

# DEVELOPMENT OF INTER-DIGITAL H-MODE DRIFT-TUBE LINAC PROTOTYPE WITH ALTERNATIVE PHASE FOCUSING FOR A MUON LINAC IN THE J-PARC MUON G-2/EDM EXPERIMENT

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## Abstract

An inter-digital H-mode drift-tube linac (IH-DTL) is developed in a muon linac at the J-PARC E34 experiment. IH-DTL will accelerate muons from 0.34 MeV to 4.5 MeV at a drive frequency of 324 MHz. Since IH-DTL adopts an APF method, with which the beam is focused in the transverse direction using the RF field only, the proper beam matching of the phase-space distribution is required before the injection into the IH-DTL. Thus, an IH-DTL prototype was fabricated to evaluate the performance of the cavity and beam transmission. As a preparation of the high-power test, a test coupler is designed and fabricated. In this paper, the development of the coupler and the result of the low-power measurement will be presented.

In our IH-DTL, an alternative phase focusing (APF) method [5] was employed in order to realize the simplification of the cavity and the short distance acceleration. In the APF method, the beam is focused only on the RF field without a focusing element. The basic design of an actual cavity [6] has already been completed. A prototype is fabricated to study the cavity performance. Table 1 shows the basic parameter of the IH-DTL prototype. We measured the resonant frequency and electromagnetic field in the prototype cavity [7], and confirmed the field distribution of prototype cavity is consistent with the simulation by using CST MicroWave Studio [8].

Table 1: Requirements for the APF IH-DTL Prototype

Resonant frequency	324 MHz
RF power	60 kW
Repetition rate	25 Hz
RF duty factor	0.25 %
Input energy	0.34 MeV
Output energy	1.3 MeV

## INTRODUCTION

The muon anomalous magnetic moment ( $g_\mu - 2$ ) is one of the promising quantities used to investigate beyond the Standard Model (SM) of particle physics. The  $g_\mu - 2$  was measured at Brookhaven National Laboratory [1], and a discrepancy of  $3 \sim 4\sigma$  was observed between the measured value and the SM prediction [2]. Higher precision measurement of the  $g_\mu - 2$  and electric dipole moment (EDM) is planned using a new technique at the Japan Proton Accelerator Research Complex (J-PARC E34 [3]). In this experiment, a low emittance muon beam obtained from muon linac [4] shown as Fig. 1 is used to reduce a systematic error derived from the muon beam.

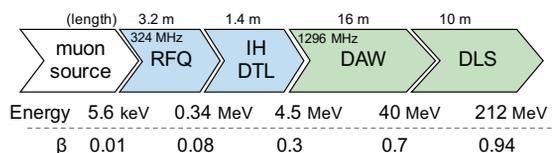


Figure 1: Schematic image of muon linac.

Coupling of RF power to the cavity is a critical element in the development and operation of the prototype cavity. The difference between a high shunt impedance of the cavity and a characteristic impedance of an input coupler as an RF transmission line leads to reflection of the RF power from the cavity and reducing the efficiency of cavity performance. The input coupler loop is designed to match the impedance of the transmission line with that of the cavity. When a coupling constant  $\beta$  equals unity, so-called critically coupled, the RF power coupled to the cavity is maximum.

In this paper, first of all, the development of the coupler is described. Then, we show the results of the low-power measurement for optimization of the coupler loop. Finally, the summary and prospect are presented.

## DESIGN OF A TEST COUPLER

The required RF power is 60 kW and the duty factor is 0.25 %, so that a temperature increases of the cavity and

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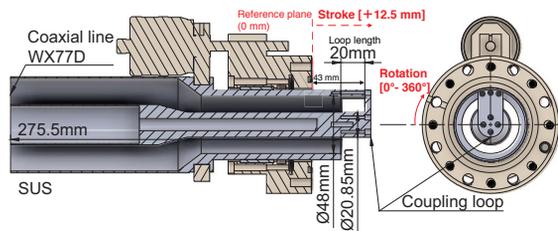


Figure 2: Design of a test coupler for the low-power measurement.

a coupler is small. A coaxial coupler, which has a simple structure and no cooling system, based on the model for RFQ at J-PARC LINAC [9] is designed. The coupler and a frequency tuner are attached to the cavity, the axial symmetry of the RF field is disturbed. It will cause an emittance growth or a deviation of a trajectory. Thus, the coupler has to be optimized to suppress the insertion amount of a coupling loop to a necessary minimum. Figure 2 shows the structure of a test coupler to optimize the coupling loop. The  $\beta$  of this coupler can be changed by a loop length, loop stroke, and loop rotation. The coupler loop is used that of 20 mm length to achieve a critically coupling. The insertion amount can be changed by using the loop stroke of +12.5 mm with a micrometer head (MHQ-50, Mitutoyo). The loop rotation is used for a fine adjustment of the  $\beta$  over an angular range of  $0^\circ \leq \theta \leq 360^\circ$ . The connecting section of the coupler and the coaxial waveguide is the WX77D. That of the coupler and cavity is tapered.

## OPTIMIZATION OF THE COUPLER

### S-Parameter Measurement

Figure 3 (a) shows an experimental setup for optimization of coupler loop in the low-power measurement. Three tuners are respectively installed at different positions so that the symmetry of RF field derived from the tuner can be improved. Tuners are capable of frequency tuning over the frequency range from 0 to 5 MHz by hand. It has sufficient stroke corresponding to the 324 MHz, since the resonant frequency with only cavity is 321.2 MHz [7]. Figure 3 (b) shows the cross-section of the cavity. The coupler is installed by an angle of 45 degrees based on the cavity. Extractions of an input and output signal are used the coupler loop ( $\beta_1$ ) and a pickup loop ( $\beta_2$ ), respectively. A vector network analyzer (VNA) is used for measuring the S-parameter of the coupler and cavity.

The  $\beta$  in the RF loop due to the magnetic field of the cavity is given [10] by

$$\beta = \frac{\omega_0^2 \mu_0^2 A^2 \cos^2 \theta H^2}{2Z_W P_c} \quad (1)$$

where  $\omega_0$  is an angular frequency,  $\mu_0$  is the permeability of free space,  $A$  is area of the loop,  $\theta$  is the angle between the magnetic field and area of loop,  $Z_W$  is the characteristic

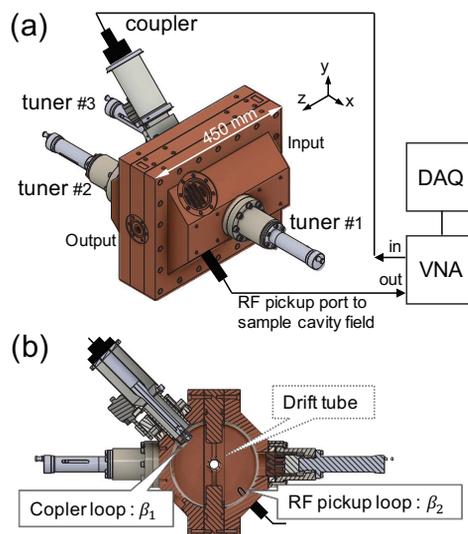


Figure 3: (a) Experimental setup for low-power measurement. The coupler and an RF pickup loop, to sample RF field in the cavity, is connected the VNA. (b) Cross-sectional view of the cavity.  $\beta_1$  and  $\beta_2$  are determined by the structure of these loops.

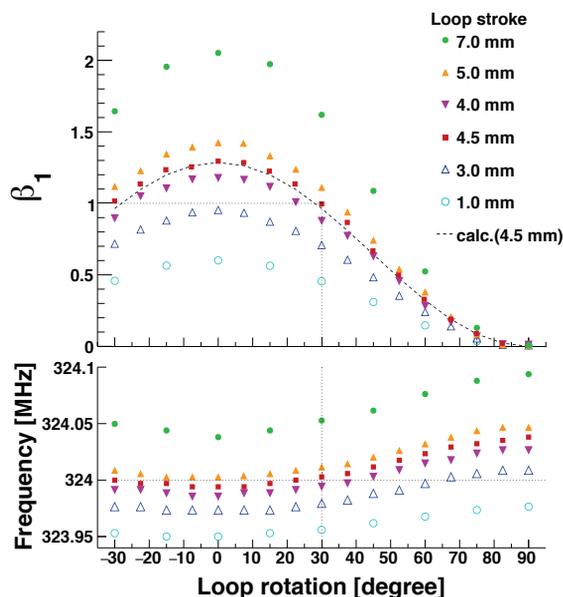


Figure 4: Loop rotation dependence of the  $\beta_1$  (upper) and the resonant frequency (lower). Optimize the  $\beta$  at the loop rotation angle of 30 degrees. The dotted line shows the calculated value for the loop stroke of 4.5 mm.

impedance of the transmission line,  $H$  is the peak cavity magnetic field at the region of the loop, and  $P_c$  is the power losses in the cavity. In case of a high-power input, loop stroke is not operated to prevent from vacuum leakage, so that fine-tuning of the  $\beta$  is accomplished by rotation of the loop. When the coupler loop is optimized with  $\theta = 0^\circ$ , the  $\beta$  is only decreased even if the loop is rotated. When the loop

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is intentionally rotated at an angle, for examples,  $\theta = 30^\circ$ , the  $\beta$  can adjust either increasing or decreasing. Thus, In this measurement, the coupler is optimized at an angle of 30 degrees.

The upper and lower plots of Fig. 4 shows the loop rotation dependence of  $\beta_1$  and the resonant frequency, respectively. The  $\beta_1$  increase in proportion to the  $A^2$  determined by the loop stroke. The  $\beta_1$  is 1.011 when the loop stroke is 4.5 mm at the loop rotation angle of 30 degrees. The measured  $\beta$  is consistent with the calculated  $\beta$  by Eq. 1 within a range of 4%. The resonant frequency also increases in proportion to the loop stroke. In addition, the frequency variation by the rotation is about 0.44 kHz per degrees. This frequency perturbation is capable of being adjusted by using tuners.

Figure 5 shows a typical Smith chart and SWR of the coupler port for  $\beta_1 = 1.011$  at 324.00 MHz. In addition, the impedance of S21 is indicated for calculating Q factor. Table 2 shows the results of the optimization of the coupler and three tuners.  $Q_0$  decreased by 18% with tuner and coupler. The cause is presumed to be a large stroke of tuners and coupler loop. The experimental results make it clear the coupler loop stroke and rotation for critically coupling.

Table 2: The Result of an S-Parameter Measurement with Tuners and Coupler or Not

Tuner 1 stroke[mm]	0	46.0
Tuner 2 stroke[mm]	0	45.0
Tuner 3 stroke[mm]	0	45.0
Coupler length [mm]	no	20.0
stroke[mm]	no	4.5
rotation[degree]	no	30
Resonant frequency [MHz]	321.21	324.00
$Q_L$ (loaded $Q$ )	6674.90	3257.00
$Q_0$ (unloaded $Q$ )	7844.34	6647.54
$\beta_1$	-	1.011
$\beta_2$	0.08	0.03

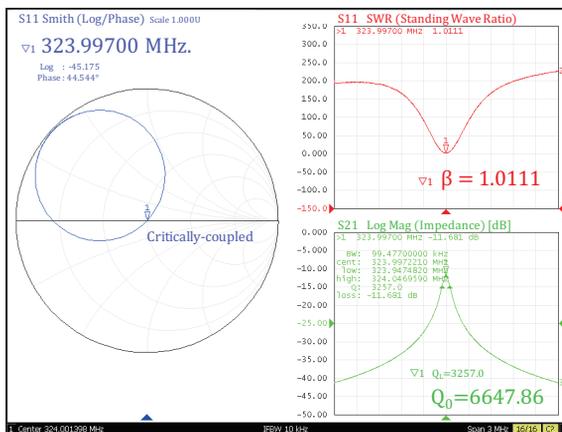


Figure 5: The S-parameter plots show the Smith chart of coupler port of 324 MHz with critically-coupled (left), SWR tuned to  $\beta_1 \sim 1$  (upper right), and S21 measurement (lower right).

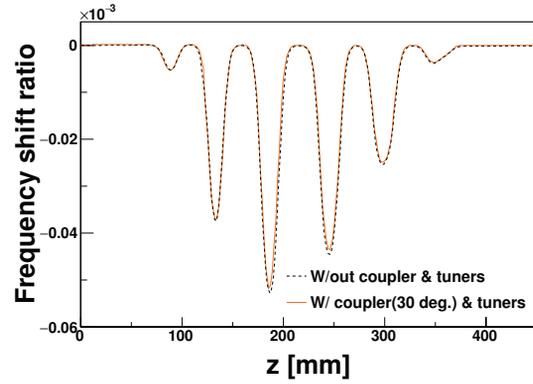


Figure 6: The solid line and the dotted line shows the measured frequency shift ratio in the cavity with the coupler and tuners or not as a function  $z$ .

### Bead-Pull Measurement

When the loop stroke is 4.5 mm at the loop rotation angle of 30 degrees, the RF field in the cavity with the coupler and tuners is measured by using a bead-pull measurement [11]. The perturbation of the resonant frequency, so-called frequency shift, depends on the relative strengths of the RF field. An aluminum bead with a 1.5 mm radius is attached to a fishing line, which is stretched between the input port and output port. A data of frequency shift, when the bead is moved from the input port ( $z = 0$  mm) to the output port ( $z = 450$  mm), is acquired using VNA and DAQ. The solid and dotted line in Fig. 6 show the measured frequency shift ratio with coupler and tuners or not. A disturbance of the RF field derived from coupler and tuners can be suppressed under approximately 7%. Thus, we decided to adopt the loop length of 20 mm and the loop stroke of 4.5 mm at the loop rotation angle of 30 degrees.

## SUMMARY AND PROSPECT

The IH-DTL prototype is developed in a muon linac at the J-PARC E34 experiment. The test coupler as an RF transmission line was designed and fabricated. The coupler loop was optimized to match the critically coupling with an angle of 30 degrees. In addition, the variation of  $\beta$  with loop stroke and rotation has also been studied. The results of bead-pull measurement confirmed that the effect of the coupler and tuners on the RF field along the beam axis is very small.

The design of an RF window is required for high-power coupler. We plan to design a tapered RF window, made by alumina ceramic, without changing the present dimensions of coaxial line coupler.

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