RADIO FREQUENCY MEASUREMENT STUDY IN THE LINEAR ACCELERATOR SYSTEM*

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Abstract

To accelerate particle beams in accelerators, RF systems that generate high-frequency electric fields are essential. In this study, we explored the structure and function of RF cavities and practiced measurement techniques using tools such as a vector network analyzer (VNA) and time domain reflectometry (TDR). We measured the resonant frequency and quality factor of a small cavity and evaluated impedance matching and signal transmission efficiency through S-parameter analysis. Using a conducting wire in place of a beam, we examined how beam position monitors (BPM) detect RF-induced signals. A tour of the eLABs accelerator facility provided hands-on insight into how real accelerator components work together. This study helped us understand how precise RF control underpins efficient particle acceleration and diagnostic systems.

INTRODUCTION

A bunch of particle beams are accelerated by the radio frequency (RF) along the beamline cavity. The accelerating system is essential to increase the speed of the beam to near that of light to obtain bright synchrotron radiation or to use it in particle collision experiments. For example, accelerators for High Energy Physics (HEP) require large amounts of energy, many of them have the form of RF power, and have utilized available RF power sources mainly in the form of vacuum tube technology [1]. RF typically has a frequency of several MHz to several GHz, and an appropriate frequency is selected depending on the structure of the accelerator. In particular, the linear accelerator adopts RF cavity structure where the electric field is formed to accelerate the particle beam whenever the particle acceleration and RF resonate. This repeatably increases the particle speed and has enabled us to operate high-energy accelerator.

We measured resonance frequency of a small version of the cavity sample to understand the RF cavity and visited the Electron Linear Accelerator for Basic Science (eLABs) to learn the basic beam position monitoring (BPM) as a sub-theme. A vector network analyzer (VNA) can assess the condition inside the specific cavity such as quality factor and resonance. Another measurement tool is time domain reflectometry (TDR) that can sense the response of device to the signal in certain time domain. In addition, we utilized BPM to check the signal generated by RF-accelerated beam that is substituted by a conducting wire, followed by the eLABs facility tour. In the eLABs, various beam diagnostic systems are demonstrated by taking advantage of the characteristics that it has a compressed form of an actual accelerator which is in the unit of several meters long.

Through this process, we are able to establish the way to operate RF-related measurement instruments. It is crucial to learn the fundamentals of RF by handling a variety of equipment because the RF system is the keystone for accelerating the particle to the desired velocity. Equipments we are supposed to use in this experiment are all related to optimizing and controlling the precise condition of the RF cavity. Furthermore, we can verify the RF condition by monitoring the beam position which indicates RF signal inside the beamline. By experiencing both the measurement techniques and the application of RF systems in a working accelerator environment like eLABs, we gain insight into how these technologies enable high-precision, high-energy beam control that is essential for modern accelerator physics.

RF THEORY

Transmission of electrical signals

Electric fields are physical fields in space generated by electric charges and have the property of exerting force on other electric charges. The electrostatic field generated from a fixed charge spreads through space according to Coulomb's law and has a vectorial direction and size. However, the RF electric field used in an accelerator is an electric field that changes over time, and it is transmitted through the free space in the form of electromagnetic waves.

The changing electric field induces a magnetic field, and this magnetic field induces an electric field again, and they go through a cyclic process of generating each other. This interaction is explained by Maxwell's equations. According to Maxwell's equations, when an electric field changes over time, a magnetic field is generated, and these two fields are propagated in the form of waves through a medium such as a vacuum or a dielectric.

$$\mathbf{E}(\mathbf{r},t) = \mathrm{Re}\left[\mathbf{E}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}\right] \quad (1)$$

$$\mathbf{B}(\mathbf{r},t) = \mathrm{Re}\left[\mathbf{B}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}\right] \quad (2)$$

The above equations express the propagation of the electric and magnetic field for free space, in which E_0 and B_0 are the amplitude and ω is the angular frequency. Of these, the electric field is the one that directly affects particle acceleration. The RF cavity of an accelerator is a structure that resonates these high-frequency signals to concentrate the electric field at a specific location. At this time, the electric field varies over time and location in the following form:

$$E(z,t) = E_0 \cos(kz - \omega t + \phi) \quad (3)$$

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where z means the direction of the particle and ϕ is the initial phase. If this oscillating electric field is exerted on the particle in the correct phase while the particle passes through the cavity, the particle receives a forward accelerating force from the electric field and can increase the speed. The energy transfer is optimal only when the position of the particle and the phase of the electric field are exactly aligned, and the electric field signal changes in real time by RF according to the position of the particle bunch. That is, the RF signal of the accelerator determines the oscillating pattern of the electric field, and this electric field becomes the medium that exerts a force directly on the particle [2].

RF Waves

As the frequencies become higher, it is more convenient to express the electric circuit which generates RF signals in terms of wave. After the RF singals are generated, they are conveyed along the transmission line on which the impedance is one of the most important factors. In an RF system, every component — power, cable, cavity, antenna — has its own impedance, and when these values do not match, signal reflection occurs. A S-parameter, also known as scattering parameter, is used in assessing the electrical response of the circuit netwrok. The waves going towards the measurement port are defined as $a = (a_1, a_2, ..., a_n)$, the waves traveling away from the port are $b = (b_1, b_2, ..., b_n)$. In general, it can be written as the following equations:

$$a_i = \frac{U_i + I_i Z_0}{2\sqrt{Z_0}} \tag{4}$$

$$b_i = \frac{U_i - I_i Z_0}{2\sqrt{Z_0}} \tag{5}$$

where U_i, I_i, and Z_0 are the voltage, current, and reference impedance, respectively. The relation between a_i and b_i ($i = l...n$) can be written as a system of n linear equations (a_i being the independent variable, b_i the dependent variable) and has a matrix formulation as in the following.

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \tag{6}$$

The physical meaning of S_{11} is the input reflection coefficient with the output of the network terminated by a matched load ($a_2 = 0$). S_{21} is the forward transmission (from port 1 to port 2), S_{12} the reverse transmission (from port 2 to port 1) and S_{22} the output reflection coefficient.

Taken together, S_{11} represents the input reflection coefficient, indicating how much of the incident signal is reflected back due to impedance mismatch. S_{21} indicates how efficiently the signal is transmitted through the cavity, serving as a key metric for resonance and power transfer. These parameters allow us to quantify the impedance matching and energy flow characteristics of the RF system across a frequency range [3].

HANDS-ON EXPERIENCE

Vector Network Analyzer

Figure 1: An overview of the VNA used in this study.

The VNA is the instrumenation tool that can check the characteristics of RF facilities in the range of the frequency, and it especially measures the impednace. Impedance measurement is a key evaluation factor that determines the performance and signal transmission efficiency of RF systems. In this experiment, we chose a Danish cookie pillbox as a RF cavity and measured the S-parameter after the calibration of the VNA. It can display each S-parameter, allowing us to find the range of the frequency where S_{11} is the minimum value. As we can see in the VNA monitor, S_{11} and S_{21} are plotted and they show the symmetrical structure with the highest and lowest points facing each other. The quality factor is consequently calculated based on the resonance frequency, and this process is repeated while narrowing down the range of the frequency.

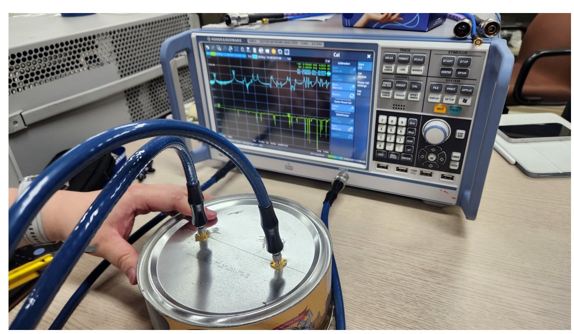


Figure 2: S-parameters of the pillbox cavity is measured by the VNA which displays the parametric graph.

Beam position monitoring

The BPM detects the high-frequency electromagnetic fields induced by the beam bunch. These RF signals are picked up by electrodes placed symmetrically around the beam pipe, and the relative signal amplitudes are used to determine the beam's transverse position. By analyzing these signals with RF diagnostic tools, pickup BPM in this

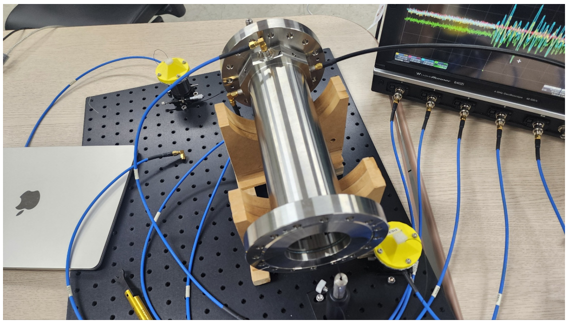
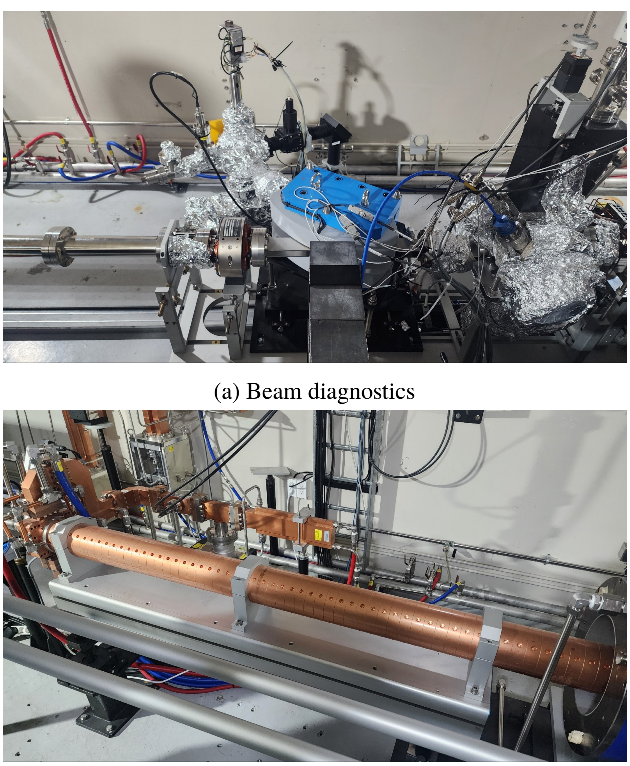


Figure 3: Pickup type BPM sensors measuring the signal of conducting wire and TDR is employed together.

experiment, we can extract both the position and intensity of the beam in real time. However, since we cannot use real electron beam, we substituted it with the conducting wire that oscillates with a high frequency of 500 MHz as if it diverges RF signals inside the cavity. This BPM is also a type of sensor, which inevitably involves the impedance underlying the overall structure. A TDR is utilized to check the impedance that is associated with the intensity of the signal response, and any impedance mismatch in the BPM. This is repeated while moving the conducting wire in the BPM and changing the signal amplitude.

eLABs



(a) Beam diagnostics

(b) RF cavity for the particle to be accelerated

Figure 4: eLABs facility tour.

We toured the eLABs experimental facility, which is designed for educational and practical purposes. Although the size is small compared to the actual version, the facility is equipped with all the core components used in real accelerators, such as particle sources, RF cavities, beam diagnostic devices, and magnets, allowing us to directly observe the operating principles of real accelerators. In this facility, a lot of diagnostic techniques are studied ranging from BPM to Cherenkov radiation monitor. We could look around the accelerating part, that is the RF cavity in the eLABs and learned how the beam bunch is generated and reach the end-station.By observing the entire accelerator in a nutshell, we are able to acquire how RF energy is utilized in the acceleration process, and we understood that how the accelerator components were organically linked and worked together. We also observed the beam diagnostic chamber such as BPM, which helped us with learning how diagnostics were involved in the accelerator.

CONCLUSION

In this report, we experimentally analyzed how the electric field transfers energy to particles, focusing on the RF system, which is a core component of particle accelerators. The oscillating electric field formed inside the RF cavity must be aligned with the phase of the particle beam to effectively accelerate. To quantitatively evaluate this process, we measured the S_{11} and S_{21} parameters using a VNA and analyzed the resonant frequency. In addition, we understood the principle of deriving beam position information from RF signals through the BPM system, and diagnosed the impedance mismatch within the system using TDR equipment. By directly observing these measurement tools in the eLABs, which is an actual miniature accelerator experimental device, we were able to confirm how the components of the accelerator, which we had only understood theoretically, actually work together. The experimental process allowed us to visually understand the process in which RF signals are converted into electric fields to transfer energy, and we experienced that precise RF control is a very important factor in the quality and consistency of particle acceleration. In the future, we will be able to acquire more sophisticated accelerator control technology by exploring automated measurement systems or more precise RF phase synchronization technologies.

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