DESIGN OF COUPLER FOR DIRECT COUPLED AMPLIFIER TO DRIFT TUBE LINAC CAVITIES OF THE INJECTOR RILAC2 FOR RIKEN RI BEAM FACTORY

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Abstract

Drift Tube Linac cavities for the new injector RILAC2 for RIKEN RI-Beam Factory were designed and constructed. To reduce an installation area and cost, we adopted a direct coupling method for a power amplifier to the cavity without using a long transmission line. A change of resonant frequency of the cavity caused by the coupler and amplifier must be accurately taken into account. The lumped element circuit model was not sufficient to estimate such a change. A complicated design procedure for the coupler and cavity was performed using a three-dimensional electromagnetic calculation software. The required input impedance seen from the amplifier was successfully achieved.

INTRODUCTION

The new heavy-ion linac RILAC2 was successfully constructed and commissioned at RIKEN RI Beam Factory [1, 2]. The main part of the accelerating cavity consists of three drift tube linac (DTL) cavities, operate in continuous wave mode at a fixed frequency of 36.5 MHz. Their structure is a quarter wavelength resonator because the size of the resonator is the smallest available in this frequency range. In order to reduce an installation area further, and to save a construction cost, we adopted a direct coupling method for a power amplifier to each DTL cavity without using a long transmission line. However, the direct coupling of the power amplifier changes the resonant frequency of the coupled system considerably from that of the cavity itself. Thus, the cavity design is dependent on that for the amplifier. Therefore, a detailed cavity and coupler design was carried out by using the three-dimensional electromagnetic calculation software, CST Microwave Studio (MWS).

REQUIRED PERFORMANCES FOR DTL CAVITIES

The design parameters of DTL cavities as determined by beam dynamics calculations [3] are listed in Table 1. The required gap voltages were 110, 210, and 260 kV for DTL1, DTL2, and DTL3, respectively. The height and diameter of the cavity to be used were required to be less than 3 m and 1.3 m, respectively, due to space restrictions in the AVF cyclotron hall. Each cavity consists of an outer and inner conductor, drift tubes, a capacitive coupler, and a capacitive tuner. The amplifiers for the three DTLs were based on the tetrode 4CW50,000E (Eimac). Their maximum output powers were 25, 40, and 40 kW for the respective DTLs. The required gap voltages were obtained when the parallel shunt impedances of each cavity are higher than 1.1 M Ω. The first two cavities (DTL1 and DTL2)

Table 1: Design Parameters for DTL Cavities

Cavity	DTL1	DTL2	DTL3
Frequency (MHz)	36.5	36.5	36.5
Duty (%)	100	100	100
Mass-to-charge ratio	7	7	7
Input energy (keV/u)	100	220	450
Output energy (keV/u)	220	450	670
Diameter (m)	0.8	1.1	1.3
Height (m)	1.32	1.429	1.890
Gap number	10	10	8
Gap length (mm)	20	50	65
Gap Voltage (kV)	110	210	260
Drift tube aperture radius (mm)	17.5	17.5	17.5
Peak surface field (MV/m)	8.9	12.3	13.7
Synchronous phase (°)	−25	−25	−25
Power amp. (Maximum: kW)	25	40	40

were newly constructed, while the DTL3 cavity was modified from the decelerating cavity of the Charge State Multiplier (CSM) [4]. The design of the cavity without a coupler and amplifier was performed by MWS [5].

AMPLIFIER DIRECT COUPLING

Figure 1 shows images of the amplifiers and coupler, coupled to the DTL3 cavity. The RF coupler consists of

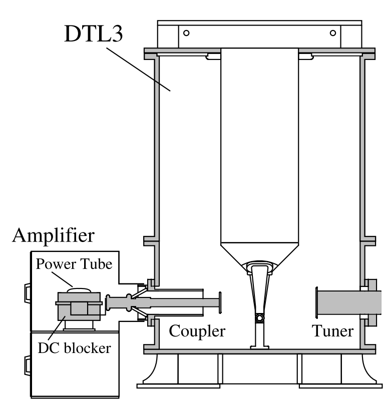

Figure 1: Schematic of the amplifiers coupled to cavity of DTL3. The output from the amplifier is directly connected to the coupler through a capacitor (DC blocker).

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a non-50 Ω coaxial cylinder and a coupler disk attached to the tip of the inner cylinder. A position of the inner cylinder is manually adjustable within ± 20 mm to tune input impedance.

The standard method is that an output impedance of the amplifier is matched to 50 Ω using a stub and an output capacitor. As compared with that, the direct coupling method of the power amplifier to the cavity reduces the number of the parts used in the amplifier. Thus its cost and size are reduced. However, it is required to match the input impedance to the cavity taking into account the capacity of the tetrode as well as the characteristic impedance and length of the coaxial part. The resonant frequency changes considerably by a value more than that for the case of the standard method. In particular, the assumed tunable frequency range of the capacitive tuner for DTL3 was ±0.6% (±220 kHz). To tune the resonant frequency of the whole system within the range, the frequency of the cavity alone should be within a third of it (±73 kHz). It means that, in the design of the cavity, the calculation of the resonant frequency of the cavity must be performed with an accuracy of ±0.2 %.

DESIGN OF RF COUPLER

We first tried to calculate frequency changes due to a direct coupling scheme by using a lumped element circuit. The circuit model for the direct coupled system is shown in Fig. 2. Here, $Z_{cav}, C_{cpl}, Z_w, l, C_p$, and L_{choke}

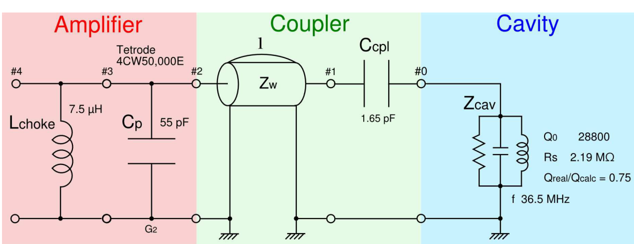

Figure 2: Lumped circuit element diagram of the coupled system of the amplifier, coupler, and cavity of DTL3.

denote the impedance of the cavity, coupling capacitance, impedance and length of the coaxial line, parallel capacitance of the tetrode, and parallel inductance of the choke coil, respectively. The optimum input impedance seen from #4 is 700–1100 Ω, which corresponds to the optimum output impedance of the tetrode. The frequency of the cavity alone was temporarily set to be 36.5 MHz, the actual value of Q_0 was assumed to be 75% of the calculated value, and C_p was 55 pF as obtained from the specification sheet of the tetrode. The input impedance was matched when C_{cpl} was 1.65 pF, where the frequency change was −458 kHz. The lumped element circuit calculation overestimated the frequency change (c.f. actual change is ~ -300 kHz).

The lumped element circuit model calculation was also performed with a 50-Ω coupler system. The impedance seen from #2 in Fig. 2 was calculated assuming $Z_w = 50\Omega$, $l = 1700$ mm, and the resonant frequency of the cavity alone was 36.975 MHz. The input impedance was matched to 50 Ω when C_{cpl} was 0.5 pF. The calculated input impedances are shown in Fig. 3 as well as the measured data. The frequency change by the cou-

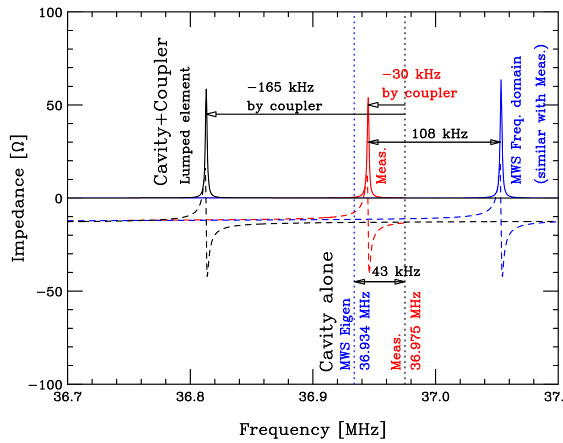

Figure 3: Input impedance for 50 Ω-coupler calculated by lumped circuit element. The real and imaginary parts of the input impedance are shown by solid and broken lines, respectively. The measured values are shown by red lines.

pling was −162 kHz for the lumped element circuit calculation, whereas −30 kHz for the measured data. The lumped element circuit calculation overestimated again the actual value by a factor of more than five. The result of the MWS frequency domain solver shows a poor agreement of the frequency change (+78 kHz), however, the distribution of the impedance was well reproduced. The frequency change was more precisely calculated by using the MWS eigenmode solver. The frequency change by the eigenmode solver was −21 kHz, which was close to the measured value. Therefore, by combining the frequency domain and eigenmode solver of the MWS, the coupled system of the coupler and cavity can be designed. The tetrode, which was difficult to be treated in MWS, was taken into account by a method of the lumped circuit element.

DETERMINATION OF COUPLING STRENGTH AND CAVITY HEIGHT

Input impedances were calculated by using the frequency domain solver of MWS. The calculations with MWS were performed without accounting for the tetrode, and subsequently, the tetrode was taken into account as a parallel capacitor by the method of lumped element circuits. In order to simulate the ratio of the Q_0 factor (78% of the ideal value), the electric conductivity was set to be 61 % of the conductivity of copper ($5.8\times10^7\times0.78^2 = 3.53\times10^7$ [S/m]). The tuner position measured from the center of the cavity was set at 362.8 mm, at which distance the frequency attained the center of its variable range. To determine the coupling strength, calculations were performed by varying the diameter of the coupling disk from 110 to 170 mm. The impedances without the tetrode are plotted

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on a Smith chart in Fig. 4. Without the tetrode, the desired impedance Z' is written as $1/Z' = 1/700 - j\omega C_p$. The plot of impedances against frequency is shown in

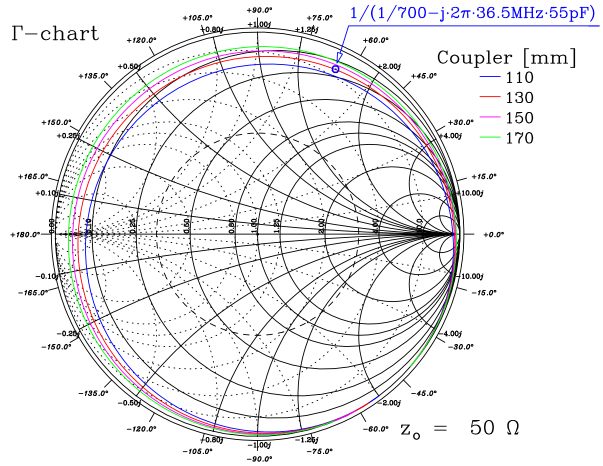

Figure 4: Calculated input impedance without the tetrode shown in a Smith chart. Desired impedance Z' is shown by a blue circle.

Fig. 5. The impedance with the tetrode was calculated with $1/Z = 1/Z' + j\omega C_p$. The calculations showed the frequency change by the coupler was -290 kHz, and the change by the tetrode was -19 kHz (-309 kHz in total). The input impedance was calculated to be 750 Ω, which was close to the desired value of 700 Ω. The size

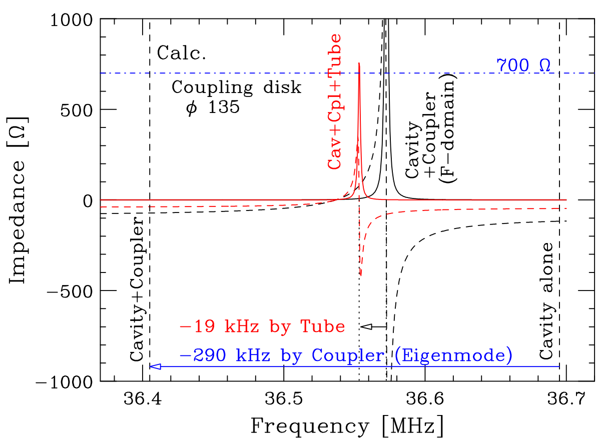

Figure 5: Calculated input impedances for DTL3 with the coupling disk of ϕ 135 mm. Black solid and broken lines indicate the real and imaginary impedances, respectively, for the case without the tetrode. Red solid and broken lines denote the real and imaginary impedances, respectively, when the tetrode was attached in parallel as a lumped element.

of the coupling disk was finely tuned by measuring the impedance with the actual cavity. Figure 6 shows the measured impedance with a coupling disk of ϕ130 mm. The input impedance was 690 Ω at 36.5 MHz. The frequency changes by the coupling of the coupler and tetrode agreed well with the calculation.

Based on these results, the cavity height was determined as follows. The frequency of the cavity alone was set to

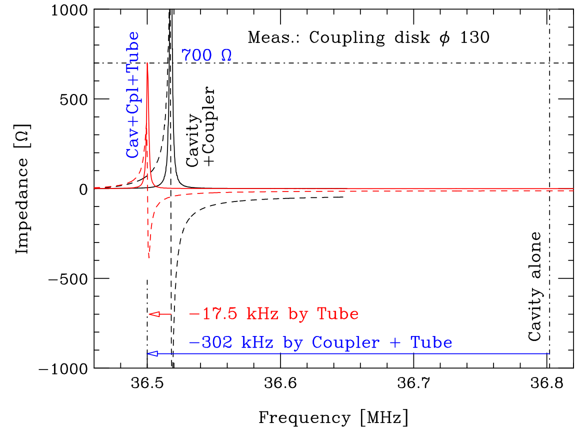

Figure 6: Measured coupling impedances for DTL3 with the coupling disk of ϕ130 mm. The notation is the same as that in Fig. 5.

be 36.725 MHz (0.225 MHz higher than the required frequency of 36.5 MHz). When the CSM cavity was modified to DTL3, a movable shorting plate was removed, and a flange was attached between the inner conductor and the top plate. The frequency was estimated to be increased by 0.125 MHz using the eigenmode solver. Based on the relation between the cavity height and frequency measured before the modification, the cavity height of DTL3 was determined to be 1890 mm (Fig. 7).

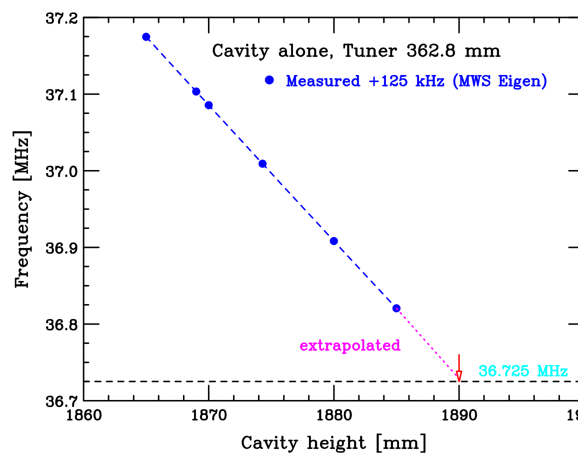

Figure 7: Measured resonant frequency of DTL3 with a movable shorting plate. The frequency shift caused by a removal of the shorting plate (0.125 MHz) is taken into account.

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