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ESTIMATION OF ALIGNMENT ERROR BY MEASURING HIGHER-ORDER-MODE OF INJECTOR SUPERCONDUCTING CAVITY AT KEK-cERL

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Abstract

cERL is a test accelerator of an energy recovery linac scheme which can realize a high quality beam in a high averaged current. In order to realize a low emittance beam, beam position control in the superconducting accelerating cavity is important. By measuring higher-order-modes (HOM) excited in the cavities, the electrical center of the cavity can be detected. Comparing the HOM signals of the three independent cavities in the injector cryo-module, we estimated the relative alignment errors of the three cavities. The relative positioning errors were found to be 2.5 mm and 0.3 mm in the horizontal and vertical planes, respectively.

INTRODUCTION

The energy recovery linac (ERL) is the unique scheme to realize a low emittance and short bunch beam of linac quality at a high averaged current. A test ERL accelerator (cERL [1]) has been constructed in KEK for demonstrating the feasibility of future ERL facilities.

In order to realize the low emittance, precise tuning of the beam trajectory in the accelerator cavities is important. The beam trajectory should be aligned on the field center of all the cavities. In the case of SRF accelerator of the cERL injector, three independent 2-cell cavities are installed in the cryo-module. If the three cavities are not aligned on a straight line, the beam has to have finite offsets with respect to each cavity even if one tryed to tune the incoming beam trajectory. The requirement of the alignment precision was estimated to be better than 0.4 mm for keeping the emittance degradation less than 10 %.

It is difficult to directly check the alignment of the cavities by an mechanical method once they were installed and cooled in the cryo-module. One promising and most effective method is to measure the beam signal. We have developed a setup to detect the higher-order-modes (HOM) of the cavities excited by the beam passage. By measuring the dipole mode signal of each cavity while scanning the beam trajectory, the field center of each cavity can be estimated.

PRINCIPLE

Excitation of rf modes in a cavity structure by a beam passage is a well established phenomenon. When a bunch of charge q passes a cavity, the output power from an extraction port of the cavity is given as

$$P_{out} = \frac{\omega q^2}{4Q_{ext}}(R/Q) \quad , \tag{1}$$

where ω is the angular frequency of the mode, Q_{ext} is the external quality factor of the port. The R/Q is the integration of the electric field of the mode along the beam trajectory normalized by the total energy of the mode U, given as

$$R/Q = \frac{|\int \vec{E} \cdot \vec{ds}|^2}{\omega U} \quad . \tag{2}$$

Since a dipole mode (TM110) has a node at the cavity center, the excited amplitude of the dipole mode is proportional to the beam offset with respect to the field center. When the beam passes at the electrical center of the cavity, the dipole modes are not excited.

SETUP

Injector Accelerator Cavity

The injector accelerator consists of three 2-cell 1.3 GHz SRF cavities installed in a cryo-module [2]. Figure 1 shows a drawing of the cavity. In order to remove various HOM excited by the beam passage, 5 HOM couplers are attached for each cavity, 3 in the upstream side and 2 in the downstream side. The parameters related to HOM has been reported in elsewhere [3]. Table 1 summarizes the important parameters of the dipole mode used in this study.

Table 1: Parameters of the TM110 Mode

Parameter	value	comment
Frequency	1800 MHz	
Q_{ext}	~3000	for 5 port
R/Q	0.04 Ω	for 1 mm offset

Figure 2 shows the beam line layout around the injector module. The electron beam from a DC-gun, the beam energy was 390 keV in this experiment, is accelerated up to 6 MeV by this injector accelerator. There are steering magnets, namely ZH4 for the horizontal and ZV4 for the vertical plane, at the upstream of the cryo-module. We used these magnets for scanning the beam trajectory in this experiment. The screen monitor, MS3, located at the downstream was used to calibrate the steering kick. The signal from HOM pick-up ports are transferred to the detection electronics located at the outside of the accelerator shield.

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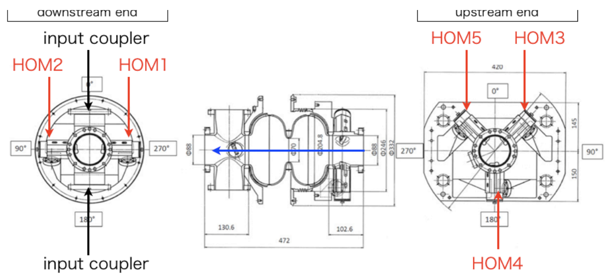

Figure 1: Layout of the HOM couplers.

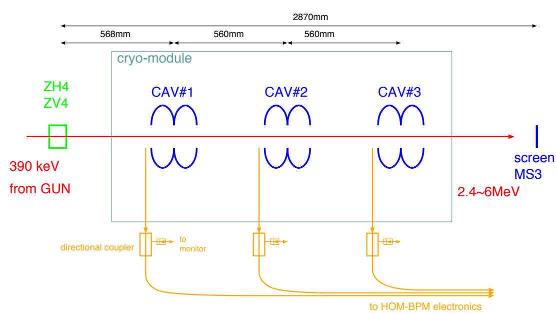

Figure 2: Layout of the injector.

Detection Electronics and Beam Signal

The signal from the HOM ports includes various modes other than the dipole modes which is useful for the beam position measurement. Especially, the acceleration mode of 1300 MHz and harmonics of the bunch repetition, 162.5 MHz in this experiment, have to be carefully removed to detect the dipole modes in a good sensitivity. The schematics of the detection electronics is shown in Fig.3. It is a two stage heterodyne system. The first down-mix stage removes the 1300 MHz by converting it to DC. The second down-mix stage is for removing the nearest bunch repetition harmonics of 1787.5 MHz (=11 × 162.5 MHz). The dipole mode of 1800 MHz appears as 13 MHz at the output of the electronics. It was recorded by a oscillo-scope.

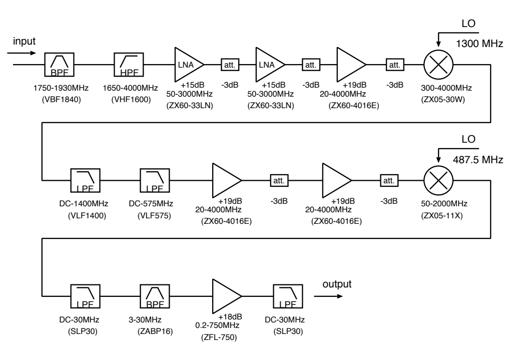

Figure 3: Scheme of the detection electronics.

Since the cavity modes are continuously excited by the beam repetition, the eigen frequency of the modes does not appear in the continuous beam. But in a transient case such as the decaying time after the beam stops, the eigen frequency can be detected. In this measurement, the beam was operated in a macro-pulse mode of 1 μs pulse width. We measured the signal that appeared after the pulse. Figure 4 shows examples of the detected signals from HOM4 ports in each cavity when the beam was kicked in both planes. We measured the peak-to-peak of the waveform as the amplitude of the HOM signal.

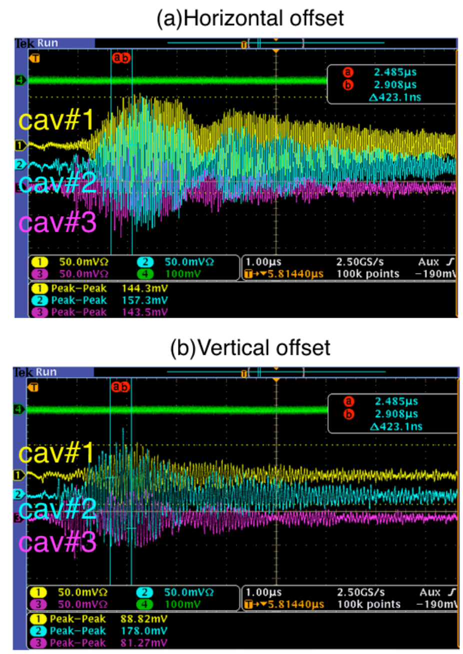

Figure 4: Examples of the signal waveform.

The orientation of the HOM couplers were designed to couple various modes by the combination of the five. The coupling strength for a specific mode can be different for each coupler. We compared the sensitivity to the dipole mode for some of the couplers. Figures 5 and 6 show the sensitivity for horizontal and vertical beam position, respectively. The HOM4 port has sensitivity for both planes. Since the channel numbers of the detection electronics is limited, we used HOM4 of each cavity in the following experiment.

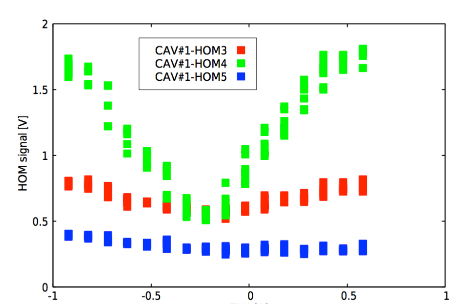

Figure 5: Comparison of HOM ports (horizontal scan).

ESTIMATION OF ALIGNMENT ERROR

By scanning the beam position while measuring the dipole HOM, we can find out the electrical field center of each cav-

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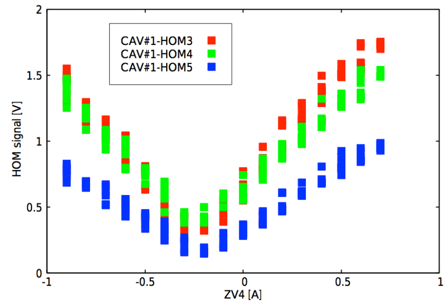

Figure 6: Comparison of HOM ports (vertical scan).

ity. The beam conditions of the measurement is summarized in Table 2. In order to avoid effects of trajectory kick due to the focusing electric field of the accelerating mode of the cavities, this measurement was done without RF power in the cavities.

Table 2: Beam Parameter in the Measurement

Parameter	**value**	**comment**
Bunch charge	6 pC/bunch	
Bunch repetition	162.5 MHz	1/8 of 1300 MHz
Macro-pulse width	1 µs	
Kinetic energy	390 keV	Inj. cavity turned off

Figures 7 and 8 show the results of horizontal and vertical scan, respectively. The data shows V-shape that have minimum when beam is at the field center. By fitting the data with a parabolic curve, the settings of the steering magnets that gave the minimum were obtained. The result is summarized in Fig. 9. The data of the three cavities on a straight line shows that the three cavities are relatively well aligned on a straight line. The overall inclination is somewhat arbitrary depending on the initial beam angle. Especially in the horizontal plane, an apparent deviation from a straight line is observed. By using the calibration factor of steering kick, the relative alignment error in the three cavities can be estimated. The error in the horizontal plane was estimated to be 2.5 mm. The result are summarized in Table 3.

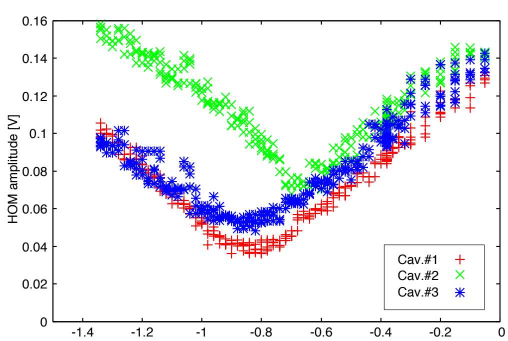

Figure 7: HOM signal v.s. horizontal offset.

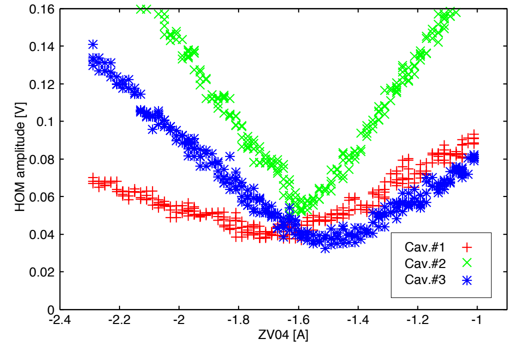

Figure 8: HOM signal v.s. vertical offset.

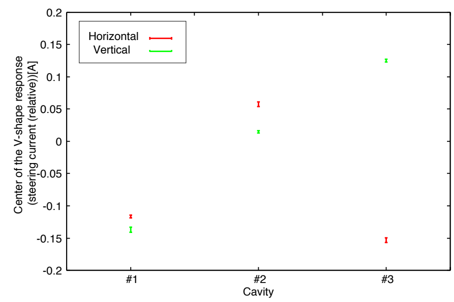

Figure 9: Condition (relative current of the steering magnets) to minimize HOM excitation for each cavity.

Table 3: Summary of the Relative Misalignment

Plane	**Deviation from linear line**
Horizontal	2.31±0.05 mm
Vertical	0.27±0.04 mm

SUMMARY

We have developed a HOM detection system for the injector superconducting accelerator cavities in the cERL. By measuring the TM110 mode amplitude excited in a macro-pulse operation mode, the beam trajectory offset with respect to the field center of each cavity was estimated. Assuming that the beam trajectory was straight, the relative alignment error in the three cavities was estimated.

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