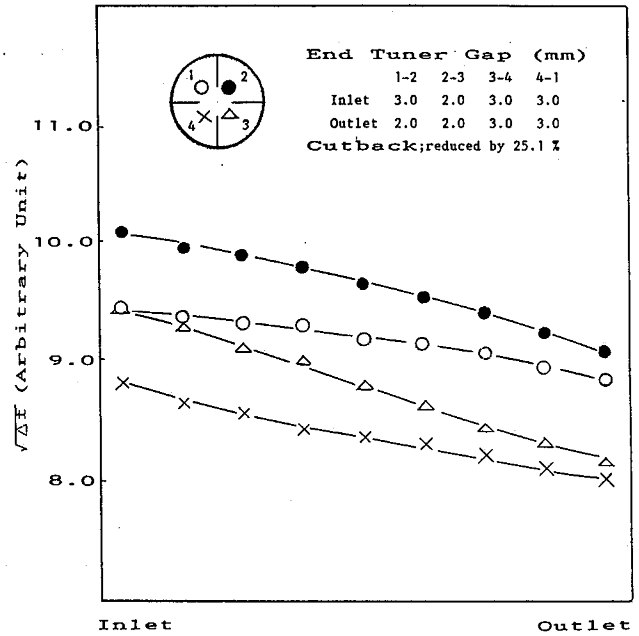

Fig. 5. Distrubitions of the magnetic field in the RFQ cavity coupled through slot A-5 (f_π =404.96 MHz)

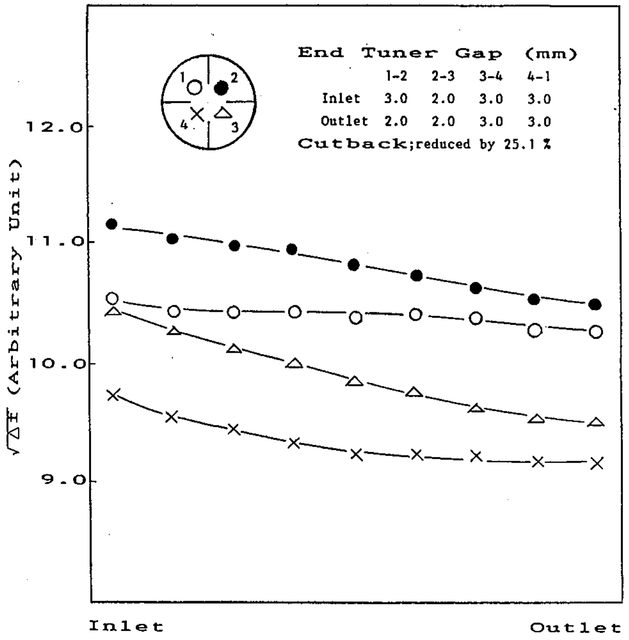

Fig. 6. Distributions of the magnetic field in the RFQ cavity coupled through slot A-6 (f_π =404.72 MHz)

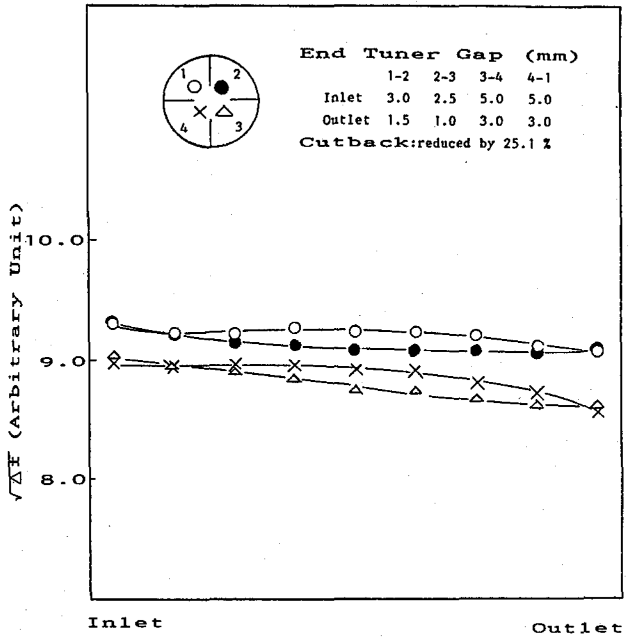

Fig. 7. Distributions of the magnetic field in the RFQ cavity coupled through slot A-5 (f_π =404.88 MHz)

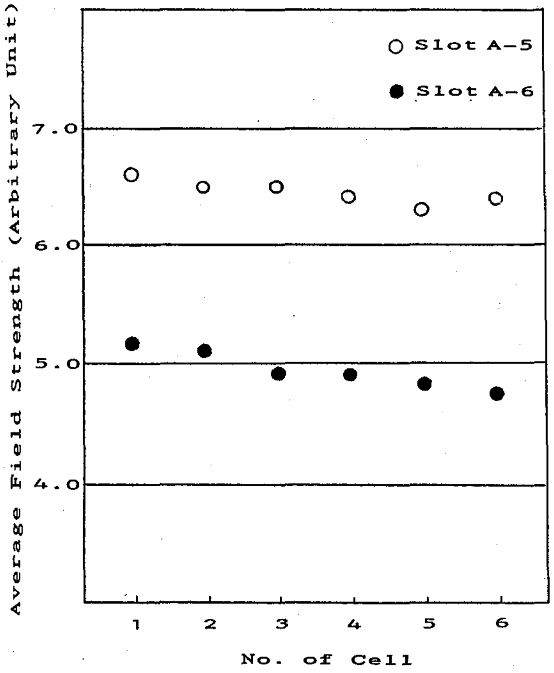

Fig. 8. Distributions of the average electric field strength on the axis of the DTL cavity with slot A-6 (f_π =404.72 MHz) and A-5 (f_π =404.88 MHz)

nal field uniformity is within ±2.3% in the DTL cavity with A-5.

3.3 Effect of the Cutback-blocks

The cutback-blocks mostly used in this test are those which reduce the cutback space by 25.1%. The effect of the cutback-blocks on the coupling was examined by replacing the four cutback-blocks at the outlet with larger ones. As seen in Table 3, the use of the larger cutback-blocks slightly enhances the coupling. On the other hand, the measurements of the magnetic field in the RFQ cavity indicate that the fields tend to decline towards the outlet, which is similar to that observed when the slot is too much enlarged. It seems better to use two larger cutback-blocks on the slot-sides instead of four larger ones in view of the field distribution in the RFQ cavity.

3.4 Longitudinal Position of the Slots

As for the effect of the longitudinal position of the slot on the excitation of the RFQ and DTL, the following measurements were carried out: A brass rod of 10 mm diameter and 15 mm length was inserted through a hole in the wall of the RFQ and DTL cavity coupled through slot A-5 and the frequency shift was measured. Then, the longitudinal position of slot A-5 was shifted from the nominal position by 2.0 mm to the DTL side and the perturbation measurement was repeated. Using the result of $\Delta f/f$, the ratio of the magnetic field on the wall of the RFQ to DTL cavity was estimated. Table 4 gives the result together with the value of k. On the other hand, the SUPERFISH calculations give the ratio of 2.13 which corresponds to the intervane voltage of 80 KV (1.8 times Kilpatric field criterion) in the RFQ and the average accelerating field of 3.0 MV/m in the DTL. It can be seen from this table that the appropriate ratio of the excitation of the RFQ to DTL is obtainable by shifting the longitudinal position of the slot slightly.

3.5 Resonant Coupling

The use of a resonant slot was not successful: The arc-angle of the slot was enlarged to

Table 3. Effect of the cutback-block on the coupling

Cutback-block (outlet)	Reduction in Cutback Space (%)	f_π (MHz)	f_0 (MHz)	$f_\pi - f_0$ (MHz)	k (%)
M	25.1	404.95	401.93	3.02	0.75
L-1	37.7	405.65	402.51	3.14	0.78
L-2	50.0	406.29	403.13	3.16	0.78

Table 4. Effect of the slot position on the coupling and the ratio of the field of RFQ to DTL

Shift to DTL Side (mm)	f_π (MHz)	f_0 (MHz)	k (%)	Ratio of the Field of RFQ to DTL
0	404.95	401.93	0.75	2.26
2.0	404.94	402.06	0.71	1.74

270° and the middle of the slot was narrowed to 2.0 mm for the purpose of bringing down the resonant frequency to about 400 MHz. This slot excited the TE110 mode very strongly instead of the TE210 mode.

With regard to keeping the azimuthal field symmetry in the RFQ cavity, the dual-slot is preferable as the coupling device. Because the number of the coupling device for the resonant coupling should be one, the dual-slot cannot be a resonant device. To couple the RFQ and DTL cavity, one can insert a coupling cavity (CC) between them. The two end plates of the CC are shared by the RFQ and DTL respectively. Each end plate has the dual-slot, and the field ratio of the RFQ to DTL can be adjusted by changing the coupling ratio of the RFQ-CC to CC-DTL. Because the CC does not excite in the $\pi/2$-mode, the cavity adjustments can be made separately while the CC is detuned. The operating frequency of the $\pi/2$-mode should not move when the detuning of the CC is removed. This scheme will be investigated later.

4. CONCLUSION

The cold model test of the slot coupling between the RFQ and DTL cavities has been carried out. The shape of the slot used in the test is a curved racetrack whose arc-angle and width are in the range from 90 to 150° and from 9.0 to 27.0 mm respectively. The maximum k is 1.15% which is obtained with the largest slot. The π-mode coupling is better than the 0-mode coupling in view of the field distribution in the RFQ cavity.

The end tuners are useful for improving the azimuthal field symmetry as well as the longitudinal field uniformity in the RFQ cavity. It seems that the dual-slot coupling scheme improves the azimuthal field symmetry. On the other hand, when the slot is too much enlarged, the magnetic field in the RFQ cavity tends to decline towards the outlet, resulting in the lower field in the outlet region. An excessive tilt cannot be removed by using only the end tuners. Therefore, it is needed to compromize between the strong coupling and the good field distribution.

This test shows that when the k is 0.75%, the pretty good distribution of the magnetic field in the RFQ cavity is obtainable; both the azimuthal field symmetry and the longitudinal field uniformity are within ±2.3%. It is also found that the longitudinal shift of the slot is effective to set the appropriate ratio of the excitation of the RFQ to DTL. Therefore, it is concluded that the RFQ cavity can be driven from the DTl cavity through the dual- slot provided in the common end plate.

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