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DEVELOPMENT OF COMMERCIAL RFQ TOWARD CW APPLICATIONS

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Abstract

TIME Co. developed a new 4-vane RFQ structure that can be used for a very high-duty factor operation. We eliminated the tuners to flatten the field distribution. The tuners increase RF contacts which may trigger unexpected local heat spots and subsequent discharges. In addition, we hollowed out the entire vane to achieve large cooling water channels. A high-power test showed that the commissioning was completed within one day. We could input a nominal RF power without experiencing almost any discharge. The applied duty factor was 5 % at the 200 MHz resonant frequency, and the measured frequency shift was not detected.

INTRODUCTION

In recent years, linear accelerators have been becoming superconducting, especially in the high energy range [1]. Also, applications that require high beam power, such as neutron generation [2] including BNCT [3] and alpha emitter production, have been increasing. These trends have led to strong worldwide demand for high-duty RFQ accelerators. However, the strategy for producing high-duty RFQs is not well established.

Time co. has been supplying three-layered structure RFQs [4] and IH-type linear accelerators, mainly for the Japanese domestic market for more than 10 years. Based on our accumulated technologies and experiences, we have decided to develop a new 4-vane RFQ that can be operated at a high duty factor. Although it is relatively not difficult to achieve a high duty factor by employing a long and large accelerating cavity with a low Kilpatrick limit and a low frequency, this approach [5] is not suitable for industrial use. We developed an RFQ that has a resonant frequency of 200 MHz, a total length of 3.0 m, and an output beam energy of 2.5 MeV. By eliminating stub tuners for voltage distribution and frequency adjustment and significantly strengthening the water channels for cooling passage, the accelerator was able to operate very stably. The first production unit of the RFQ has now been delivered to the Hungarian Academy of Sciences (MTA) is waiting for beam commissioning. The design parameters of the RFQ are summarized in Table 1.

Table 1: Design Parameters of RFQ

Frequency	200.3 MHz
Q Value	14600 (Simulated)
	13400 (Measured)
Design species	Proton
Beam Current	20 mA
Injection beam energy	35 keV
Extraction beam energy	2.5 MeV
Length of Cavity	3060 mm
Weight of Cavity	2.3 ton

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THREE-LAYER STRUCTURE

The three-layer structure has been employed by some IH-Linacs in the past. This structure enables us to easily access the inside of the cavity. This means that precisely controlled machining can be applied directly to any interior segment of the cavity. We employed this structure to a 4-vane RFQ and provided several cavities to the market in Japan. The structure is illustrated in Fig. 1.

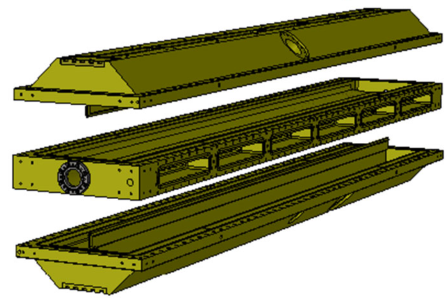

Figure 1: Three-layer structure of TIME RFQs.

As seen in the figure, the 4-vane acceleration cavity is composed of three parts, which are called the upper minor vane, major vane, and lower minor vane, respectively.

The upper minor vane has the vertical vane facing downwards, which is machined as a part of the upper vacuum vessel. The structure of the lower minor vane is the same as that of the upper minor vane but is arranged facing upward. The major vane, the centerpiece, consists of a rectangular frame with two horizontal vanes facing each other. Each of these three pieces is machined from a single forged oxygen-free copper block.

Figure 2: In process of assembling three-layer structure RFQ.

The major vane has grooves in its flange part and an O-ring and RF contact is installed. Although not visible in the Fig. 2, the back side of the major vane has the same structure and vacuum tight and good RF contact conditions are achieved. This structure allows the cavity to be disassembled and reassembled with a high degree of reproducibility. Furthermore, the inside of the vane can be hollowed out directly from the outside of the cavity. Thus, additional

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modifications of the cavity interior and large cooling channels can be machined while maintaining very high precision of electrode positions.

ELIMINATING TUNERS

The Disadvantage of Stub Tuner

Normally, some stub tuners are installed on the inner wall of a cavity to adjust the frequency and electric field distribution. However, stub tuners have a sharp effect on the local electric field distribution. In addition, they concentrate on the surface current distribution in the cavity. Furthermore, this current flows through the RF contacts, which are circular around the stub but difficult to install with perfect symmetry, inducing local heating. This is a major cause of problems in long-term operation. Localized heating leads to the release of gases, resulting in cavity discharges. This is very unfavorable for high-duty accelerators. The story applies not only to the movable tuners for frequency tuning but also to the many fixed tuners that are installed to adjust the electric field distribution.

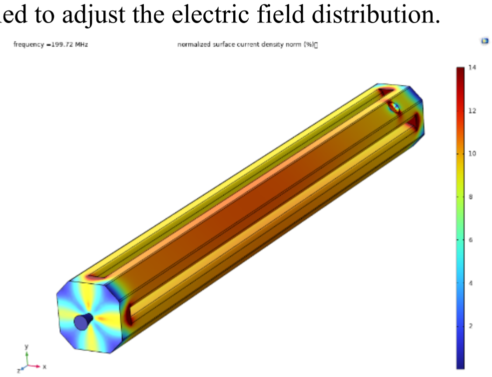

Figure 3: Surface current distribution on the inner surface of the cavity with a single stub tuner. To clarify the effect, the simulation adopts a long insertion length which is 60 mm with a diameter of 65 mm.

The presence of a stub tuner is examined by RF simulation as seen in Fig. 3. A single stub tuner is placed against a perfectly balanced 4 vane RFQ. The shape shown in the figure is the density of current flowing over the surface of the vacuum volume; the current in the RFQ flows in the azimuthal direction relative to the beam axis, which is collected by the tuner cylinder. As a result, the surface current near the tuner will pass through the RF contacts. Figure 4 shows the effect of the single stub tuner on electric field distribution near the beam region. The dotted line shows the tuner position, and a dip of the field is observed. Smooth adjustment is not easy to apply.

Tuner-less Structure

To eliminate the vulnerability caused by tuners, we eliminated cylindrical structures in the interior of the cavity. Movable tuners for tracking temperature changes can be replaced by adjusting the RF frequency supplied by the amplifier. In addition, we can minimize the temperature change of the cavity by having an efficient cooling structure, which will be discussed in the next section.

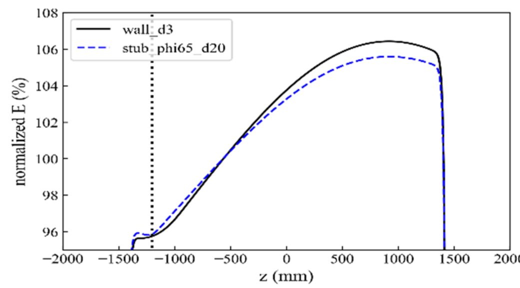

Figure 4: Electric field distribution with a stub tuner (dotted line) and surface cut tuning (solid line). The stub tuner creates a local dip in the distribution.

However, even when cavities are machined with high precision, the final adjustments of the electric field distribution are unavoidable. Therefore, we established a strategy to adjust the electric field distribution by directly machining the inner wall of the cavity. The strategy was made possible by adopting the three-layer structure in which the cavity can be reassembled with very high reproducibility.

For this purpose, the cavity was initially fabricated with a small cavity interior size to have a higher resonance frequency before adjustment. After the cavity was fabricated and assembled, the distribution of the electric field was measured using 'bead pull'. Next, we determined the machining amount of the inner wall according to the algorithm we have developed, which assumes that the effect of the cutting amount on the electric field distribution is linear. In this cavity, the inner wall is divided axially into 6 sections, and the cutting depth in each section, i.e., 24 sections, is determined. The cavity was then disassembled, and additional machining was performed. After that, the cavity was reassembled, and the electric field distribution was checked again. The advantage is that additional wall machining can also be applied on the surface where the feed loop and pickup loops exist.

In total, adjustment processing was performed three times since it was the first test. The impact of the cutting location is across the entire cavity, including the opposing quadrant, and careful planning is essential.

The bead-pull results are shown in Fig. 5. As seen, it was already balanced to some extent before the adjustment process. This proves that the initial machining accuracy is already high. The adjustment has achieved a uniformity of less than 5 %. This is a sufficient balance considering the measurement accuracy and effect on the acceleration performance. The frequency has been changed by the adjustment process from 201.634 MHz to 200.277 MHz.

When operating a 4-vane RFQ at high duty, the most severe heat dissipation occurs at the ends of the vanes facing the end wall of the cavity. In our latest model, the cooling water channels were shaped from the outside of the cavity. Since no gun drilling is used, the channel with the variable cross-sectional area can be made in any shape. The structure of the channel is shown in Fig 6. By applying liquid flow simulation, as indicated in Fig. 7, any stagnating flow spot was eliminated.

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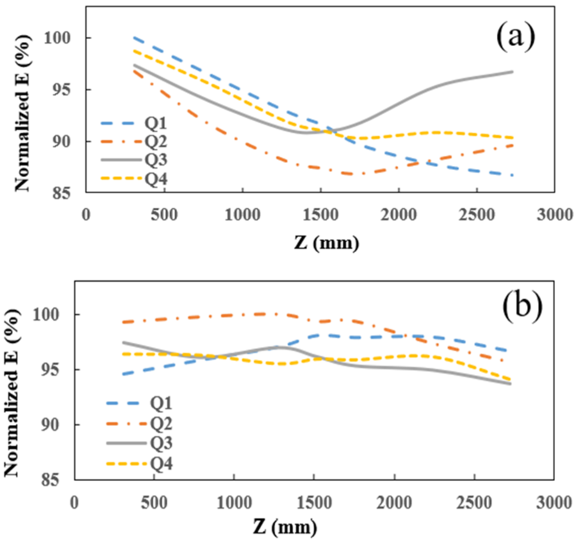

Figure 5: Field distributions before (a) and after (b) adjustment machining processes.

COOLING CHANNELS

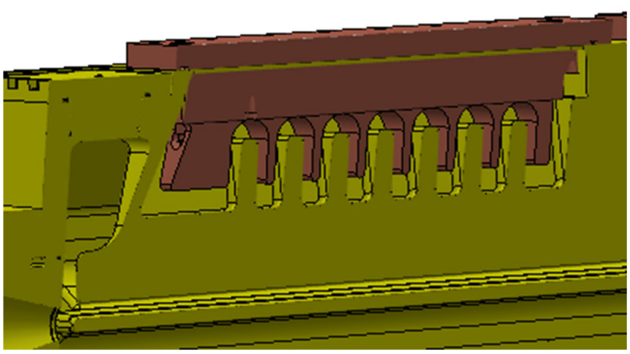

Figure 6: Cut view of the cooling channel at the vane end.

At cavity commissioning, 20 ° C cooling water was supplied at 20 L/min and the recorded maximum temperature increase was 1.3 ° C in the vane and 0.3 ° C in the RF input loop, when the RF power was 201 kw, 1.25 ms of pulse width and 5 % duty factor. The temperature rise was observed in linear relationship to the RF power. This implies that the heat exchange efficiency has been dramatically improved by increasing the contact area of the cooling water.

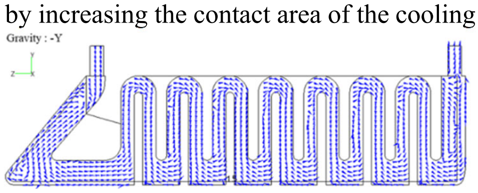

Figure 7: Simulated water flows in the cooling channel.

CONCLUSION

We have established a method to build a high-duty RFQ. Although CW operation has not been experimentally applied, 5 % duty operation showed very good performance at high-power commissioning. The predelivery test was performed at RIKEN at a 3 % duty factor. And 5 % duty factor commissioning was done in Hungary. In both tests, we were not required to have a training period and nominal RF power was achieved within only one day. The observed frequency shift was zero.

Now we are ready to supply high-duty RFQs to the market.

ACKNOWLEDGMENTS

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