THE π-MODE STABILIZING LOOP FOR FOUR-VANE TYPE RFQs

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Abstract

The tuning of four-vane type radio-frequency quadrupole (RFQ) linacs is difficult, mainly because dipole modes whose resonant frequencies are close to that of the accelerating mode easily mix with the accelerating mode. In order to avoid dipole mode mixing, several pairs of the vane coupling rings (VCRs), which provide periodic electrical connections between diametrically opposite vanes, have been mainly used so far. However, the VCR is difficult to fabricate and is less reliable under high-duty operation. Thus, a new field-stabilization concept has been proposed, and is referred to as a π-mode stabilizing loop (PISL). The concept is based on mode stabilization by magnetic coupling between two neighboring quadrant cavities with closed loop couplers. The results of recent calculations using the MAFIA code package with an increased number of meshes are presented.

Introduction

In a four-vane type RFQ cavity, the lowest mode is a dipole mode (TE110-mode), the magnetic field pattern of which is schematically shown in Fig. 1b) or 1c). Its resonant frequency is slightly lower than the accelerating mode of the lowest-order quadrupole mode (TE210-mode), the magnetic field pattern of which is schematically shown in Fig. 1a). An RFQ, being long compared with its rf wavelength, has many other higher-order dipole modes (TE11n-mode), the resonant frequencies of which are higher or lower than that of the accelerating mode, or sometimes close to that of the accelerating mode.[1] 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. Since the dipole mode gives rise to beam bending, the mixing of the dipole mode reduces the acceptance of an RFQ. Also, the mixing of the other modes to the accelerating mode is a cause of accelerating field nonuniformity.

In order to increase the frequency of the lowest-order dipole mode higher than the accelerating mode, several pairs of vane coupling rings (VCRs),[2] which provide periodic electrical connections between diametrically opposite vanes, have been used in most of the successfully operating four-vane type RFQs. Although an RFQ with several pairs of 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 has been proposed, that is based on mode stabilization by magnetic coupling between two neighboring quadrant cavities with closed-loop couplers. This concept is referred to as a PISL (p-mode stabilizing loop),[3] since the quadrupole mode is considered to be a π-mode azimuthally and the PISL is effective not only for the four-vane type RFQ cavity, but also for a π-mode cavity. In ref. 3 the PISL is compared with the VCR; it is shown that the VCR can be regarded as one version of the PISL.

In this paper, the results of recent calculations are presented concerning the PISL using the MAFIA code package[4,5] with an increased number of meshes. These calculations were carried out in order to design the RFQ with the PISLs for the Japanese Hadron Project (JHP).[6] A practical installation method of the PISL is also described.

Principle and Installation Method of the PISL

The principle of the PISL is detailed in ref. 3. It is briefly described by using one type of the possible PISL arrangements shown in Fig. 2, which will be used for the RFQ of the JHP. It can be seen that two closed loops made of a conductor are formed by adding two bars to a conventional four-vane type RFQ cavity. Each bar is connected to the walls of two neighboring quadrant cavities through a clearance hole bored in the vane. These loops are referred to as PISLs. The area surrounded by the PISL is shown by the hatched region in Fig.2. It is noted that the cavity wall was used as a part of the PISL.

In order to understand the principle of the PISL, it is important to note that the total magnetic flux normal to the surface surrounded by a conductive closed loop will be zero, since the tangential electric field vanishes at the surface of the conductor, as does the integral of the electric field along the closed loop. Then, the magnetic flux shown in Fig. 1a) or 1c) can enter inside of the PISLs, while the flux of Fig. 1b) cannot. Therefore, the PISLs have little effect on the field pattern and, thus, on the resonant frequency for the modes shown in Figs. 1a) and 1c). On the other hand, the magnetic flux shown in Fig. 1b) will make a detour around the loop, increasing the resonant frequency. In this way the PISL pushes up the resonant frequency of one of the dipole modes. It is noted that the hatched area is proportional to the coupling strength as the lowest-order approximation. Since the PISLs shown in Fig. 2 have little effect on the other dipole mode shown in Fig. 1c), the other pair of PISLs must be installed to remaining two vanes for suppressing this dipole mode.

A practical way to install and cool the PISLs is schematically shown in Fig. 3. The PISLs can be fabricated from outside of the cavity by inserting bars after assembling the entire four-vane cavity. It is thus expected that the fabrication of the PISL will be much easier than that of the VCR. The PISLs can be cooled by the water conducted through the pipe used as the bar. Then, the connection point of the water path can be chosen at the outside of the cavity and independently with the rf contact point. Therefore, high reliability for electrical and thermal contacts is expected.

Results of MAFIA Calculations

In order to save CPU time, a small number of meshes ($N_x \times N_y \times N_z = 20 \times 20 \times 49$) were used in calculations of ref. 3, where the shape of the cavity was rather different from the actual state. Thus, after increasing the number of meshes ($N_x \times N_y \times N_z = 34 \times 34 \times 71$) we carried out a MAFIA analysis on a realistic cavity, which has almost the same shape as the RFQ for the JHP.

At first, the resonant frequencies of the lowest-order quadrupole and dipole modes (TE210- and TE110-modes) were calculated for an ideally symmetric four-vane type RFQ cavity with infinite length. Because of its symmetry, only one-quarter of the structure was necessary for the calculation, as shown in a three-dimensional computer plot of Fig. 4. This structure, whose length L_z is 17 cm, is referred to as STD (standard). For the TE210-mode the boundary condition is given by perpendicular magnetic fields to the boundary surfaces of x=0, y=0, z=0, and z=L_z, while for the TE110-mode the magnetic fields perpendicular to the boundary surfaces of y=0, z=0, and z=L_z and parallel to x=0.

The effects of the PISL were studied with the struc-

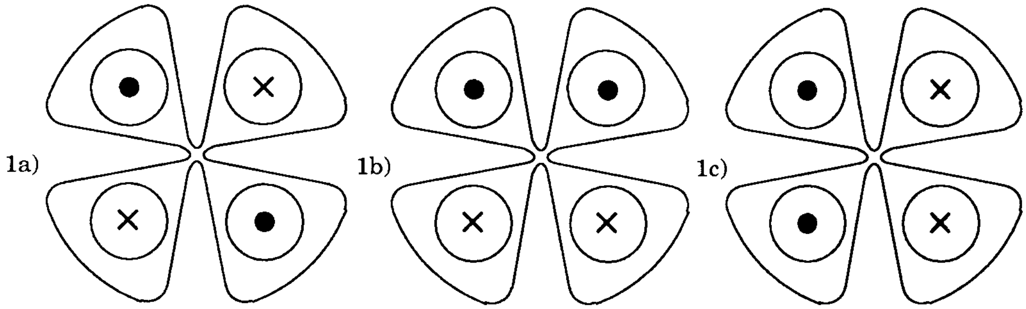

Fig. 1. Magnetic field patterns of the quadrupole mode (a) and the two degenerated dipole modes (b,c).

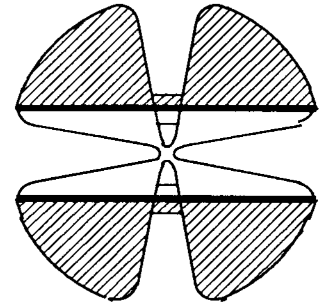

Fig. 2. Arrangement of PISL.

ture shown in Fig. 5. This structure is the same as the structure shown in Fig. 4, except for the bars, which are parts of the PISLs shown in Fig. 2c), and clearance holes through which the bars pass from one quadrant cavity to the neighboring quadrant cavity. The cross sections of the bar and the clearance hole are circles with radii of 2.5 and 7.5 mm, respectively. These values and the position of the PISL were chosen in order to satisfy such technical requirements as the cooling path and rigidity. This structure is referred to as a PISL-JHP. The obtained magnetic field patterns of the lowest-order quadrupole and dipole modes are shown in Figs. 6 and 7, respectively. The magnetic flux of the dipole mode cannot enter inside of one of the PISL (see Fig. 7a)), as described above.

The results of the calculations are summarized in Table I. In order to study the accuracy of the calculations with the MAFIA we also listed the results of the two-dimensional precise calculations ($N_x \times N_y = 150 \times 150$) with SUPERFISH,[7] designated by STD-SF. The symbols of f_Q and Q_Q are the resonant frequency and Q-value of the lowest-order quadrupole mode, respectively; f_D and Q_D are those of the lowest-order dipole mode, and $\Delta f_{QD} = f_D - f_Q$.

It is noted that the dipole mode has a lower frequency than that of the quadrupole mode in the ideally symmetric four-vane type RFQ cavities (STD-SF and STD). Although the resonant frequencies, f_Q and f_D, of the STD are about 3 MHz lower than those of STD-SF, respectively, the frequency difference, Δf_{QD}, of the STD is in good agreement with that of the STD-SF. Therefore, it is expected that the relative values, such as the frequency differences, are fairly reliable in calculations with the MAFIA.

In contrast to the ideally symmetric four-vane type RFQ cavity, the lowest dipole mode of PISL-JHP has about a 35 MHz higher resonant frequency than does the lowest quadrupole mode, indicating that the tuning of the four-vane type RFQ becomes easier with the PISLs. In designing an RFQ cavity with PISLs, it should be noted that the PISLs lower the Q-value by about 5 % and the resonant frequency by about 4 %, respectively.

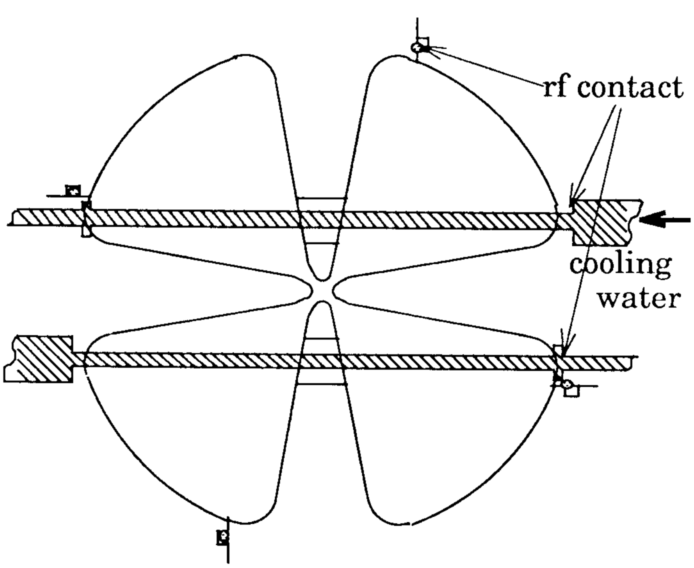

Fig. 3. Practical way to install and cool the PISLs.

Conclusion

A practical way to install and cool the PISL, which satisfies such technical requirements as the cooling path and the rigidity, are presented. The MAFIA analysis on this arrangement shows promising results: the lowest dipole mode has about a 35 MHz higher resonant frequency than does the accelerating mode, and the decrease of the Q-value caused by the PISLs is less than 5 %.

The next step of the study of the PISL is to test the performance of the PISL empirically by installing the PISLs in the cold model of the RFQ cavity for the JHP. If the results are promising, the PISLs will be installed in the RFQ linac for the JHP.

References

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TABLE I
Summary of the calculations.

Structure Name	f_Q (MHz)	Q_Q	f_D (MHz)	Q_D	Δf_{QD} (MHz)
STD-SF	432.244	10014	418.810	9836	-13.434
STD	429.410	9707	416.156	9532	-13.254
PISL-JHP	412.698	9227	447.778	7243	35.080

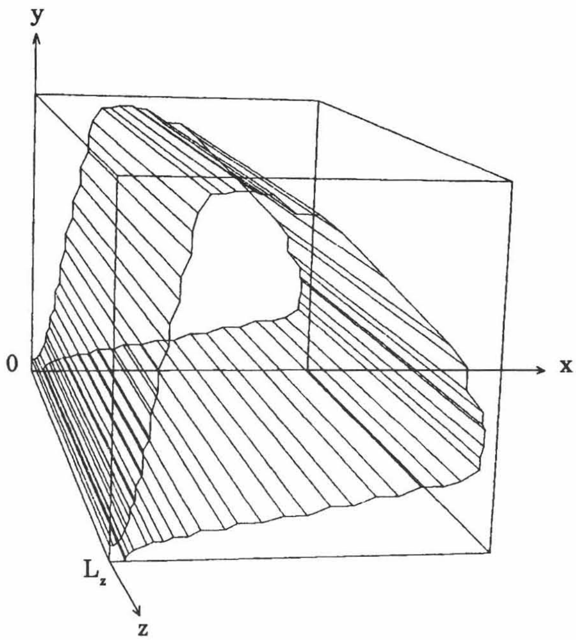

Fig. 4. Three-dimensional computer plot of the STD structure.

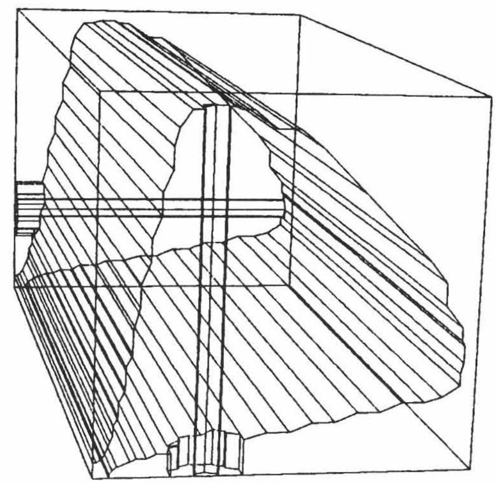

Fig. 5. Three-dimensional computer plot of the PISL-JHP structure.

6a)

6b)

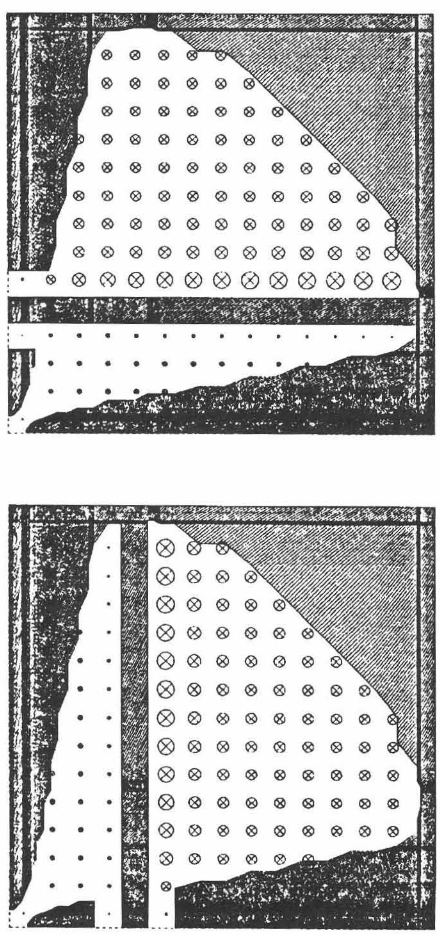

Fig. 6. PISL-JHP's magnetic field patterns of the lowest-order quadrupole mode on the surfaces of z=0 (a) and z=L_z (b).

7a)

7b)

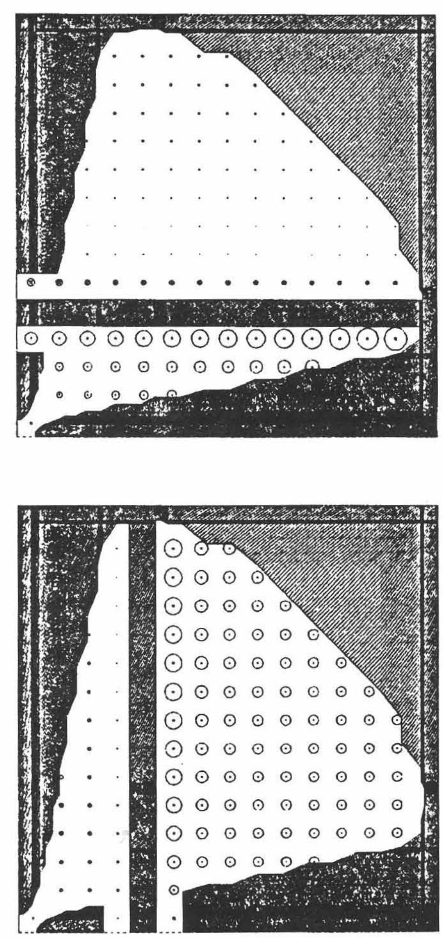

Fig. 7. PISL-JHP's magnetic field patterns of the lowest-order dipole mode on the surfaces of z=0 (a) and z=L_z (b).