PHYS719P REPORT NO.3: ACCELERATOR RF TECHNOLOGY AND AN EXERCISE ON THE USAGE OF RF INSTRUMENTS

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Abstract

Radiofrequency (RF) based acceleration serves as a more efficient alternative compared to direct current (DC) acceleration, overcoming the limitations of electrical breakdown at high voltages. By generating alternating electromagnetic fields within resonant cavities, RF accelerators enable particle beams to gain energy by synchronizing the arrival of particles with the oscillating RF field. This report provides an overview of the fundamental concepts underlying RF acceleration, including transmission lines, waveguides, and cavity resonances. In addition, hands-on practices using key diagnostic instruments such as oscilloscopes, time-domain reflectometers (TDRs), and vector network analyzers (VNAs) to characterize RF systems are conducted, using a beam position measurement (BPM) setup and evaluation of S-parameters of a pillbox cavity. Finally, an operational tour of the eLABs facility at Pohang Accelerator Laboratory (PAL) is presented.

I. INTRODUCTION

Radiofrequency (RF) based acceleration offers greater efficiency compared to DC based accelerators, which is limited by possibility of electrical breakdown in high voltages. By generating an alternating electromagnetic fields within resonant cavities, the beam in the RF accelerator gains energy through phase matching - synchronization of the arrival time of particles with the oscillating RF field.

The core components of an RF accelerator involves high-voltage DC power supply, RF amplifiers such as a klystron or solid-state amplifier, low-level RF (LLRF) control systems, and the accelerating cavity. The DC voltage from power supply is converted into high-voltage pulses by modulators, where its stability is important to match the requirement of RF source. The generated RF signal is delivered to the cavity through transmission lines, where impedance matching is crucial to minimize power load and prevent reflections.

In order to optimize and manage the performance of RF accelerator, one needs to understand the usage of instruments to characterize transmission lines and diagnose system behavior. Oscilloscopes serve a measurement of time-domain signals in various time scales, time-domain reflectometers (TDR) help identify impedance mismatches. In particular, vector network analyzers (VNA) determine resonance frequencies inside the accelerating cavity, since the pattern of standing wave patterns or modes should be understood and controlled for managing system stability.

This report is organized as follows: in section II, concept of the transmission line, waveguide, and cavities are reviewed. Section III presents the report on hands-on practice on RF instruments such as oscilloscope, TDR, and VNA. Following in section IV, introduction and tour of eLABs facility will be presented.

II. BRIEF REVIEW ON RF TECHNOLOGY

Transmission lines

While low-frequency signals have long wavelengths so that the current travels down the wires easily, high-frequency signals need transmission lines with matched characteristic impedance. Impedance nismatch can lead to formation of standing waves and power losses by reflections. The voltage reflection coefficient(Γ) is generally expressed as following:

$$\begin{aligned} \Gamma &= \frac{Z_L - Z_0}{Z_L + Z_0} \quad (l = 0), \\ \Gamma(l) &= \Gamma(0)e^{-2j\beta l} \quad (l \neq 0), \end{aligned} \tag{1}$$

Where Z_L and Z_0 are impedance of load and transmission line respectively.

The smith chart is a powerful tool to visualize complex impedance when working with cavities or waveguides. In order to map the reflection coefficient onto the complex plane, eq. 1 can be rearranged into following form by letting $\Gamma = \Gamma_r + j\Gamma_i$ and $z_L = Z_L/Z_0 = r_L + jx_L$:

$$\begin{aligned} \left(\Gamma_r - \frac{r_L}{1+r_L}\right)^2 + \Gamma_i^2 &= \left(\frac{1}{1+r_L}\right), \\ (\Gamma_r - 1)^2 + \left(\Gamma_i - \frac{1}{x_L}\right)^2 &= \left(\frac{1}{x_L}\right)^2. \end{aligned} \tag{2}$$

Eq. 2 lets the mapping of Γ_r and Γ_i onto the Smith chart, making it feasible to analyze network matches. Depending on the distance and frequency, one can trace how impedance changes along the transmission line.

Waveguides and cavities

Electromagnetic modes in waveguide structure can be categorized on the basis of field configurations, primary into TE (traverse electric) mode where longotudal electric component is zero ($E_z = 0$) and TM (traverse magnetic) mode where the longitudal magnetic component is absent ($H_z = 0$). In a cylindrical waveguide, the solutions to TM mode are typically expressed in terms of Bessel functions:

$$\begin{aligned} \mathbf{A} &= A_z\hat{z}, \\ A_z &= C \times J_m(k_\rho \rho)\cos(m\phi)e^{\pm i k_y z}, \end{aligned} \tag{3}$$

where C is a constant which is generally complex.

An example of TM mode appears in the pillbox cavity, whose walls are perfect conductors. Solutions of standing

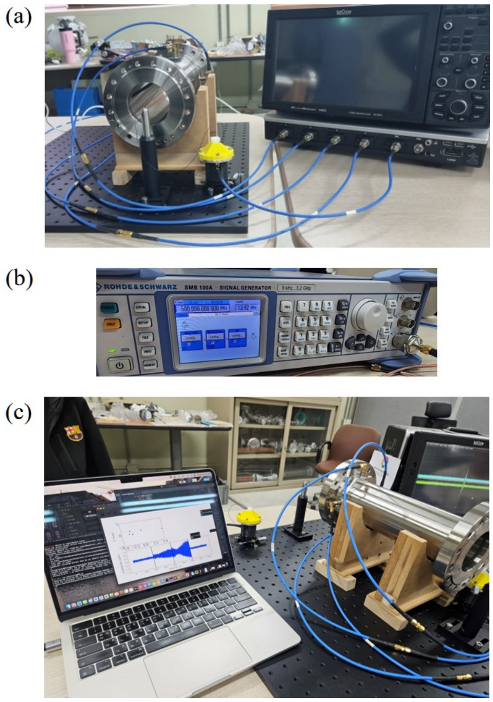

Figure 1: Setup for the practice of using beam position measurement(BPM) system. (a) Raw signals from the sensors are measured by an oscilloscope (channel 1-4), and the RF signal carried by the wire is sent to the trigger input for synchronizing the data acquisition. (b) Signal generator provides sinusoidal signal of 500 MHz to the wire. (c) From the information on the amplitude measured by the oscilloscope, the python-based script calculates the position of wire.

wave inside the cavity can be obtained by superposing the forward ($+z$) wave and backward ($-z$) wave component, in equation 3. Skipping the details, the lowest frequency mode of the pillbox cavity is the TM_{010} mode, where fields, wavenumber, and frequency are explicitly expressed as [1]:

$$E_z = E_0 J_0(k_\rho \rho) e^{-i\omega t},\ B_\theta = -i\frac{E_0}{c} J_1(k_\rho \rho) e^{-i\omega t} \\ k_\rho = \frac{2.405}{a},\ \omega = \omega_{010} = \frac{2.405c}{a}, \tag{4}$$

where a is the radius of the cavity.

III. HANDS-ON PRACTICE ON RF INSTRUMENTS

Practice on handling of basic instruments to characterize RF system is conducted, with two experiment setups:

(1) Beam position measurement (BPM): using a prototype for BPM system, the position of a RF carrying wire is measured instead of the electron beam. Raw signals are measured by an oscilloscope, and the information on amplitude are sent to the computer which calculates the beam (wire) position. Furthermore, the impedance characteristics of BPM is evaluated with time-domain reflectometry.

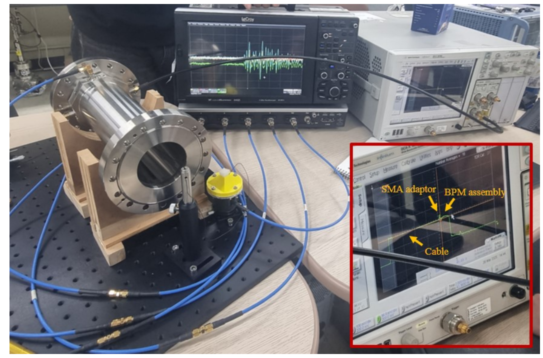

Figure 2: Utilizing time-domain reflectometer (TDR) to evaluate the impedance of BPM sensors.

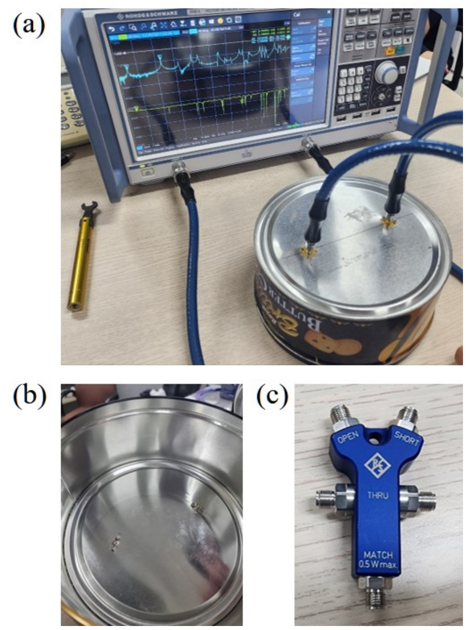

Figure 3: Evaluation of S-parameters of a pillbox cavity. (a) Picture showing the measurement setup, with the display of the vector network analyzer showing the spectral dependence of S_{11} (cyan) and S_{21} (green). (b) Interior side of pillbox cavity showing the antennas. (c) Calibration kit for VNA measurement.

(2) Evaluation of S_{11} and S_{21} parameters of a pillbox cavity: provided with proper calibration, the vector network analyzer (VNA) displays the parameters in frequency domain.

Figure 1 shows the picture for BPM, where the wire carries a sinusoidal 500 MHz signal generated with the signal generator shown in figure 1(b). Note that the frequency (500 MHz) is selected to mimic bunches of the electron beam having time-domain width of 2 ns. The position of RF-carrying wire is measured with four sensors around the cylinder, each spaced 90 degrees apart. Time-domain reflectometry (TDR), shown in figure 2, measures the impedance characteristics of BPM. The impedance is uniform in the cable, but bunps

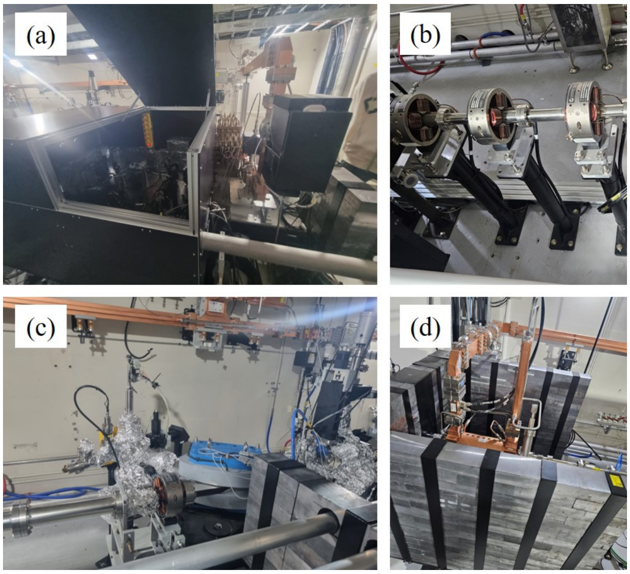

Figure 4: eLABs facility in PAL: (a) sample stage, (b) quadrupole magnets surrounding the accelerating tube, (c) bending magnet and chamber for beam position diagnostics and (d) beam dump.

appear after the SMA adaptor, implying the possiblity of loss and reflectons of RF signal at the adaptor.

Setup of vector network analyzer (VNA) for measuring the S-parameters of pillbox cavity is shown in figure 3. Before the measurement, one needs to calibrate the VNA, with the calibration kit shown in figure 3(c). Traverse magnetic (TM) mode is formed inside the cavity, by the resonance of electromagnetic waves launched by the antennas shown in figure 3(b). Figure 3(a) shows the S-parameters displayed on the VNA, where the cyan and green lines indicate S_{21} and S_{11} respectively. The frequencies corresponding to the peaks in S_{21} match with those corresponding to valleys in S_{11}. One of the identified resonant frequencies, $f = 1.908\,\mathrm{GHz}$, is comparable to the frequency of TM_{110} mode which can be calculated as following [2]:

$$\begin{aligned} f_{nml}^{\mathrm{TM}} &= \frac{c}{2\pi}\sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}, \\ f_{110}^{\mathrm{TM}} &= 1.922\,\mathrm{GHz}. \end{aligned} \tag{5}$$

This confirms the formation of traverse magnetic mode (TM) inside the pillbox cavity.

IV. OVERVIEW AND TOUR ON eLABs FACILITY IN PAL

eLABs (electron linear accelerator for basic science) is first introduced as the injector test facility (ITF) to develop a high-brightness photocathode RF gun [3], which was also applicable to the source of PAL-XFEL. A tour and trial operation of eLABs facility is conducted, as shown in figure 4. Actual operation of the accelerator facility included in the tour gave an interactive display on how accelerators work, as shown in figure 5.

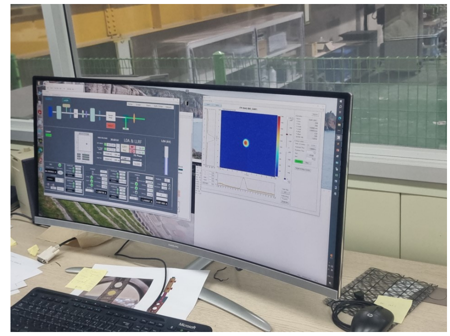

Figure 5: User interface for manipulation of eLABs and monitoring beam state.

V. SUMMARY

In this report, the fundamental principles and diagnostic techniques essential for understanding and managing RF acceleration systems are introduced. Through practical exercises, the use of time-domain and frequency-domain measurement tools such as oscilloscopes, TDRs, and VNAs was demonstrated, highlighting their roles in evaluating transmission line integrity, cavity resonance, and beam diagnostics. The experiments, including beam position monitoring and cavity mode analysis, provided hands-on experience in RF system characterization. Additionally, the tour and operation of the eLABs facility at PAL offered valuable exposure to the composition and operation of an electron linear accelerator, reinforcing the theoretical knowledge with practical implementation.

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REFERENCES

[1] M. Chung, *Lecture note on RF basics*, Division of Advanced Nuclear Engineering (DANE), POSTECH, Pohang, Korea, Apr. 2025

[2] C.-K. Sung, *Lecture note on RF basics and beam operation using eLABs facility*, Division of Advanced Nuclear Engineering (DANE), POSTECH, Pohang, Korea, Mar. 2025

[3] S.J. Park *et al.*, *Construction of Injector Test Facility (ITF) for the PAL-XFEL*, Proc. IPAC'13, Shanghai, China, May 2013, paper WEPWA043, pp. 2220-2222