ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY02

DEMONSTRATION OF CAVITY FIELD MAPPING BY FALLING DROPS OF LIQUID*

X. Du, L. Groening
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

This paper presents a novel bead-falling method for precise mapping of electromagnetic fields in radio-frequency (RF) cavities, critical for accelerator design. Unlike the traditional bead-pull method, which relies on a wire-pulley system prone to mechanical errors, this technique uses free-falling beads to eliminate perturbations from wires. A compact, portable device integrates a bead release system, detection mechanism and a mini-computer for rapid and accurate field measurements. Tested on a three-gap buncher cavity and a scaled Alvarez-type cavity, the method demonstrates high precision even under low signal-to-noise ratios and environmental vibrations. This approach simplifies setup, enhances measurement speed, and offers potential as a new standard for RF cavity diagnostics.

INTRODUCTION

Radio-frequency (RF) cavities are fundamental components in particle accelerators, shaping electromagnetic fields to accelerate charged particles. Precise field measurements are essential for ensuring cavity performance aligns with design specifications, particularly for applications in high-energy physics and medical accelerators. The bead-pull method, rooted in Slater's perturbation theory [1], has been the standard for mapping field distributions by measuring frequency shifts induced by a bead moved through the cavity via a wire-pulley system. However, this method faces challenges, including mechanical complexities, wire-induced perturbations (especially for higher-order modes), and time-consuming setup processes.

To address these limitations, we developed a bead-falling measurement method, as detailed in [2], which eliminates the wire-pulley system by using free-falling beads or droplets to perturb the cavity field. This technique simplifies the experimental setup, reduces mechanical errors, and enables rapid measurements suitable for real-time monitoring. The method's versatility allows it to be applied to various cavity types, such as Radio-Frequency Quadrupoles (RFQs) and Drift Tube Linacs (DTLs), enhancing the efficiency of cavity tuning and diagnostics. This paper elaborates on the method's design, hardware, software, and experimental validation, demonstrating its potential to redefine RF cavity field measurements.

* Work supported by GSI Helmholtzzentrum für Schwerionenforschung GmbH

CONCEPTUAL DESIGN AND ADVANTAGES

The bead-falling method induces perturbations by releasing a bead or droplet to fall freely through the RF cavity along the beam axis, with a VNA capturing resulting phase or frequency shifts (Fig. 1). The bead's position is correlated with time using kinematic equations, accounting for gravitational acceleration, to map the field distribution accurately.

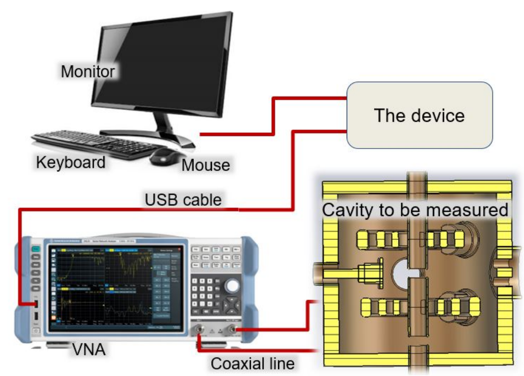

Figure 1: Scheme of bead-fall RF-measurements. The cavity is connected to two of the VNA ports. The device includes the bead/droplet release system and the bead detector. It is positioned such that the falling bead is aligned to the beam axis of the cavity. Beads are released from the top and fall freely through the bead-detector and subsequently through the cavity.

Compared to the bead-pull method, this approach offers several advantages:

- **enhanced precision**: small beads (0.5–1 mm) minimize field variations across their volume, and the absence of a wire eliminates perturbations, particularly for dipole modes.
- **rapid measurements**: free-fall durations of less than 0.5 s enable measurements at 2 Hz, supporting real-time field monitoring during tuning.
- **simplified setup**: eliminating the wire-pulley system reduces setup time and mechanical complexity, making the method adaptable to various cavity geometries.
- **material flexibility**: the use of liquid droplets (e.g., water) allows for rapid, iterative measurements, enhancing experimental efficiency.
- **robustness**: the method performs reliably under challenging conditions, such as low signal-to-noise ratios

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY02

or environmental vibrations, as demonstrated in our experiments.

These advantages make the bead-falling method particularly suited for tuning multi-gap cavities like RFQs and DTLs, where iterative field measurements are critical to correct machining-induced deviations [3].

HARDWARE AND SOFTWARE

Hardware Design

The measurement device (Fig. 2) is a compact, portable unit integrating a bead release system, detection mechanism, and control system, costing less than \$300. A medical drip infuser generates water droplets, with a valve controlling droplet size and release rate to ensure consistent measure iterations. A laser diode and light sensor form a photoelectric barrier, triggering the VNA (Rohde & Schwarz ZNB-4, 10 kHz IF bandwidth) when the bead passes a predefined point. A Raspberry Pi 4B serves as the control and computing unit, enabling data acquisition and processing. A 3D-printed cap aligns the bead with the cavity's beam axis.

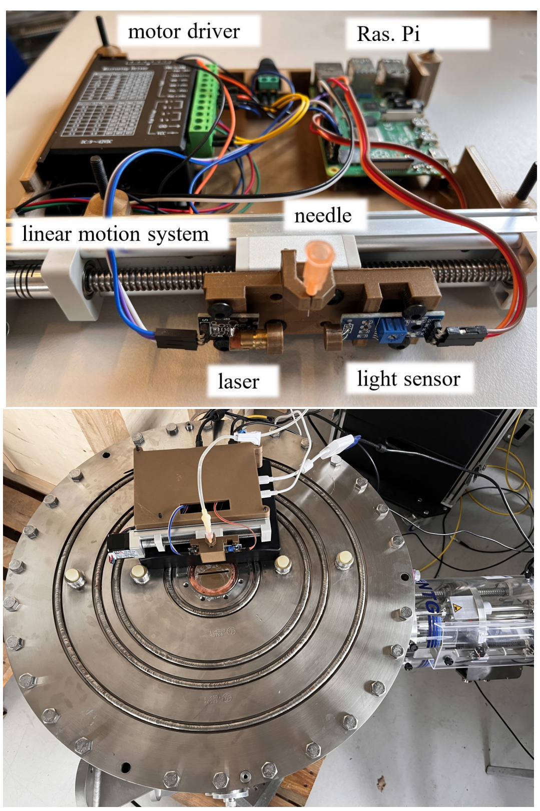

Figure 2: All components are fixed to the 3D printed case (a). Measurement device installed on top of the cavity to be measured (b).

For cavities requiring off-axis measurements (e.g., RFQ quadrants), a linear motion system adjusts the release position, though this was not needed for the experiments described here. The entire device's volume is only half the size of a letter-sized sheet of paper, making it portable and lightweight compared to the traditional wire-pulley system, and it is universal for all kinds of cavities, except the cavity is not suitable for vertical standing.

Software Implementation

The software, with an intuitive user interface (Fig. 3), is pivotal in orchestrating the device's operations, offering several key functionalities that enhance the measurement capabilities and data processing efficiency.

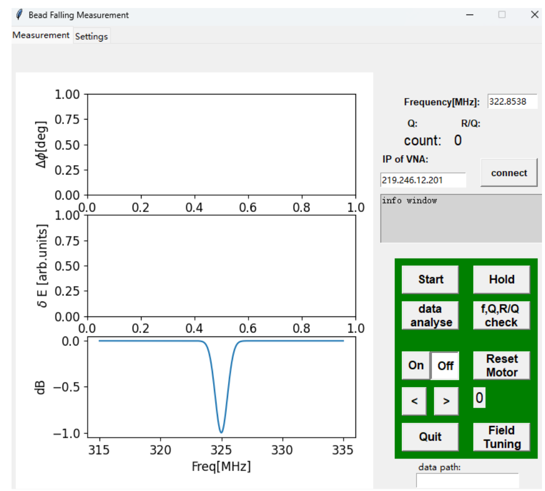

Figure 3: User interface for measurement control and visualization.

The programe converts measured phase-time curves to field-position curves using kinematic models and applies Singular Value Decomposition (SVD) to filter noise from repeated measurements. The software automates iterative measurements, enabling real-time field updates at 2 Hz, and includes features to mitigate frequency drift by re-measuring resonance frequency every 120 s.

Field Tuning Program

The tuning algorithm uses a response matrix to model the effect of each tuner on field components at various longitudinal positions [3]. The field distribution is measured using the perturbation technique, represented as a vector$[\delta E_1, \delta E_2, \ldots, \delta E_M]$, where δE_m is the gap voltage (for DTL cavities) or magnetic field (for RFQs) at the m_{th} position.

Adjusting a tuner changes the field distribution. The initial tuner setting is zero, and the required tuner adjustments, δT, are found by solving:

$$\begin{pmatrix} \delta E_1 \\ \delta E_2 \\ \vdots \\ \delta E_M \end{pmatrix} = \begin{pmatrix} \frac{\partial E_1}{\partial T_1} & \frac{\partial E_1}{\partial T_2} & \cdots & \frac{\partial E_1}{\partial T_N} \\ \frac{\partial E_2}{\partial T_1} & \frac{\partial E_2}{\partial T_2} & \cdots & \frac{\partial E_2}{\partial T_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial E_M}{\partial T_1} & \frac{\partial E_M}{\partial T_2} & \cdots & \frac{\partial E_M}{\partial T_N} \end{pmatrix} \begin{pmatrix} \delta T_1 \\ \delta T_2 \\ \vdots \\ \delta T_N \end{pmatrix}. \quad (1)$$

This overdetermined system is solved to minimize the difference between measured field distributions respect to the

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY02

desired one. For RFQ tuning with four quadrants, the field distributions of 4 quadare concatenated, increasing M to $4M$. The tuning program's user interface is shown in Fig. 4. Due to non-linear tuner effects and adjustment errors, the process is iterative to achieve the desired field distribution.

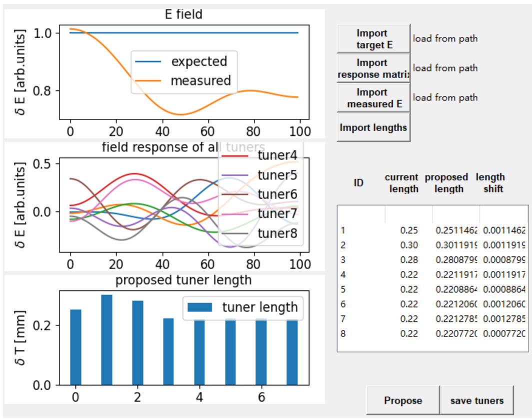

Figure 4: The user interface of the tuning program.

MEASUREMENTS

Three-Gap Buncher Cavity

A three-gap buncher cavity (36.136 MHz, Q=1000, Fig. 5) was tested, its parameters are listed in Table 1. The cavity was aligned vertically using a plumb line and adjustable legs, with a 3D-printed cap ensuring droplet alignment. Calibration involved dropping beads from various heights to determine the system delay (78.32 ± 0.85 ms) and initial velocity, using phase shift data from three equidistant gaps.

Table 1: Parameters of the Buncher BB3

Parameter	Unit	Value
RF-frequency	MHz	36.136
Gaps	#	3
Gap length	mm	12.7–13.5
Drift tubes	#	2
Drift tube length	mm	38.1–40.8
Aperture	mm	100
Tank diameter	mm	420
Tank length	mm	525.7
Q-factor		1000

Despite a low Q-factor, SVD processed 500 iterations of 3000-point data, yielding clear field distributions (Fig. 7). Comparisons with simulations showed minor deviations due to machining inaccuracies (Fig. 6).

Two-dimensional field measurements, facilitated by a slit in the 3D-printed cap, provided detailed field maps, confirming the method's ability is not limited to on-axis field measurement. With proper translation and scaling, the measured field (denoted by $\hat{E}_{abs}$) can be compared with the

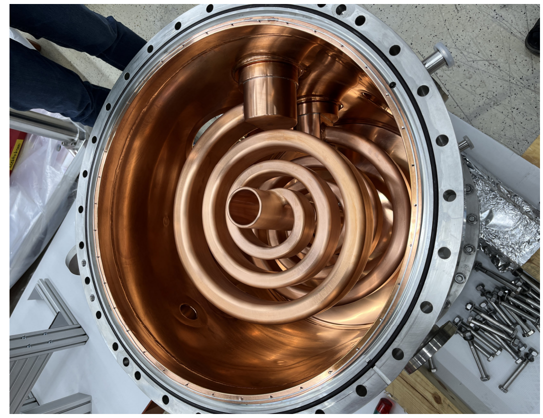

Figure 5: Three-gap buncher cavity (36 MHz).

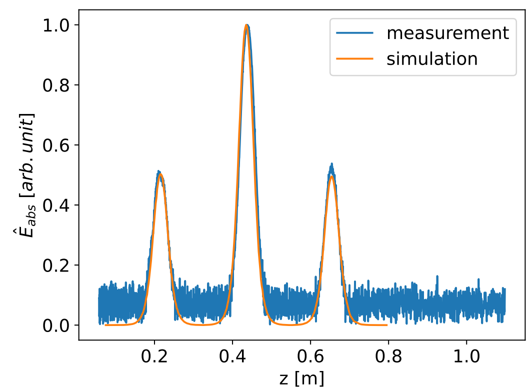

Figure 6: Measured vs. simulated electric field in the buncher cavity.

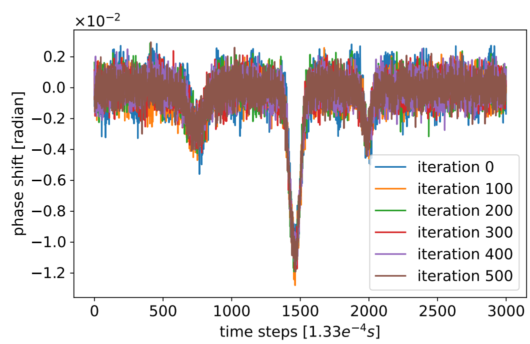

Figure 7: Measured data taken with the buncher cavity with 3000 discrete time points within 0.4 second each, corresponding to a length of about 1.2 m along the cavity axis.

corresponding field obtained from simulation(denoted by E_{abs}), as shown in Fig. 8. The rapid measurement capability allowed real-time monitoring during tuning, enabling iterative adjustments to achieve the desired field flatness, being critical for buncher cavities in accelerator systems.

Alvarez-Type Cavity Model

A 1:3 scale aluminum Alvarez-type cavity [4,5] was tested under challenging conditions (low Q, environmental noise). It is depicted in Fig. 9 and its parameters are listed in Table 2.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY02

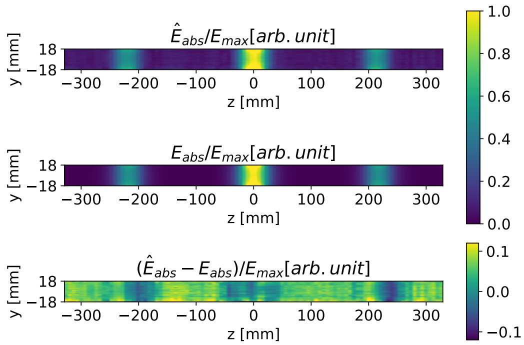

Figure 8: The distribution $\hat{E}_{abs}$ represents the experimentally measured two-dimensional field, while E_{abs} denotes the corresponding field obtained from simulations. Both fields are normalized to their respective maxima, specifically the peak value observed at the middle gap. The term $\hat{E}_{abs} - E_{abs}$ quantifies the deviation of the measured values from the simulated ones.

Despite a 2:1 signal-to-noise ratio, rapid iterative measurements and SVD analysis extracted clear field distributions (Fig. 10).

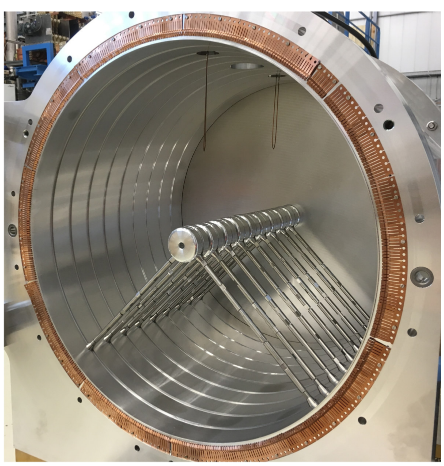

Figure 9: 1:3 scale Alvarez-type cavity model.

Table 2: Parameters of the Alvarez-Type DTL Cavity

Parameter	**Unit**	**Value**
RF-frequency	MHz	325.224
Gaps	#	10
Gap length	mm	12.7–13.5
Drift tubes	#	9
Drift tube length	mm	38.1–40.8
Drift tube diameter	mm	60.0
Aperture	mm	10.0
Tank diameter	mm	634.5
Tank length	mm	525.7
Q-factor		500

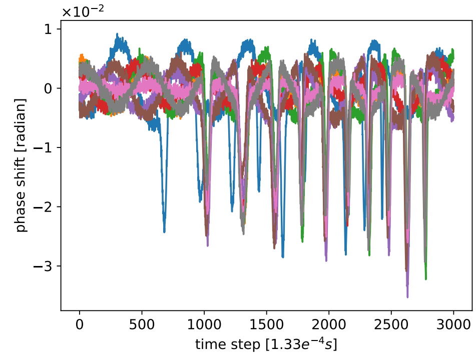

Figure 10: Measured phase shift data from the Alvarez-type DTL, with a signal-to-noise ratio of approximately 2. Different colors represent multiple phase shift measurements conducted using the DTL. Only five representative results from thousands are presented.

In the measurement results for the buncher cavity, the field distribution overwhelmingly dominates relative to the noise, allowing the first singular vector to be approximately regarded as the field distribution. However, The measurement data for the aluminium cavity is more complex, with the magnitude of background noise being on the same order as the field distribution. Results from Singular Value Decomposition (SVD) indicate a clear periodic oscillation within the background, which is not orthogonal to the real field distribution. Since the singular vectors obtained from SVD must be orthogonal, the primary singular vector does not represent the actual field distribution. To address this, the real field distribution is considerd as a linear combination of the first four singular vectors with specific weights. By using a small segment (0-900 out of 3000) of the measurement data without gaps as a reference, the four weights can be solved, thus yielding the final measurement field distribution (Fig. 11).

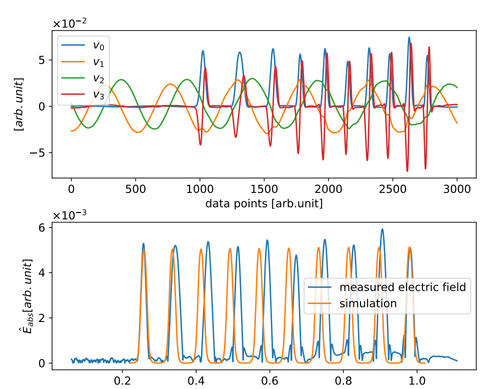

Figure 11: Upper: the first four singular vectors. Lower: measured electric field along the beam axis of the DTL model cavity.

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-THY02

LIMITATIONS

The method is limited to cavities shorter than 3.5 m due to sampling rate constraints and Coriolis force effects (0.22 mm deflection at 3.5 m). It is unsuitable for cavities with significant gravity-induced deformation, such as Alvarez resonators with slender support rods, as observed in the model cavity measurements.

CONCLUSION

The bead-falling measurement method, as detailed in [2], offers a transformative approach to RF cavity field mapping, combining precision, speed, and simplicity. Its compact, low-cost device and noise-resilient measurements make it a versatile tool for accelerator diagnostics. Future developments will focus on enhancing its applicability to diverse cavity types and integrating advanced tuning algorithms to further streamline the tuning process, potentially impacting the design and optimization of next-generation accelerators.

REFERENCES

[1] L. C. Maier and J. C. Slater, "Field strength measurements in resonant cavities", *J. Appl. Phys.*, vol. 23, no. 1, pp. 68–77, 1952. doi:10.1063/1.1701980

[2] X. Du and L. Groening, "Radio-frequency cavity field measurements through free falling bead", *Phys. Rev. Accel. Beams*, vol. 28, no. 1, p. 012001, 2025. doi:10.1103/PhysRevAccelBeams.28.012001

[3] B. Koubek, A. Grudiev, and M. Timmins, "RF measurements and tuning of the 750 MHz radio frequency quadrupole", *Phys. Rev. Accel. Beams*, vol. 20, no. 8, p. 080102, 2017. doi:10.1103/PhysRevAccelBeams.20.080102

[4] A Seibel, O. K. Kester, X. Du, L. Groening, and S. Mickat, "Ten gap model of a new Alvarez DTL cavity at GSI", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3748–3750. doi:10.18429/JACoW-IPAC2015-THPF027

[5] M. Heilmann *et al.*, "Scaled Alvarez-cavity model investigations for the UNILAC upgrade", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 916–919. doi:10.18429/JACoW-IPAC2018-TUPAF079