FUNDAMENTAL ACCELERATOR EXPERIMENTS: RF RESONANCE, BPM RESPONSE, AND QUADRUPOLE SCANS AT ELABS

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Abstract

This paper describes experimental studies conducted at the e-LABs facility to provide hands-on education in accelerator physics and technology. Three principal experiments were performed: microwave characterization of pillbox cavities, beam position monitoring using conducting wires, and electron beam operations with quadrupole scanning. The resonant frequencies and quality factors of the cavities were measured using vector network analysis, demonstrating agreement with theoretical predictions. Beam position monitors (BPMs) were evaluated through wire measurements and time-domain reflectometry to assess position sensitivity and identify impedance mismatches. In addition, practical accelerator operation was performed by scanning quadrupole magnet strengths to analyze beam envelope variations and determine transverse emittance. These experiments integrate theoretical principles with experimental techniques, offering comprehensive training opportunities for students and young researchers. The results not only validate fundamental concepts in beam instrumentation and beam dynamics but also highlight effective approaches to education in accelerator science.

INTRODUCTION

Accelerator physics and beam diagnostics are fundamental to the advancement of particle accelerator technology. Understanding the behavior of electromagnetic fields in resonant structures is essential for designing and operating accelerator facilities. This paper presents experimental studies conducted at the electron Linear Accelerator for Basic science (eLABs) facility, focusing on three key aspects of accelerator technology: microwave measurements for pillbox cavities, beam position monitoring using conducting wires, and electron beam operation.

Pillbox cavities represent one of the fundamental resonant structures in accelerator physics, serving as essential components for particle acceleration and beam diagnostics. The accurate determination of their resonant frequencies, and quality factors is crucial for optimizing accelerator performance. In this work, we investigated the electromagnetic properties of pillbox cavities through theoretical calculations and experimental measurements using Vector Network Analyzers (VNA) and Time Domain Reflectometry (TDR) techniques. The calibration procedures for these instruments were thoroughly examined to ensure measurement accuracy.

Beam Position Monitors (BPMs) are indispensable diagnostic tools in accelerator facilities, providing real-time information about beam trajectory and stability. Our study employed a conducting wire technique to simulate beam-induced signals in BPMs, allowing for systematic characterization of position sensitivity and resolution without requiring an actual particle beam. This approach enables efficient testing and calibration of BPM systems under controlled laboratory conditions.

Our experimental results demonstrated good agreement between theoretical predictions and measured values for pillbox cavity resonant frequencies. The quality factor measurements revealed the impact of material properties and geometric factors on cavity performance. The beam position monitoring experiments successfully demonstrated position sensitivity within expected parameters, while the electron beam operation provided valuable data on beam characteristics at the eLABs facility.

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THEORY AND HANDS-ON TRAINING

Pillbox cavity measurements

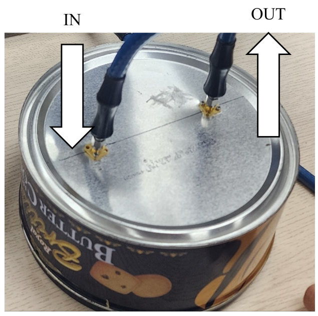

Figure 1: Used pillbox cavity

Pillbox cavities are cylindrical resonant structures widely used in accelerator applications for both acceleration and diagnostics purposes. We use the pillbox cavity as shown in Fig. 1. The electromagnetic field distribution inside these cavities can be described by solving Maxwell's equations with appropriate boundary conditions. For $\mathrm{TM}_{\mathrm{nml}}$ modes in a pillbox cavity with radius a and length d, the resonant frequency can be calculated using [1]:

$$\begin{aligned} f_{nml}^{TE} &= \frac{c}{2\pi}\sqrt{\left(\frac{p_{nm}}{a}\right)^2+\left(\frac{\ell\pi}{d}\right)^2} \\ f_{nml}^{TM} &= \frac{c}{2\pi}\sqrt{\left(\frac{p_{nm}}{a}\right)^2+\left(\frac{\ell\pi}{d}\right)^2} \end{aligned} \qquad (1)$$

where c is the speed of light, and p_{0n} is the n-th root of the Bessel function $J_0(x)$. For the fundamental TM_{010} mode, $p_{01} = 2.405$.

The measured TM_{010} and TM_{110} modes are 1.198 and 1.910 GHz (Fig. 2), compared to theoretical values of 1.207

Radius a (mm)	95
Length d (mm)	80
Freq. (GHz)	1.207 (TM_{010}) 1.922 (TM_{110}) 2.080 (TM_{011}) 2.412 (TE_{111}) 2.575 (TE_{112})

Table 1: Theoretical cavity resonance frequencies.

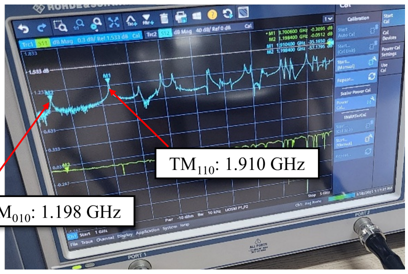

Figure 2: Network analyzer measurement of a cylindrical cavity showing resonant modes. The TM_{010} mode is visible at 1.198 GHz and the TM_{110} mode at 1.910 GHz. The blue trace represents the transmission coefficient (S_{21}) measurement, with resonant peaks indicating the cavity modes.

and 1.922 GHz (Table 1). The relative errors of 0.75% and 0.62% respectively demonstrate good agreement between measurement and theory, indicating the accuracy of the measurement setup and the validity of the theoretical model.

The quality factor (Q-factor) quantifies the sharpness of the cavity resonance. In this work, it was determined using the -3 dB bandwidth method:

$$Q = \frac{f_0}{\Delta f} \tag{2}$$

where f_0 is the resonant frequency and Δf is the full width at half maximum (FWHM) of the transmission peak.

Measurements were performed using a Rohde & Schwarz ZNB 8 Vector Network Analyzer (VNA) after standard calibration to remove systematic errors. The resonant frequency f_0 was identified as the frequency corresponding to the peak of the S_{21} transmission parameter.

Beam position monitor response

We employed a stripline-type BPM, which consists of four electrodes positioned symmetrically around the beam pipe. When a charged particle beam passes through the BPM, it induces electromagnetic signals on these electrodes, with signal strengths proportional to the proximity of the beam to each electrode.

To simulate a beam without requiring an accelerator, we applied a conducting wire technique. In this method, a wire is stretched through the BPM center and carries an RF signal that mimics a charged beam. The position information can be extracted from the relative signal amplitudes on the four electrodes using the following equations:

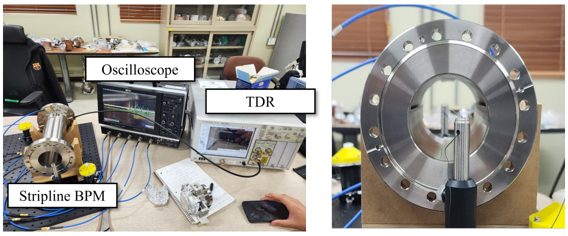

Figure 3: Experimental setup for BPM characterization. (Left) Stripline BPM connected to an oscilloscope for electrodes signal analysis. (Right) Inside of stripline BPM

$$\begin{aligned} X_0 &\equiv \frac{\Delta_x}{\Sigma_x}, \\ Y_0 &\equiv \frac{\Delta_y}{\Sigma_y}. \end{aligned} \tag{3}$$

In addition to the stripline BPM measurements, we also conducted Time Domain Reflectometry (TDR) analysis on button-type BPMs. TDR is a powerful diagnostic technique that sends a fast-rising step pulse through a transmission line and measures the reflected signal as a function of time, which can be converted to distance. This method allows for the identification of impedance mismatches and discontinuities along the transmission path.

Figure 4: Time Domain Reflectometer (TDR) used for impedance matching and discontinuity detection in the BPM system.

For the button BPM characterization, the TDR was connected to the BPM electrodes to analyze the reflection coefficient versus time (or equivalent distance). This measurement provided valuable insights into the impedance matching between the BPM components and the transmission line. A significant observation from the TDR measurements was the identification of impedance peaks caused by the capacitance between the button electrodes and the beam pipe. These impedance discontinuities can affect the signal integrity and frequency response of the BPM system, potentially impacting position measurement accuracy at certain frequencies. The TDR analysis helped in understanding the electrical characteristics of the button BPM and identifying potential areas for impedance optimization in future designs.

Electron beam operation at eLABs

The eLABs facility provides an educational platform for hands-on experience with electron beam operations. In our

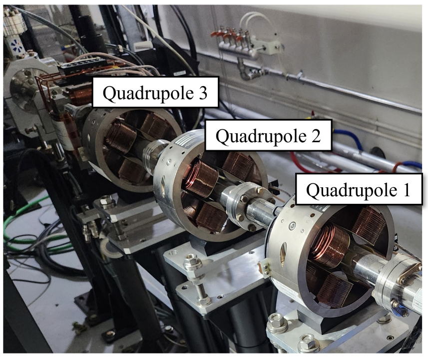

Figure 5: Triplet setup in eLABs.

experiments, we focused on beam optics and quadrupole scanning techniques to determine beam parameters.

Quadrupole magnets are used for beam focusing and can be described by a focusing strength parameter k, defined as:

$$k = \frac{1}{B\rho} \cdot \frac{\partial B_y}{\partial x} \tag{4}$$

where $B\rho$ is the magnetic rigidity of the beam, and $\frac{\partial B_y}{\partial x}$ is the magnetic field gradient.

The relationship between the beam size at a screen location (σ) and the quadrupole strength (k) can be expressed as [1]:

$$\sigma^2(k) = \sigma_{11} - 2\sigma_{12}kL + \sigma_{22}(kL)^2 \tag{5}$$

where σ_{11}, σ_{12}, and σ_{22} are elements of the beam sigma matrix, and L is the effective length of the quadrupole magnet.

By varying the quadrupole current and measuring the corresponding changes in beam size on a downstream screen, we performed quadrupole scans to observe beam envelope variations. This technique allows for the determination of beam emittance and Twiss parameters, which are fundamental properties characterizing the beam quality and dynamics. The beam profile was measured using a fluorescent screen coupled with a camera system, providing direct visualization of the transverse beam distribution. Image processing techniques were applied to extract quantitative information about beam size and shape under different quadrupole settings.

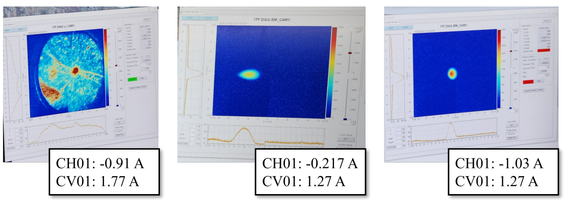

Figure 6: Quadrupole magnet scan results showing beam profile variations at different quadrupole current settings. (Left) Poorly focused beam with CH01 at -0.91 A and CV01 at 1.77 A showing scattered distribution. (Center): Beam profile with enhanced vertical focusing (CH01: -0.217 A, CV01: 1.27 A) showing improved vertical concentration. Right: Beam profile with CH01 at -1.03 A and CV01 at 1.27 A demonstrating round focusing with minimum spot size. The color scale represents beam intensity, with red indicating highest intensity regions.

Fig. 6 illustrates the effect of quadrupole magnet current variations on the electron beam profile. The quadrupole scan was performed by adjusting the horizontal (CH01) and vertical (CV01) quadrupole currents while maintaining other beam parameters constant.This quadrupole scan demonstrates how the beam envelope can be manipulated by adjusting the focusing strengths, allowing for precise control of beam size and shape at the target location. The observed beam behavior confirms the quadratic relationship between beam size and quadrupole strength as described by the beam envelope equation.

SUMMARY

The study investigates three areas critical to accelerator training. Microwave measurements determined resonant frequencies and quality factors of pillbox cavities, aligning well with theoretical models. Beam position sensitivity was examined using a conducting wire in stripline and button BPMs, with TDR analysis revealing impedance mismatches. Finally, quadrupole scans with an electron beam enabled estimation of beam emittance and Twiss parameters. Together, these experiments bridge theoretical concepts with practical diagnostics in accelerator systems.

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