# LOW-POWER RF CHARACTERISTICS OF A 432-MHz, 3-MeV RFQ STABILIZED WITH PISLs

**Akira Ueno and Yoshishige Yamazaki**
*National Laboratory for High Energy Physics, KEK*
*1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan*

## Abstract

A 432-MHz, four-vane-type, radio-frequency quadrupole (RFQ) linac was developed as a pre-injector of the 1-GeV proton linac for the Japanese Hadron Project (JHP). It accelerates a 20-mA $H^-$ beam from 50 keV to 3 MeV with a 3% duty factor. In order to stabilize the field against dipole mode mixing, a -mode stabilizing loop (PISL) was devised and several pairs of PISLs were installed in the RFQ. The frequencies of the dipole modes ($TE_{11n}$ modes) are significantly increased and well separated from the accelerating mode ($TE_{210}$ mode). We thus obtained a uniform field distribution within ±0.75% both longitudinally and azimuthally.

## Introduction

During the last six years we have been carrying out the research and development (R&D) on a four-vane-type, radio-frequency quadrupole (RFQ) linac for the 1-GeV proton linac of the Japanese Hadron Project (JHP) [1]. Its resonant frequency, duty factor, injection and final energies were determined from a beam-optics consideration of the entire system to be 432 MHz, 3% (600 μsx50 Hz), 50 keV and 3 MeV, respectively. In order to achieve these requirements, keeping the maximum surface electric field to less than 1.8-times the Kilpatrick limit, the RFQ should be elongated to about 2.7 m [2].

As the first step of the R&D, a low-power model cavity without any field stabilizer, vane modulation or side-tuner was constructed with small relative intervane-distance errors of less than ±30 μm in order to examine the rf characteristics of such a long RFQ cavity [3]. In this cavity we experienced not only a tuning difficulty, but also a field instability due to dipole mode mixing caused by thermal stress in the vanes: a few-percent change in the square of the magnetic field arose from a few-degree change in the ambient temperature. Since the dipole mode gives rise to beam bending, the mixing of any dipole mode reduces the acceptance of an RFQ. The reason for the tuning difficulty and the field instability can be comprehended as follows.

•The lowest-order mode of the four-vane-type RFQ without any field stabilizer is a dipole mode ($TE_{110}$ mode). Its resonant frequency is slightly lower than the accelerating lowest-order quadrupole mode ($TE_{210}$ mode). An RFQ, being long compared to its free-space rf wavelength, has many other higher order dipole modes ($TE_{11n}$ modes). 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. Since the duty factor of the JHP RFQ is significantly higher than that of conventional RFQs, the thermal deformation of the vanes caused by the input rf power cannot be negligible. Therefore, we concluded that the field stabilizer against dipole mode mixing is inevitable for the JHP RFQ.

After a significant amount of studies concerning the field stability, we devised a new method, referred to as a -mode stabilizing loop (PISL) [4,5]. Several pairs of PISLs installed in an RFQ enlarge the frequency separations between the accelerating mode and the dipole modes in essentially the same way as the vane coupling rings (VCRs) [6], which have been used in most of the successfully operating four-vane-type RFQs. Owing to its simple shape, a PISL is significantly easier to fabricate than a VCR. The water-cooling and electrical contact for a PISL (important for high-duty operation) are also easier than those for a VCR. The field stabilizing effect of a PISL was empirically confirmed by installing several pairs of PISLs in the low-power model cavity for the JHP [7]. We therefore decided to construct an RFQ stabilized with PISLs (see Fig. 1) for the JHP [8,9].

In this paper we present the measured low-power rf characteristics of the RFQ.

## Numbers and positions of PISLs, Tuners and so on

In Fig. 2, we show a cross-sectional view of the RFQ cavity and longitudinal views of the four quadrants of the cavity. As shown in the figure, sixteen pairs of PISLs (eight pairs of horizontal PISLs and eight pairs of vertical PISLs) are installed. The distance between the neighbouring horizontal and vertical PISLs are 170 mm (about a quarter of the free-space rf wavelength). Although the number of PISLs per the free-space rf wavelength is about twice as large as the number of VCRs in a conventional RFQ stabilized with VCRs, the longitudinal electric-field distortion due to the additional capacitance caused by the PISLs is about a quarter as small as that caused by the VCRs [4]. There are fifteen spaces on each quadrant between the neighbouring horizontal and vertical PISLs. We use these spaces as ports for the coupler (C), vacuum pumping (V), tuner (stab-tuner:T, stab-tuner with viewing hole:Tw or movable tuner:Tm) or loop monitor (M). We refer to these fifteen ports as a_port, b_port,,, and o_port. At first, the number and positions of the couplers were determined (two couplers at two h_ports on the 2nd and 3rd quadrants). We selected these two positions considering the easiness

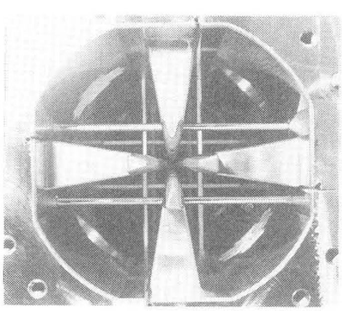

Fig. 1 A photograph of the PISLs installed to the JHP RFQ.

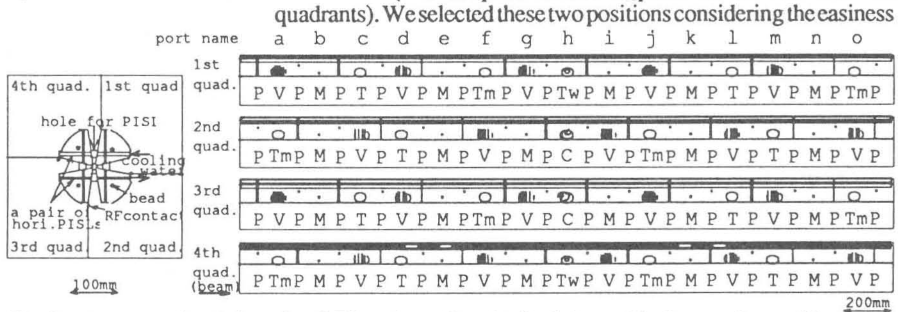


Fig. 2 A cross-sectional view of the RFQ cavity and longitudinal views of the four quadrants of the cavity. The characters of P, C, T, Tw, Tm, V and M stand for PISL, coupler, stab-tuner, stab-tuner with viewing hole, movable tuner, vacuum port and loop monitor, respectively.

of installing the coupler. At the opposite sides of these two ports (two h_ports on the 1st and 4th quadrants), two stab-tuners with viewing holes (Tw) are, respectively, located in order to observe the discharge inside the couplers. These two tuners play another role in compensating for the effect of the couplers upon dipole mode mixing. We then determined the positions of eight stab-tuners (T), eight movable tuners (Tm), twenty vacuum ports (V) and twenty loop monitors (M), as shown in Fig. 2. Note that the same elements are located at diametrically opposite ports. For example, two a_ports on the 1st and 3rd quadrants are used for vacuum ports. Such a dipole symmetrical perturbation causes no dipole-mode mixing like vane modulation. In this way, the tuners (T and Tm) are distributed at eight longitudinal positions (a_, c_, d_, f_, j_, l_, m_ and o_ports). If the same number of tuners were located quadrupole symmetrically, the tuners could be distributed at only four longitudinal positions. When all of the tuners are moved by the same distance in order to tune the resonant frequency of the cavity, the higher order quadrupole mode of the $TE_{217}$ mode would be mixed with the accelerating mode in the former arrangement of the tuners (at eight longitudinal positions), while the $TE_{213}$ mode would be mixed with the accelerating mode in the latter arrangement. The resonant frequencies of the $TE_{217}$ and $TE_{213}$ modes were estimated to be 581.076 MHz and 462.994 MHz, respectively {the resonant frequency of the accelerating mode ($TE_{210}$ mode) is 432 MHz}. The frequency separation between the $TE_{210}$ and $TE_{217}$ modes is about 5-times as large as that between the $TE_{210}$ and $TE_{213}$ modes. Therefore, the longitudinal field distortion due to the tuners in the former arrangement is about one-fifth of that in the latter arrangement. In other words, the tunable region of the resonant frequency in the former arrangement is about 5-times as large as that in the latter arrangement, the acceptable longitudinal field distortion being limited by the beam dynamics. Furthermore, the conductance for vacuum pumping is also improved by distributing the vacuum ports at ten longitudinal positions. The estimated conductance is about 50 l/sec per port.

## RF Field Measurements and Tuning

The rf field distribution of the accelerating mode is measured by the bead-perturbation method, introducing a bead into the inside of each of the four quadrant cavities. The positions of the beads for each quadrant are shown in Fig. 2. We used aluminum columns with 6 mm diameter and 6 mm length as beads. The low-power rf signals were fed through or detected by loop monitors installed on dummy end plates. Figure 3 shows a photograph of the set-up when the low-power rf characteristics were measured.

The measured magnetic-field distributions in the four quadrants before and after tuning both the distributions and the resonant frequency are shown in Figs. 4a and 4b, respectively. These distributions are presented in the 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. In Figs. 4a and 4b, sixteen steep peaks were observed for each quadrant. These peaks represent the locally modified magnetic field near to the rods for the PISLs. It can be seen from Fig. 2 that the distance between the rod and the bead is very small (the minimum value is about 6 mm). Furthermore, the field distribution can be locally modified around the vacuum ports, the couplers and the tuners. In order to correctly estimate the field uniformity not disturbed by these local effects, the field distributions are compared at the ports indicated by the arrows in Figs. 4a and 4b (b_, e_, k_ and n_ports). On these ports, the loop monitors are located quadrupole symmetrically. Since the holes bored on the RFQ cavity in order to install the loop monitors are small (the diameter of each hole is 11 mm), almost no modification in the field distribution was induced by these holes.

When the field distribution shown in Fig. 4a was measured, we used flat end plates at both ends, and each tuner was located at the position where its effect vanished. (From now on, this position is referred to as the standard position of the tuner.) As can be seen from Fig. 4a, the distributions are tilted down by about 10% (5% below the field strength) near to the beam entrance. The shapes of the vane ends were determined by using the empirical results of measurements on a cold model and analyses with the MAFIA code package [10,11], as shown in Fig. 5. However, the vane end cutting at the entrance seems to be slightly smaller than the optimum. In order to compensate for the field tilt, the end plate at the entrance was machined as shown in Fig. 5.

The dipole mode is mixed by about ±3% (±1.5% of the field strength) near to the e_ports and k_ports. This value is about a factor of 1.5 as large as the dipole mode mixing observed in the measurement in the cold model. The measured resonant frequency of 430.46 MHz is also different from the designed value of 431.50 MHz based upon the measured results in the cold model and the analyses with MAFIA. By welding the cooling-water pipes (introducing cooling water from the vacuum chamber to the cavity body) to the RFQ (see Fig. 3), the resonant frequency was shifted by about 0.8 MHz. The deformation due to the welding can be the reason for the deviation in the resonant frequency and the large amount of dipole mode mixing.

After tuning the resonant frequency and the field distribution by machining the tuners and the end plate, we obtained a uniform distribution within ±1.5% both longitudinally and azimuthally, as can be seen from Fig. 4b. (The field uniformity is within ±0.75%.) The inserted lengths of the tuners for tuning are shown in Fig. 6.

The measured dispersion curves of the dipole modes ($TE_{11n}$ modes) and the quadrupole modes ($TE_{210}$ modes) are shown in Fig. 7b. For a comparison, Fig. 7a shows the measured dispersion curves of the dipole modes and the quadrupole modes on the cold model without the PISLs. As can be seen from Figs. 7a and 7b, the frequency separation (26.9 MHz) between the accelerating mode

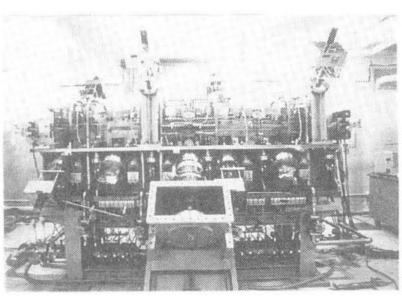

Fig. 3 A photograph of experimental set-up for the low-power rf characteristics measurement.

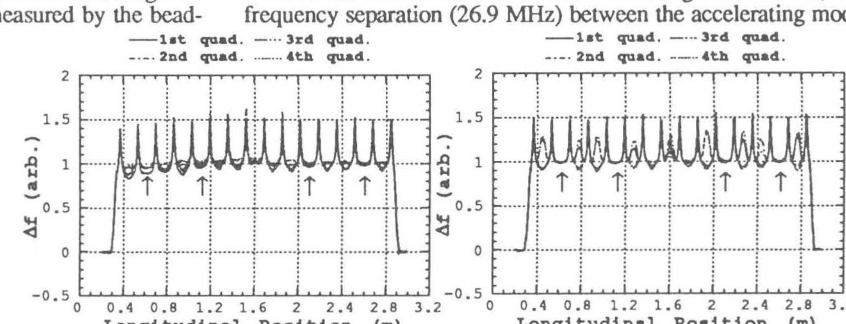


Fig. 4 Distribution of the squares of magnetic field strengths in the four quadrants measured with bead perturbation method : (a) before tuning and (b) after tuning.

($TE_{210}$ mode) and the nearest dipole mode in the JHP RFQ was about 6-times as large as that in the cold model without the PISLs (4.5 MHz).

In order to estimate the field stability against higher order quadrupole mode mixing, we inserted two movable tuners at the a_ports (near to the beam entrance) on the 2nd and 4th quadrants by 0.5 mm and extracted two movable tuners at the o_ports (near to the beam exit) on the 1st and 3rd quadrants by 0.5 mm. After moving these four tuners, the field distributions in the four quadrants were measured with the loop monitors, as shown in Fig. 8. In the figure, the vertical axis shows the pick-up power of each loop monitor normalized with that measured before moving the four tuners. Since the pick-up power is proportional to the square of the magnetic field strength, the distributions are presented in the forms of the squares of the magnetic fields. As shown in Fig. 8, the distributions are tilted linearly by ±4% (a field tilt of ±2%), even with small movements of the tuners, though almost no dipole mode is mixed. Therefore, the accelerating field is not stable against higher order quadrupole mode mixing. However, it is possible to compensate for the field tilt produced by thermal deformation due to the rf power input, since the linear field tilt was easily produced by moving the movable tuners. The field tilt was comprehended as a result of the mixing of the lowest higher order quadrupole mode ($TE_{211}$ mode) with the accelerating mode. The frequency separation between the accelerating mode and the $TE_{211}$ mode is small (3.2 MHz). As shown in Fig. 6, the difference between the inserted lengths of the tuners at the m_ports on the 2nd and 4th quadrants is about 4 mm. The different inserted lengths of these two tuners are the perturbations to mix the dipole mode to the accelerating mode. However, the variation in the amount of the dipole mode mixing was significantly small (from ±1.5% to ±0.75%) with such large perturbations. Therefore, the accelerating mode is much more stable against dipole mode mixing than against higher order quadrupole mode mixing.

At the end of the measurements, the coupling factor of the input couplers and the unloaded Q-value were measured to be 1.098 and 7170, respectively. By using the Q-value, the necessary rf power to generate the design vane voltage was estimated to be 490 kW. The measured coupling factor is close to the ideal coupling of 1.12 for no rf power reflection from the cavity with the design beam loading. The ideal coupling was calculated from a wall loss of 490 kW and a beam power of 59 kW (a 20 mA beam is accelerated from 50 keV to 3 MeV).

## Conclusions

The low-power rf characteristics of the RFQ stabilized with the PISLs were measured. Sixteen pairs of PISLs installed to the RFQ enlarged the frequency separation between the accelerating mode and the nearest dipole mode from 4.5 MHz (measured in the cold model) to 26.9 MHz. The field distribution in the four quadrants of the RFQ was measured by the bead-perturbation method. We easily obtained a uniform field distribution within ±0.75% both longitudinally and azimuthally by modifying the vane end condition and tuning the side-tuners. The measured Q-value of 7170 was 75% of the calculated value with the MAFIA.

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**References**

[1] Y. Yamazaki and M. Kihara, Proc. 1990 Linear Accelerator Conf., LANL report, **LA-12004-C**, 543, (1991).
[2] A. Ueno and Y. Yamazaki, Proc. 1990 Linear Accelerator Conf., LANL report, **LA-12004-C**, 329, (1991).
[3] A. Ueno, T. Kato and Y. Yamazaki, Proc. 1990 Linear Accelerator Conf., LANL report, **LA-12004-C**, 60, (1991).
[4] A. Ueno and Y. Yamazaki, Nucl. Instr. and Meth. **A300**, 15, (1991).
[5] A. Ueno, T. Kato and Y. Yamazaki, Proc. 1990 Linear Accelerator Conf., LANL report, **LA-12004-C**, 57, (1991).
[6] H. R. Schneider and H. Lancaster, IEEE Trans. Nucl. Sci., **NS-30**, (4), 3007, (1983).
[7] A. Ueno et al., Proc. 1992 Linear Accelerator Conf., AECL report, **AECL-10**, 728, (1992).
[8] A. Ueno et al., "High-power Test of a 432-MHz, 3-MeV RFQ Stabilized with PISLs", in this conference.
[9] A. Ueno et al., "The First Operation of a 432-MHz, 3-MeV RFQ Stabilized with PISLs", in this conference.
[10] T. Weiland, Part. Accel., **17**, 227, (1985).
[11] R. Klatt et al., Proc. 1986 Linear Accelerator Conf., SLAC report, **SLAC-303**, 276, (1986).

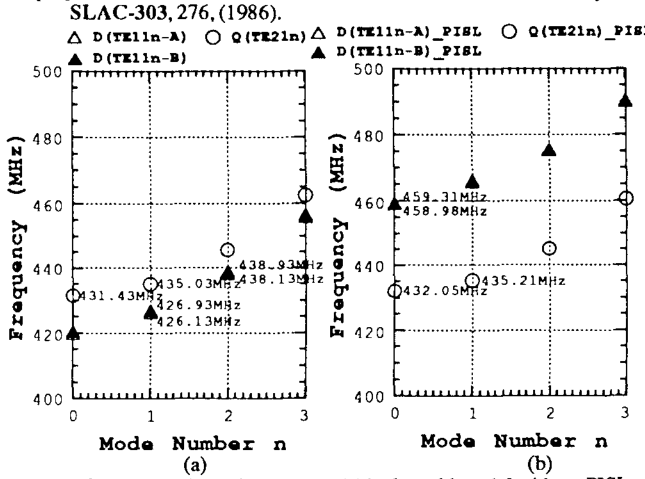


Fig. 7 Measured dispersion curves : (a) in the cold model without PISLs and (b) in the JHP RFQ.

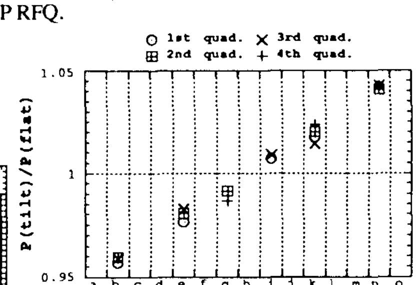


Fig. 8 Distribution of the squares of magnetic field strengths in the four quadrants measured with the loop monitors after inserting two movable tuners at a_ports by 5 mm and extracted two movable tuners at o_ports by 5mm.

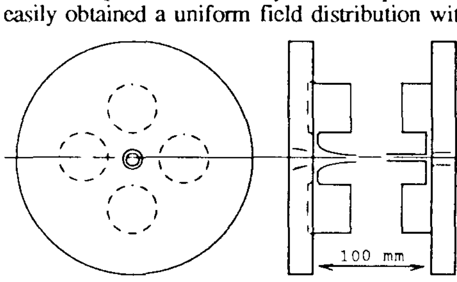


Fig. 5 A schematic drawing of the end plate at the entrance and the both vane end regions.

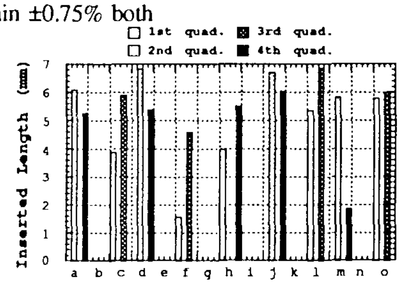


Fig. 6 The inserted lengths of the tuners from the standard positions for tuning.