RF SYSTEM IN ACCELERATOR

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INTRODUCTION

A radio frequency (RF) system is mechanisms for accelerating charged particles to high energies. DC acceleration has limitations due to electrical breakdown at high voltages, whereas RF systems use time-varying electromagnetic fields to gradually accelerate particles. The primary goal of an RF system in an accelerator is to synchronize the phase of the RF field with the arrival time of the particles, allowing them to gain energy each time they pass through the cavity.

We carried out several experimental studies for a more detailed understanding of RF system. It covers key components such as RF cavities, transmission lines and beam diagnostic systems(BPM), combining theoretical understanding with practical experimentation conducted at PAL-eLABS. Measurements using a vector network analyzer (VNA), time-domain reflectometer, and beam position monitor(BPM) are important for configuring RF systems.

EXPERIMENTS

Pillbox Cavity

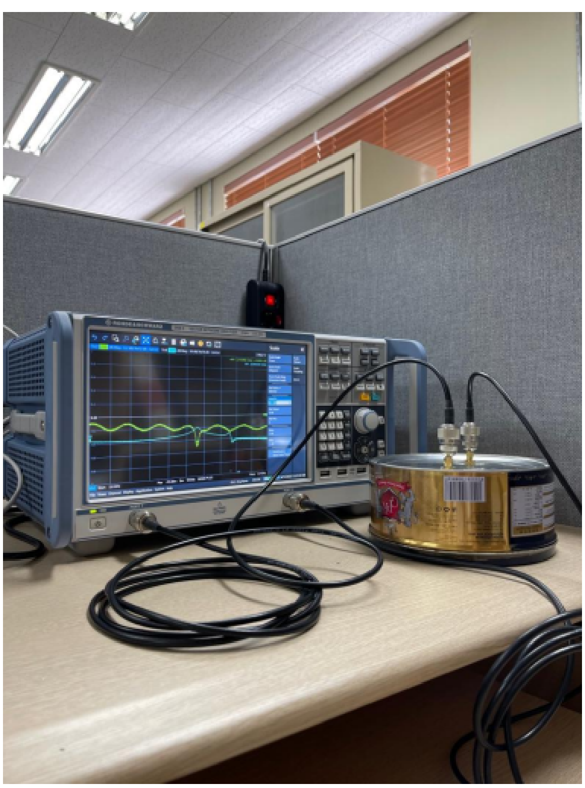

Figure 1: Pillbox cavity

Figure 1 shows the pillbox cavity that serves as an excellent experimental tool for understanding how cavities are used in accelerator applications. In this experiment, the resonant frequency and characteristics are measured by using cylindrical waveguide and compared with the theoretical analysis.

The electromagnetic mode inside this resonator can be obtained by solving Maxwell's equations under boundary conditions. Electromagnetic modes in the waveguide structure are largely classified into transverse electricity (TE), transverse magnetic field (TM) and TEM mode depending on the electromagnetic field configuration. The solution is described in the form of a Bessel function and the resonant frequency of the mode is expressed in the following way:

$$f_{nml}^{TE} = \frac{\pi}{2}\sqrt{(\frac{p'_{nm}}{a})^2 + (\frac{l\pi}{d})^2} \tag{1}$$

$$f_{nml}^{TM} = \frac{\pi}{2}\sqrt{(\frac{p_{nm}}{a})^2 + (\frac{l\pi}{d})^2} \tag{2}$$

p'_{nm}, p_{nm}: roots of the $J'_n(k_c a), J_n(k_c a)$

Table 1: Example of Row Merging

Radius, a[mm]	95
Length, d[mm]	80
	1.207 (TM010)
	1.922 (TM110)
Frequency[GHz]	2.080 (TM011)
	2.412 (TE111)
	2.575 (TE112)

We connected cavity to vector network analyzer. The VNA eliminated the system error through pre-calibration. The resonant frequency were measured using the S_{11} reflection coefficient. From The results showed that the TM010 mode appeared at 1.198GHz and the TM110 mode at 1.910GHz.

Beam Position Monitor

Stripline BPM was studied to investigate the position-sensing and electrical characteristics of beam position monitor. Instead of using an actual electron beam, a conducting wire was stretched along the axis of the BPM and driven with an RF signal, effectively replicating the electromagnetic effect of a passing charged beam. The BPM's four electrodes, arranged symmetrically around the beam pipe, detected induced signals whose amplitudes varied with the wire's offset from the center. These signals were captured via an oscilloscope, transmitted to a computer, and processed to compute the wire's position using normalized amplitude differences. This approach allowed for controlled calibration and response testing of the BPM system under laboratory conditions.

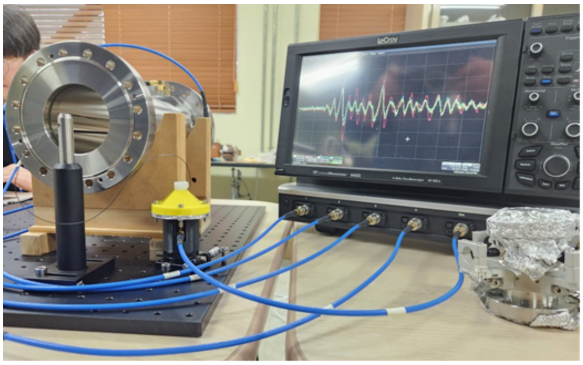

Figure 2: Experimental setup for BPM measurement

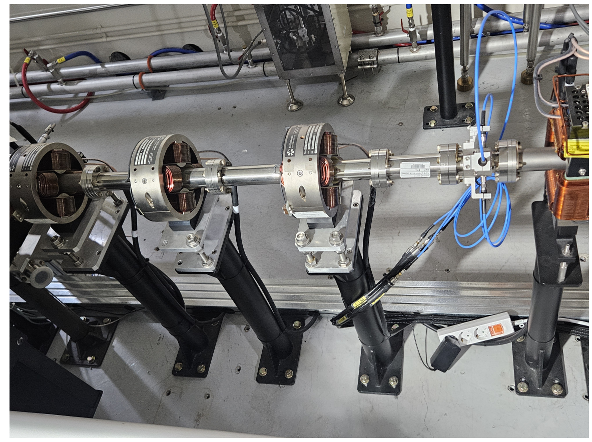

Figure 3: Quadrupole magnets in eLABs

Time-Domain Reflectometry

In parallel, time-domain reflectometry (TDR) was conducted to diagnose impedance behavior within the BPM structures. A step-function voltage pulse was injected into the transmission line connected to the BPM, and the reflected waveform was analyzed over time. Since the time domain can be translated into spatial distance, this allowed for the localization of discontinuities and impedance mismatches inside the system. For the stripline BPM, the TDR response revealed a distinct mismatch at the signal entry point, attributed to imperfect connections at the SMA interface. Button-type BPMs exhibited additional impedance variations, particularly sharp peaks caused by capacitive coupling between the button electrodes and the surrounding beam pipe. These mismatches not only degrade signal transmission quality but also influence the frequency-dependent accuracy of position measurements. The TDR analysis thus served as a powerful tool to visualize hidden electrical structures, verify signal path integrity, and guide design improvements for both mechanical and RF performance in future BPM systems.

OPERATION OF ELABS

The eLABs facility at PAL is the Injector test facility to support the development of RF gun. Over time, eLABs has evolved into a versatile research hardware, diagnostic instrumentation in a compact and accessible environment. This makes it an ideal setting for prototyping new diagnostic techniques and practicing beam tuning procedures in a low risk.

The facility consists of a photocathode RF gun, a solenoid and quadrupole magnet system, and a suite of diagnostic devices including YAG screens, BPMs, and spectrometers. Users can perform real beam experiments such as emittance measurement, energy spread analysis, and beam based alignment.

To characterize the transverse beam properties, we performed a quadrupole scan. As the focusing power of the quadrupole changes, the beam undergoes varying degrees of convergence or divergence, which becomes apparent in the projected size of the beam on a detection screen. During the experiment, we tuned the current through horizontal and vertical quadrupole magnets while keeping other parameters stable. For each setting, a beam image was captured using a camera installed behind a fluorescent screen, allwing real-time visualization of the beam's transverse shape. This variation follows a predictable parabolic trend, stemming from the transformation of the beam's second moment matrix through the quadrupole field and drift. By fitting the data to a quadratic curve, we gained access to the underlying beam matrix components. From this, we can extracted the twiss parameters and emittance, which offer complete description of the beam envelope and focusing behavior.

CONCLUSION

Through this series of experiments, we gained insights into operation of RF systems in particle accelerators. By analyzing the resonant characteristics of a pillbox cavity with a vector newtork analyzer, we successfully identified key cavity modes such as TM_{010} and TM_{110}. We can understand the cavity resonance behavior and electromagnetic field distributions.

In addition, by investigating the beam position monitor(BPM) through wire-based experiments and TDR provided valuable diagnostic information. The position sensitivity of the stripline BPM was confirmed by evaluating the induced signal asymmetries. These results highlighted the importance of impedance matching and electrical integrity in beam diagnostics.

The hands-on operation at eLABs further reinforced our comprehension of beam dynamics. Using quadrupole scans, we experimentally demonstrated the predictable parabolic relationship between beam size and focusing strength. This allowed us to extract Twiss parameters and transverse emittance.

REFERENCES

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