RF FIELD MEASUREMENT OF A FOUR-VANE TYPE RFQ WITH PISLs

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Abstract

Field instability due to a dipole mode mixing is the most significant disadvantage of an original four-vane type radio-frequency quadrupole (RFQ) linac. In order to avoid any dipole mode mixing, several pairs of vane coupling rings (VCRs) have been mainly used so far. However, the VCR has complicated shape and is difficult to fabricate particularly in the RFQ linac operated with a high-duty factor. Thus, a new field-stabilization concept was proposed and was referred to as a π-mode stabilizing loop (PISL) in the previous paper. The empirical results of the rf characteristics measurements on a low-power model cavity with or without PISLs are presented in this paper. The measurements showed that the PISLs were capable of stabilizing the accelerating mode, reducing the ratio of a dipole mode mixing from 7 % to less than 1.5 %.

Introduction

In an original four-vane type RFQ cavity, the lowest-order mode is a dipole mode (TE_{110}-mode). Its resonant frequency is slightly lower than the accelerating mode of the lowest-order quadrupole mode (TE_{210}-mode). An RFQ, being long compared with its rf wavelength, has many other higher-order dipole modes (TE_{11n}-mode). Their resonant frequencies are higher or lower than that of the accelerating mode, or sometimes very close to that of the accelerating mode. The dipole mode with a resonant frequency closer to that of the accelerating mode is more easily mixed with the accelerating mode by a small amount of perturbation. In this way, these dipole modes make it difficult to tune the field distribution. The difficulty in tuning the field distribution was also experienced at KEK in the long low-power model cavity [1], which was fabricated in order to study the rf characteristics of a cavity designed for the Japanese Hadron Project (JHP) [2]. In this cavity, we experienced not only the tuning difficulty but also the field instability due to the dipole mode mixing caused by the thermal stress in the vanes : a few-percent change of the square of the magnetic field arose from a few-degree change of the ambient temperature. Since the dipole mode gives rise to beam bending, the mixing of the dipole mode reduces the acceptance of an RFQ.

In order to enlarge the frequency separation between the accelerating mode and the dipole mode, several pairs of vane coupling rings (VCRs) [3] have been used in most of the successfully operating four-vane type RFQs. Although an RFQ with VCRs is stable against the mixing of dipole modes, it is difficult to fabricate. A VCR with a complicated shape must be machined in a narrow region inside of the cavity. In particular, the cooling of the VCR and the electrical contact between the VCR and the vanes (important for the high duty operation) are very difficult.

Thus, a new field stabilization concept was proposed and was referred to as a π-mode stabilizing loop (PISL) in the previous papers [4,5]. This concept is based upon mode stabilization by magnetic coupling between two neighboring quadrant cavities with closed loop couplers. In order to examine the effects of PISL experimentally, several pairs of PISLs were installed in the low-power model cavity fabricated for the JHP. In this paper, we present the results of rf field measurements on the cavity with or without the PISLs. The detail of the measurements are presented in ref. 6. The results are compared with the theoretical calculations using the MAFIA code package [7,8] and the computer code SUPERFISH [9].

Design of PISL unit-cell

The original low-power model cavity was designed with SUPERFISH as shown in refs. 1 and 6. This is an unperturbed RFQ cavity without vane-modulation, a radial matching section or a side-tuner, but with the vane-ends and the end plates. Therefore, the empirical results can be directly compared with the theoretical values. The calculated resonant frequencies and Q-values of the accelerating mode and the lowest-order dipole mode are listed in the first line of Table 1. In this table, suffixes of Q0 and D0 stand for the accelerating mode and the lowest-order dipole mode, respectively. The terminology of ORG-SF stands for the original cavity analyzed with SUPERFISH.

We designed the PISL installed in the low-power model cavity as follows [5,6]. At first, we attempted to carry out the three-dimensional analyses on the structure with the same cross-section as ORG-SF by using MAFIA. The structure was referred to as ORG-MF (original RFQ cavity analyzed with MAFIA). The calculated results are listed in the second line of Table 1. The absolute values calculated with MAFIA are slightly different from the values calculated with SUPERFISH probably due to the insufficient number of meshes (limited by the ability of the computer used). However, the relative values calculated with MAFIA, such as f_{D0}-f_{Q0} and Q_{D0}/Q_{Q0}, are in good agreements with those calculated with SUPERFISH. Therefore, it is probably possible to accurately calculate the frequency separation between the accelerating mode and the lowest-order dipole mode with MAFIA. This frequency separation determines the field stability of the accelerating mode against the dipole mode mixing. The design value of the separation is set to be more than 30 MHz, since the ATS RFQ with VCRs succeeded to accelerate a H^- beam with a separation of 30 MHz [10]. In practice, the PISL structure was designed to comprise several periodic unit-cells and the two vane-end regions. In this case, only the PISL unit-cell must be analyzed with MAFIA since the shapes of vane-end regions are determined empirically. In Fig. 1, we show the structure of the unit cell (referred to as PISL-MF) thus designed after iterative calculations. The length of structure PISL-MF is the same as that of structure ORG-MF (170 mm) in order to make possible the comparison between the calculated results of these two structures. It is noted that only one-quarter of the cross-section was analyzed by utilizing the symmetry of the cavity. The calculated results are listed in the third line of Table 1. The calculated frequency separation between the accelerating mode and the lowest-order dipole mode is f_{D0}(PISL-MF)-f_{Q0}(PISL-MF)=35.6 MHz. The calculated frequency shift of the accelerating mode by installing the PISLs is f_{Q0}(PISL-MF)-f_{Q0}(ORG-MF)=-16.6 MHz.

RF field Measurements

At first, the experimental setup is described in drawings. The scheme of the end plate is shown in Fig. 2. The low-power rf signals are fed through and detected with loop monitors installed on the end plates. The rf field distribution is measured with the bead-perturbation method, introducing a bead into the inside of the cavity through one of the five holes

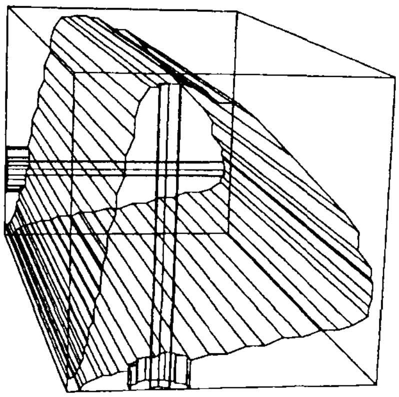


Fig.1 Three-dimensional computer plot of the unit-cell of a four-vane type RFQ cavity with PISLs.

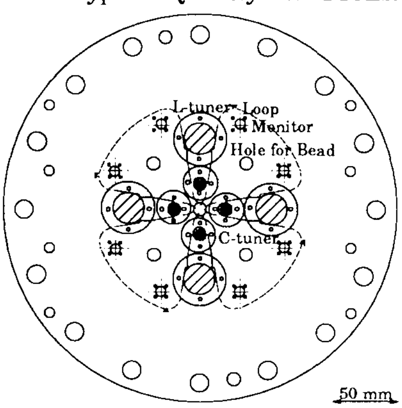


Fig. 2 Scheme of the end plate.

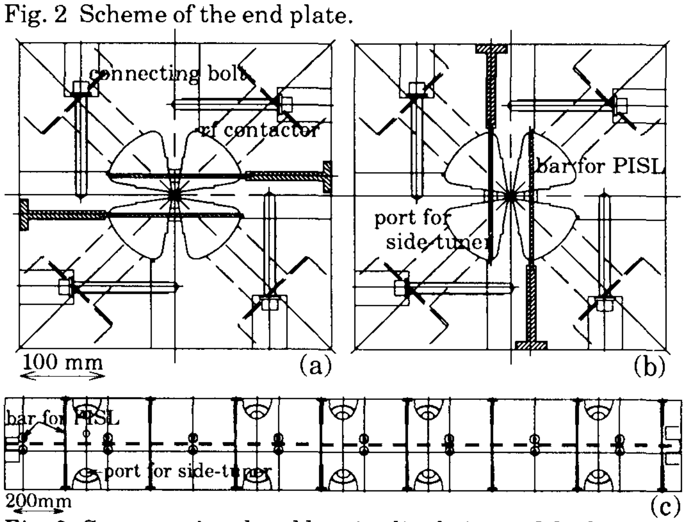


Fig. 3 Cross-sectional and longitudinal views of the low-power model cavity after equipment of the PISLs.
a. Cross-sectional view in the plane of horizontal PISLs.
b. Cross-sectional view in the plane of vertical PISLs.
c. Longitudinal view.

TABLE 1 Calculated and Measured Resonant Frequencies and Q-values.

	f_{Q0}(MHz)	Q_{Q0}	f_{D0}(MHz)	Q_{D0}
Cal.(ORG-SF)	431.221	10,013	417.873	9,835
Cal.(ORG-MF)	427.497	9,729	414.409	9,557
Cal.(PISL-MF)	410.904	9,323	446.508	7,040
Meas.(ORG)	431.438	7,460	420.114	7,073
Meas.(PISL)	416.331	6,800	450.468	4,310

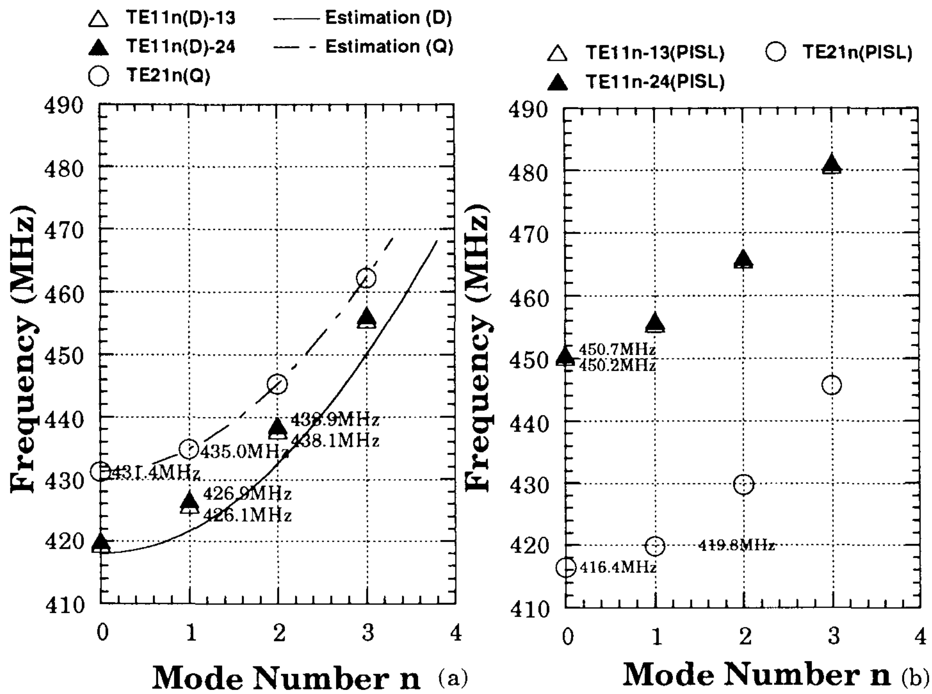
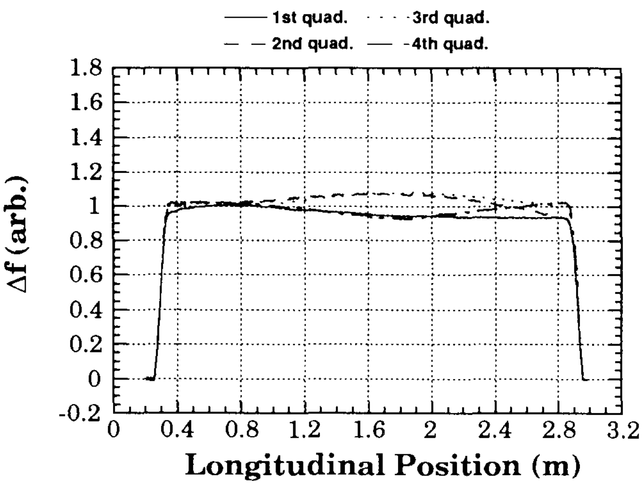


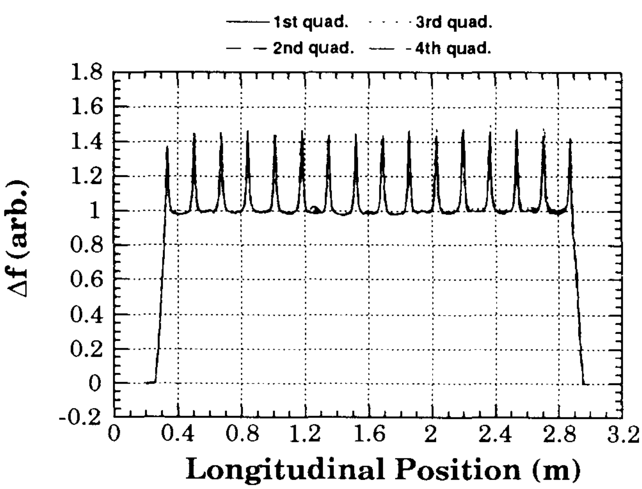
Fig. 4 Measured dispersion curves : (a) the original cavity, (b) the cavity with PISLs.

bored in each of the end plates. One hole is bored at the center of the end plate in order to measure the electric field strength near the beam axis (no field on the beam axis). The other four holes are bored in order to measure the stored energies in the four quadrant cavities. In Fig. 3, we present the drawings of the cavity after equipment of the PISLs : (a) the cross-sectional view in the plane of the horizontal PISLs, (b) the cross-sectional view in the plane of the vertical PISLs and (c) the longitudinal view.

The measured dispersion curves before and after the equipment of the PISLs are shown in Fig. 4a and 4b, respectively. As can be seen from Fig. 4a, the accelerating mode (TE_{210}-mode) is located near the middle of the two dipole modes (TE_{111}-, TE_{112}-modes) in the original cavity. The frequency separation between the accelerating mode and the nearest dipole mode is small (about 4.5 MHz). By installing the PISLs, the resonant frequencies of all the dipole modes (TE_{11n}-modes) were increased by about 30 MHz and becomes higher than that of the accelerating mode. The measured resonant frequencies and Q-values of the accelerating mode and the lowest-order dipole mode in the original cavity are listed in the fourth line of Table 1. Those values in the cavity with the PISLs were also measured as listed in the fifth line of Table 1. The resonant frequency (431.438 MHz) of the accelerating mode in the original cavity is in good agreement with the value calculated with SUPERFISH (431.221 MHz). The small difference between these two values is consistent with the mechanical measurement: the inter-vane distances are about 20 μm larger than the design value. However, the measured frequency separation (f_{D0}(PISL)-f_{Q0}(PISL)=34.1 MHz) between the accelerating mode and the lowest-order dipole mode is slightly smaller than the calculated value (35.6 MHz). Also the measured frequency shift (f_{Q0}(PISL)-f_{Q0}(ORG)=-15.1 MHz) of the accelerating mode due to installing the PISLs is slightly smaller than the calculated value (-16.6 MHz). These discrepancies are probably arising from the modifications of the cross-sections of the bar and the clearance hole due to the insufficient number of meshes. The main reason for the smaller Q-values than the calculated values can be attributed to the roughness of the cavity surface machined by the concave or convex cutters.

The magnetic field distributions in the four quadrants of the cavity before and after the equipment of the PISLs is shown in Figs. 5a and 5b, respectively. These distributions are presented in forms of the squares of the magnetic fields, since the resonant frequency shift measured by the bead perturbation method is proportional to the square of the field strength. As can be seen from Fig. 5a (before the equipment of the PISLs), the magnetic field strengths of the second and third cavities are slightly larger than those of the first and fourth cavities, indicating the mixing of the accelerating quadrupole mode with a dipole mode. The distributions are uniform within ±7 %. (The field uniformity is within ±3.5 %.) By installing the PISLs, every field distribution in each of the four quadrant cavities becomes almost identical (Fig. 5b). The difference between the two distributions of the four results is less than ±1.5 %, which is of the same order of the measurement error. (The difference of the field strength is ±0.75 %.) It is noted that there are many steep peaks, which do not appear in Fig. 5a. These are the modified magnetic field patterns observed at the positions very close to the bars, where the distance between the bead and the bar of the PISL is very short (about 7 mm). In Fig. 5c, we present the measured electric field distribution near the beam axis in the longitudinal direction. The distribution is shown in a form of the distribution of the square of the electric field. It is noted that the small peaks are also observed at the longitudinal positions of the PISLs. However, the uniformity of the square of the field distribution is significantly better than that of the magnetic field distributions (Fig. 5b) and is within about ±1.5%. (The field uniformity is within about ±0.75%.) Therefore, the PISLs have only slight effect on the accelerating electric field.





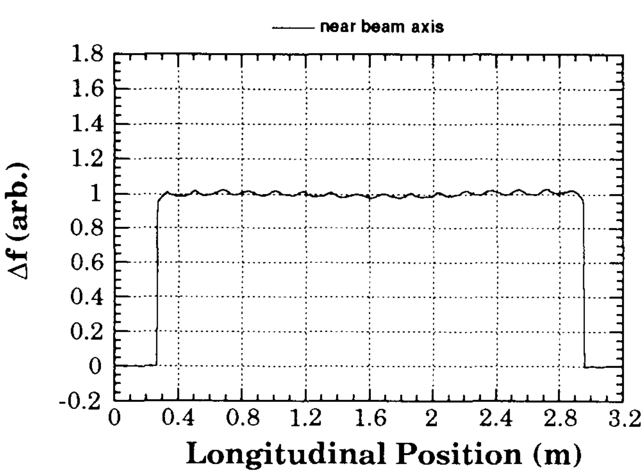


Fig. 4 Distribution of the square of field strength.
a: Magnetic fields in four quadrants of the original cavity.
b: Magnetic fields in four quadrants of the cavity with the PISLs.
c: Electric field near beam-axis in the cavity with the PISLs.

Conclusions

The PISL unit-cell was designed with the MAFIA code package. Several pairs of PISLs thus designed were installed in the low-power model cavity in order to examine the effects of PISLs empirically. By installing the PISLs, the field non-uniformity due to the dipole mode mixing was reduced from 7 % to less than 1.5 %. The measured frequency shift of the accelerating mode by installing the PISLs, which is important to adjust the resonant frequency, is slightly different from the calculated value with MAFIA. Since this discrepancy is arising from the insufficient number of meshes used in the MAFIA analyses rather than the computing errors, the PISL unit-cell for the JHP RFQ cavity can be designed with MAFIA combined with the measured results in this paper. Since the effects of PISLs were experimentally confirmed, we started to fabricate the JHP RFQ with PISLs.

Acknowledgements

The authors are indebted to Prof. Motohiro Kihara for his continuous encouragement.

The authors wish to express their sincere thanks to Mr. Kazuyuki Suzuki and the other members of Nuclear equipment Design Section and Tools Section at Hitachi works, Hitachi, Ltd. for their technical supports.

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