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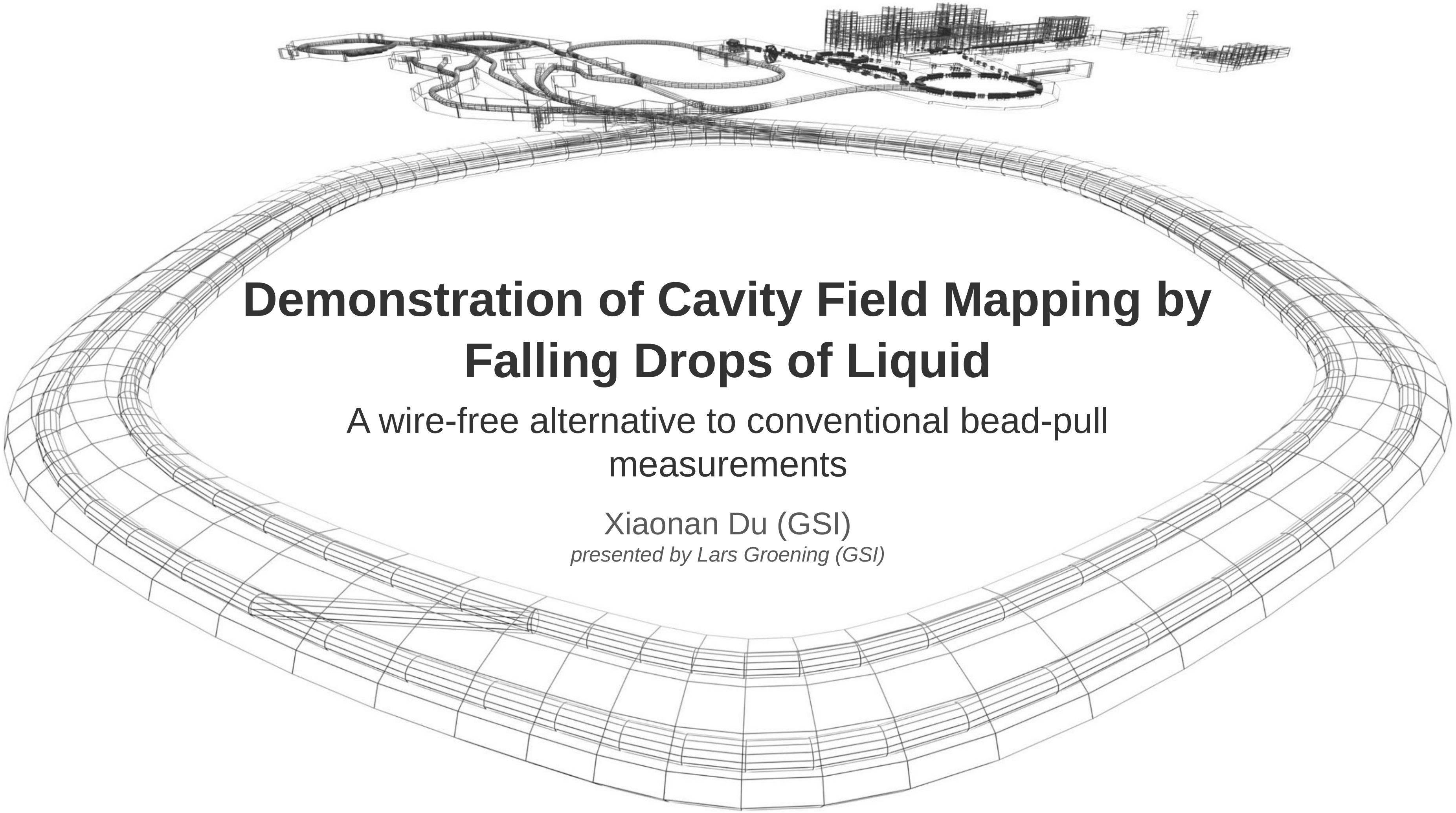

Demonstration of Cavity Field Mapping by Falling Drops of Liquid

A wire-free alternative to conventional bead-pull measurements

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presented by Lars Groening (GSI)

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Introduction

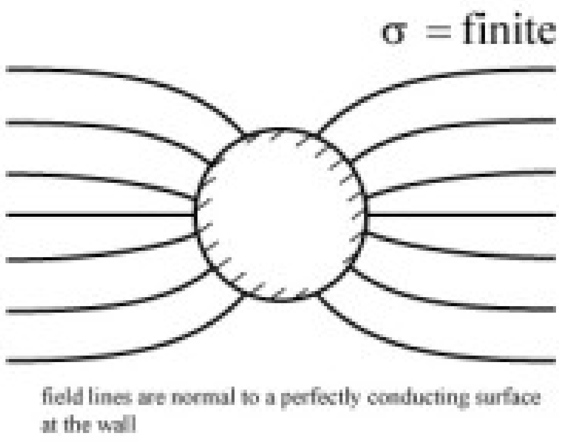
Preserving bead perturbation without a pull line

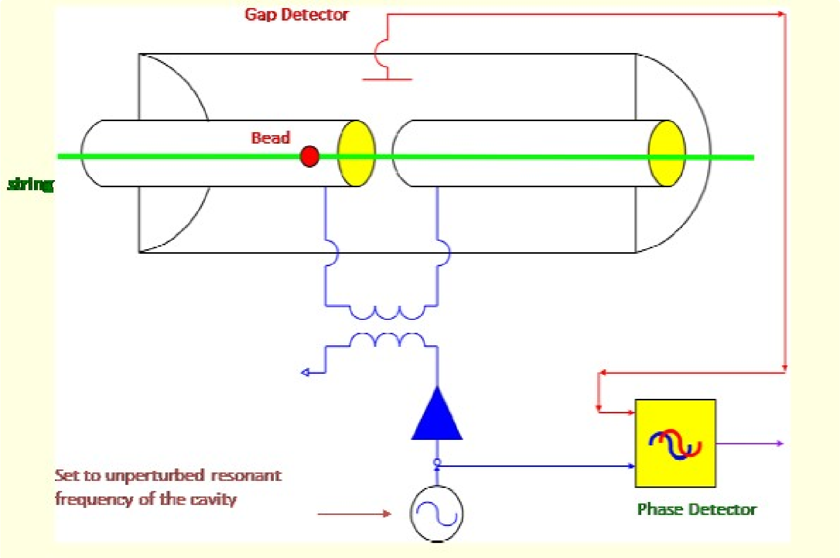
Objective: map the field distribution and flatness inside an RF cavity

Perturbation: move a small bead along a defined path and measure the resulting resonant-frequency or phase shift

Acquisition: use a vector network analyzer (VNA) to record the cavity response

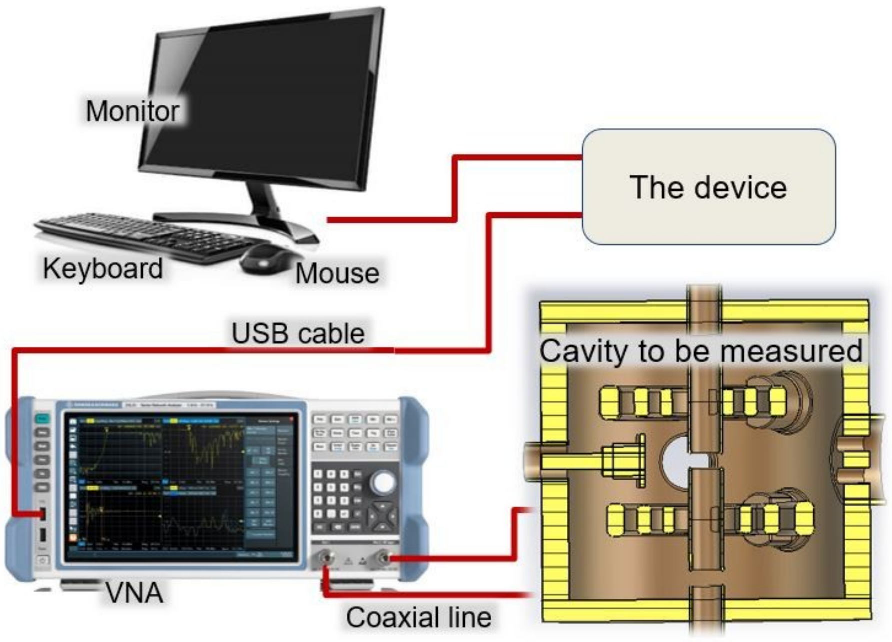
Bead-falling approach: let gravity transport the perturbing object, eliminating the pull line





Conceptual design

Each free fall is assigned to a synchronized RF-field measurement



Trajectory: the bead falls through the cavity along the selected measurement line

Positioning: a linear stage sets the launcher location

Release medium: the launcher handles solid beads or liquid droplets

Triggering: an optical detector starts RF acquisition as the bead enters the cavity

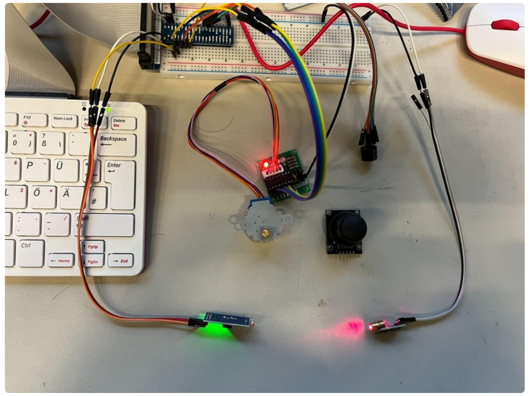
Control: a computer coordinates positioning, VNA acquisition, and data processing

Timing: transit time is calculated or measured with a high-speed camera

Hardware

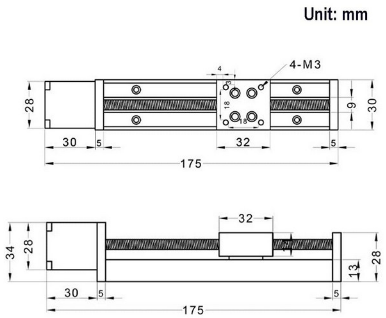
Off-the-shelf components keep the device compact and inexpensive

Raspberry Pi 4B · € 80

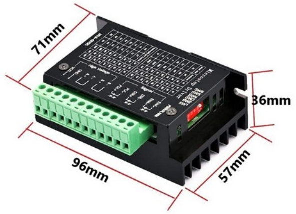


Optical bead detector · € 20

Beam interruption triggers RF acquisition

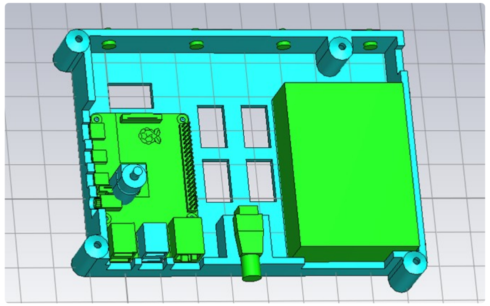


Linear-stage sketch



Motor controller · € 17

Linear motion stage · € 120

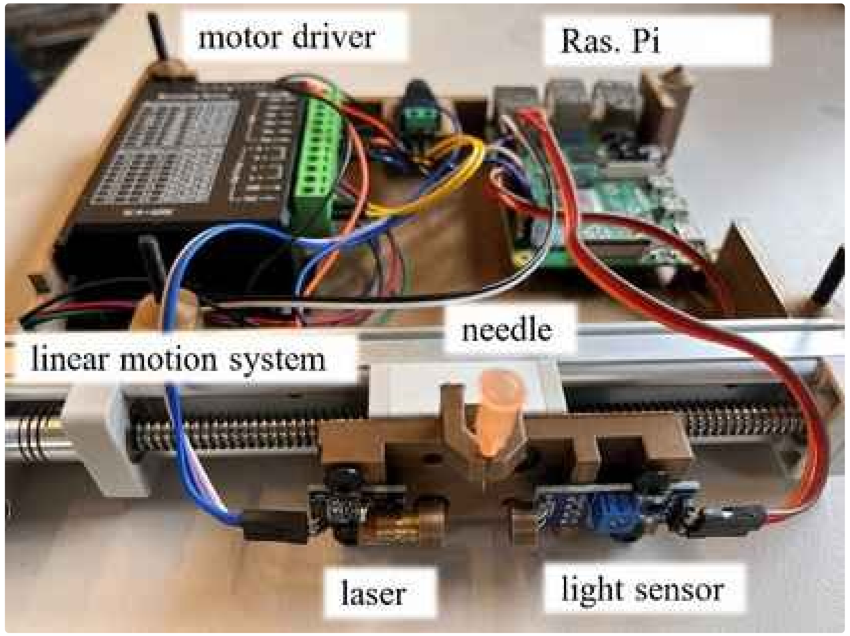


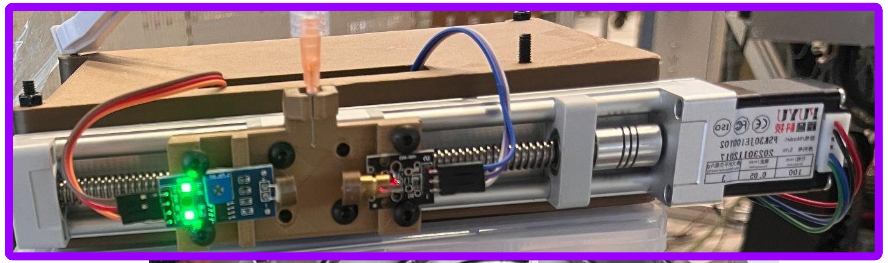
3D-printed case · ≈ € 20

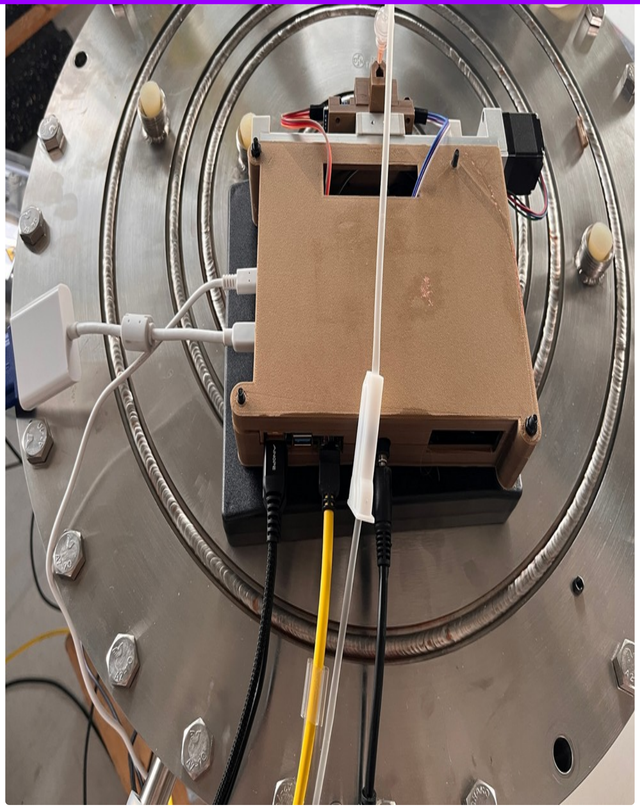
Hardware

One launcher integrates release, optical triggering, and control

Compact and portable — the integrated device occupies roughly half a letter-sized sheet and combines release, optical detection, motion, and Raspberry Pi control for cavities that can be tested vertically







Introduction

Free fall removes wire perturbation while improving speed and access

Small probe: 0.5–1 mm beads or droplets pass through narrow apertures, including RFQ vane tips

Wire-free measurement: eliminating the nylon pull line removes its field perturbation and mechanical vibration

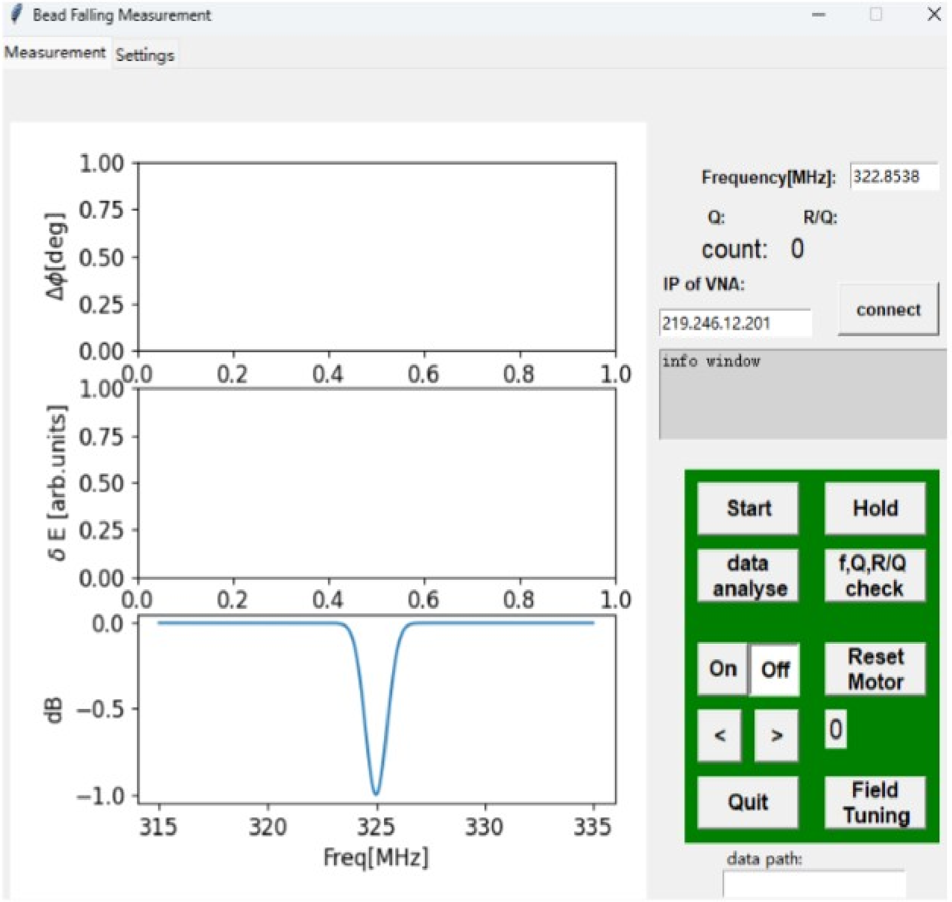
Fast acquisition: each measurement takes less than 0.5 s, supporting field updates at about 2 Hz

Flexible perturbators: solid beads or liquid droplets support rapid, repeated release

Defined trajectory: launcher position selects the measurement path

User interface

One interface coordinates motion, RF-acquisition, and analysis



Configure: set frequency, Q, network parameters, and measurement conditions

Acquire: capture VNA data when the optical detector triggers

Control: operate the VNA and linear positioning stage remotely

Process: convert phase-versus-time measurements into field-versus-position data

Monitor: display results live and accumulate repeated scans for de-noising

Automated, trigger-driven measurement

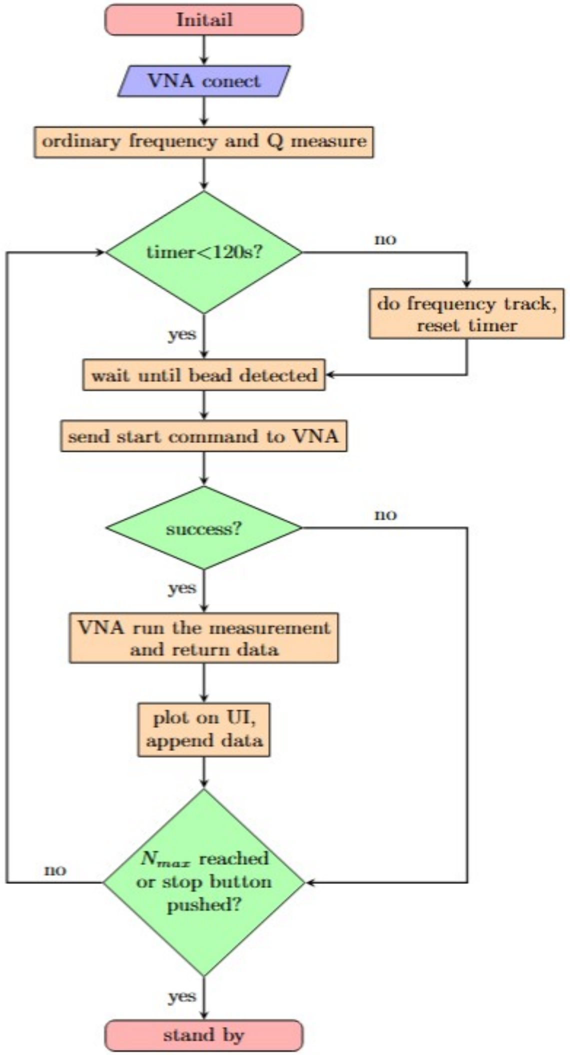
1 · Initialize: connect the VNA and measure the reference resonance frequency and Q

2 · Prepare: track the resonance if required, then wait for the optical trigger

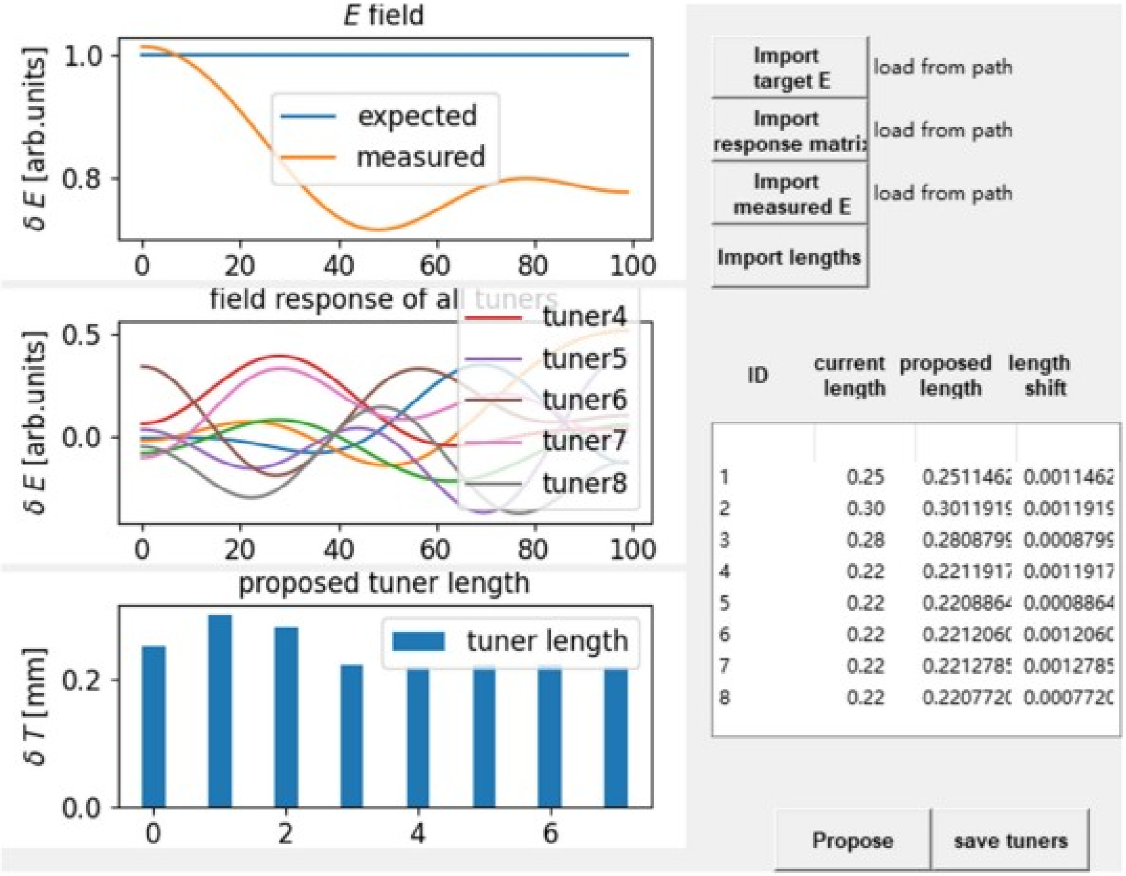
3 · Acquire: at detection, command the VNA and read the S21 phase at the target frequency

4 · Update: display the result and append it to the dataset

5 · Repeat: continue until the stop command or target scan count is reached



Response-matrix tuning



From field error to tuner corrections

- calculate the field error ΔE between the measured and target distributions
- express each tuner's effect as a field-response vector
- solve the linear system for the tuner-length corrections ΔT
- review the proposed settings before applying them

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

Software

Calibration and validation turn trigger time into a reliable field profile

Delay calibration: the three-gap buncher gives a system delay of 78.32 ± 0.85 ms

Frequency tracking: re-measure the resonance frequency at intervals of about 120 s

Sampling: record 3000 points over 0.4 s with sufficient VNA IF bandwidth

Data validation: discard acquisitions compromised by command delays or timeouts (< 5%)

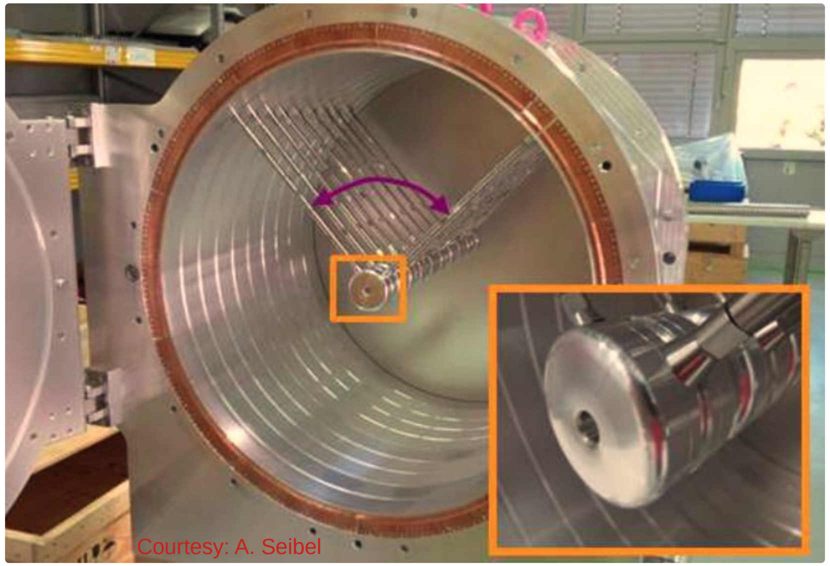
Phase reference: subtract the mean phase near both boundaries for each scan

Live versus offline: update the field at about 2 Hz; apply SVD only after enough scans have accumulated (SVD: Single Value Decomposition)

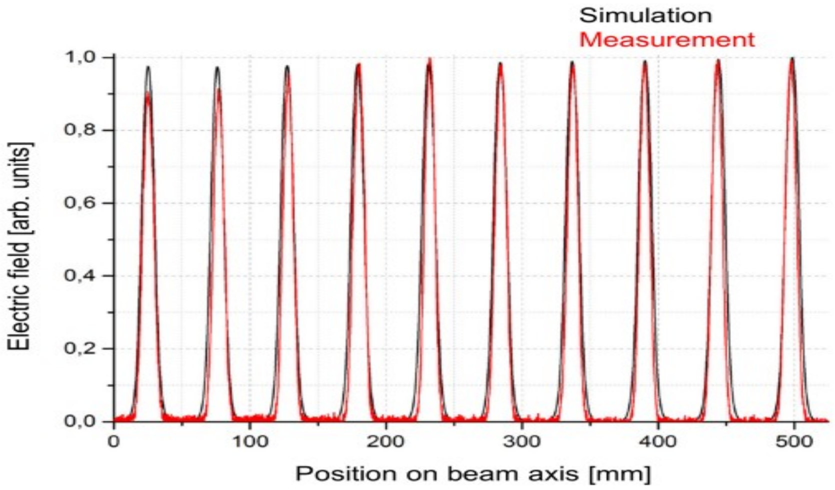
Measurement on an Alvarez model cavity

A 1:3-scale model extends validation to a ten-gap Alvarez-type cavity

Purpose: the model supports UNILAC upgrade studies, with emphasis on the stabilization scheme and field-tilt sensitivity
Validation reference: simulated and measured on-axis field profiles establish the baseline for evaluating the method



Alvarez model parameters (1:3 scale)		
Parameter	**Unit**	**Value**
RF frequency	MHz	325.224
Gaps	No.	10
Gap length	mm	12.7–13.5
Drift tubes	No.	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

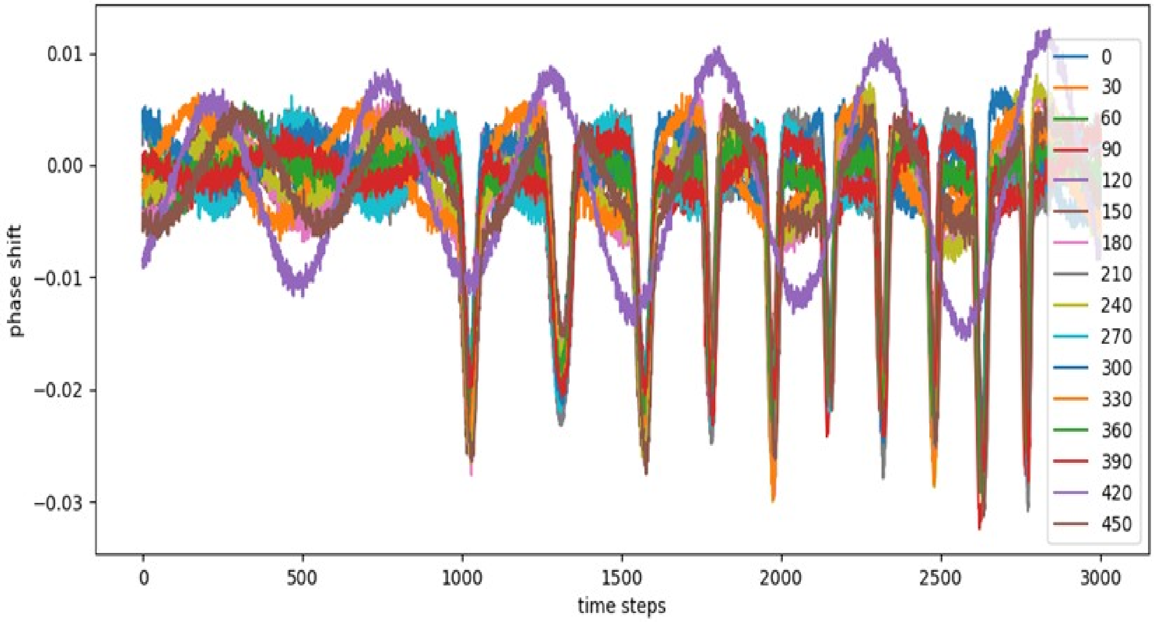


Measurement on an Alvarez model cavity

Repeated scans overcome a signal-to-noise ratio of only ≈ 2

Challenge:
A low measured Q of about 530, equipment noise, and vibration of the loose copper-wire coupler reduce the signal-to-noise ratio to approximately 2

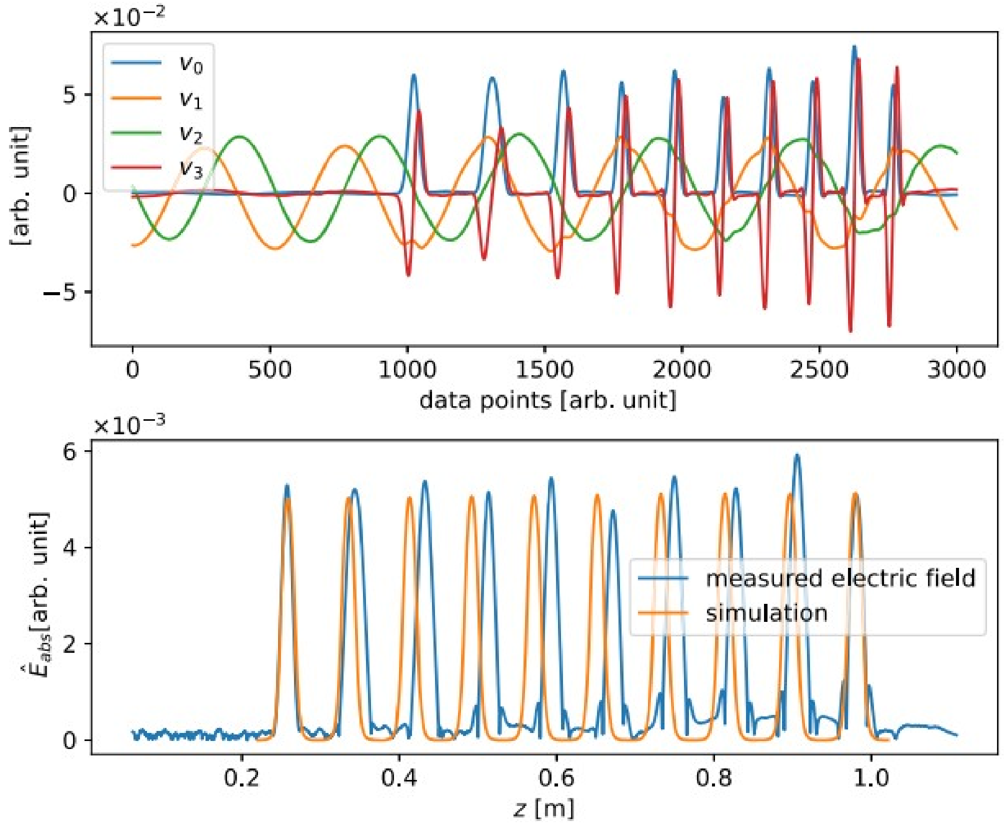
Method:
Stack each phase-shift trace as a one-dimensional vector, then apply singular value decomposition (SVD) to separate coherent field structure from noise



Repeated phase-shift traces · signal-to-noise ratio ≈ 2

Measurement on an Alvarez model cavity

SVD reconstructs the ten-gap field despite strong measurement noise



The rightward shift of the gap-field peaks is consistent with gravity-induced drift-tube displacement, revealing a limitation of vertical testing for this Alvarez model

Reconstruction:

express the true field as a linear combination of the first four singular vectors

Use the gap-free baseline segment (samples 0–900 of 3000) to solve the weights

The resulting weight ratio is 45.92 / 0.11 / 0.93 / 7.69

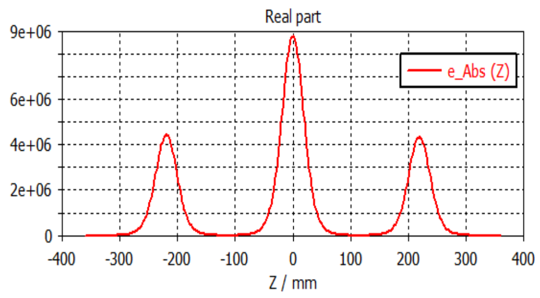
Result: The ten-gap field remains identifiable despite an SNR of about 2 and the soft coupler

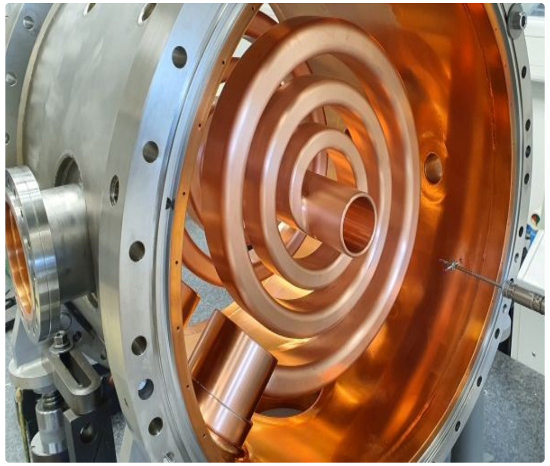
Measurement on the BB3 buncher cavity

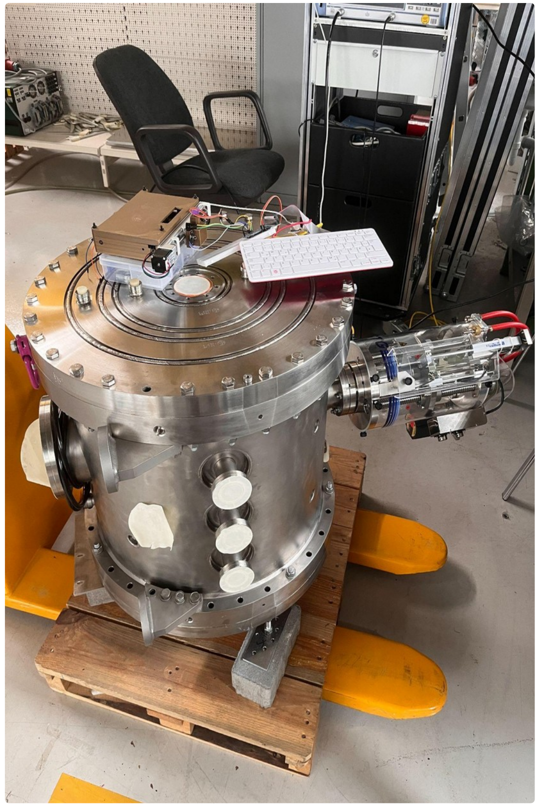
Validation setup: the BB3 spiral buncher

The three-gap BB3 spiral buncher provides known gap spacing for calibrating trigger velocity and system delay before field mapping.

Geometric parameters	BB3
Tank Inner Radius	250 mm
Tank Inner Length	520 mm
Tube Inner Radius	27.5 mm
Tube Outer Radius	32.5 mm
Gap Length	26.4 mm
Flanges	CF150, CF100, CF63, 3*CF63
RF parameters	
Frequency	36.136 MHz
Total gap voltage	875 KV
Total Power loss	74 KW
Z	12 MOhm
E_peak	49 MV/m, 6 Kilp.
Tuning range	0.5 MHz



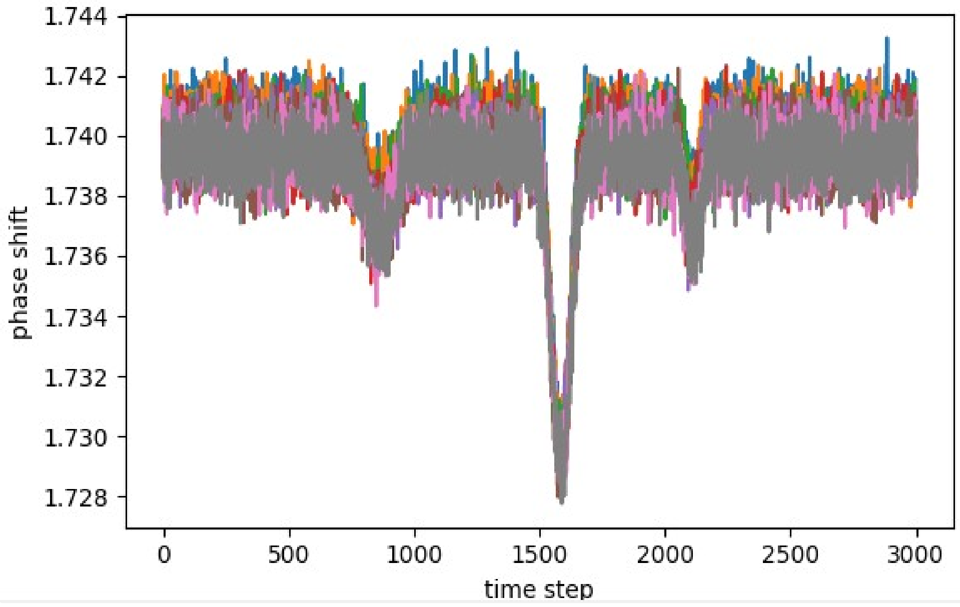




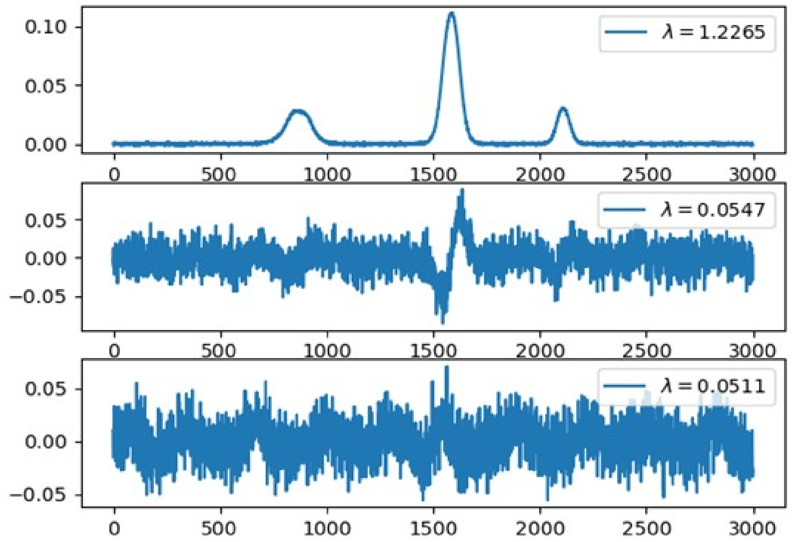
Measurement on the BB3 buncher cavity

Repeated scans reveal coherent field structure beneath the noise

At Q ≈ 1000, noise in a single scan is comparable to the signal. After 500 scans with 3000 samples each, SVD identifies the first singular vector as the dominant field profile



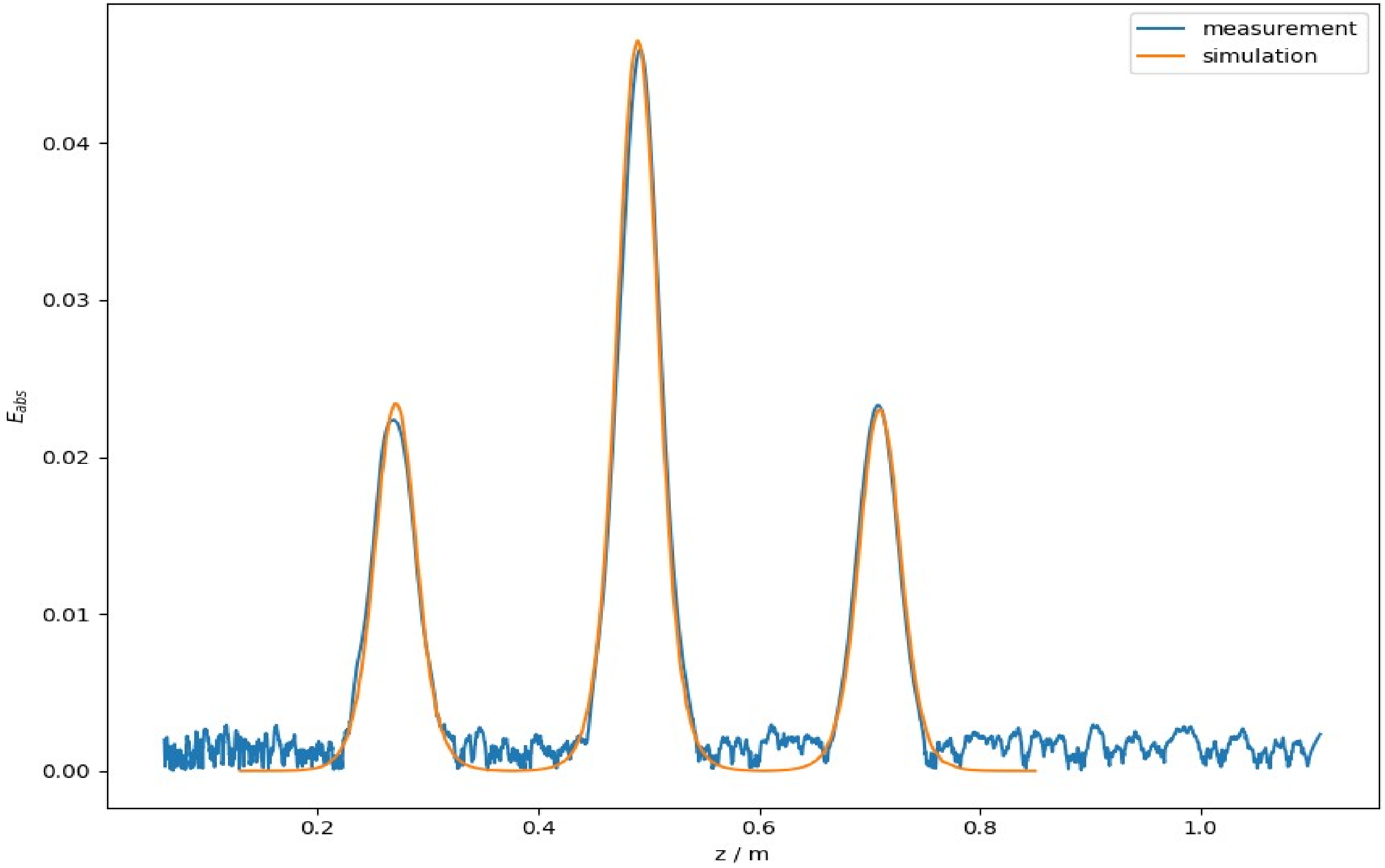
Aligned repeated measurements



SVD isolates the coherent field mode

Measurement on the BB3 buncher cavity

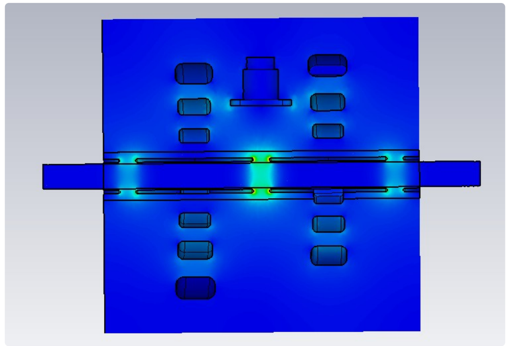
The 1D measurement reproduces all three simulated field peaks

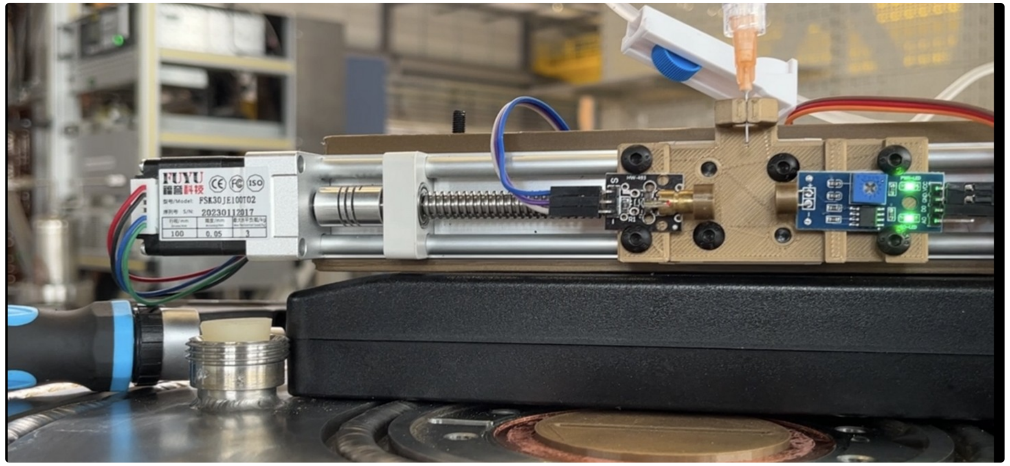


The three measured peaks closely follow the simulation; remaining deviations reflect finite machining and measurement accuracy

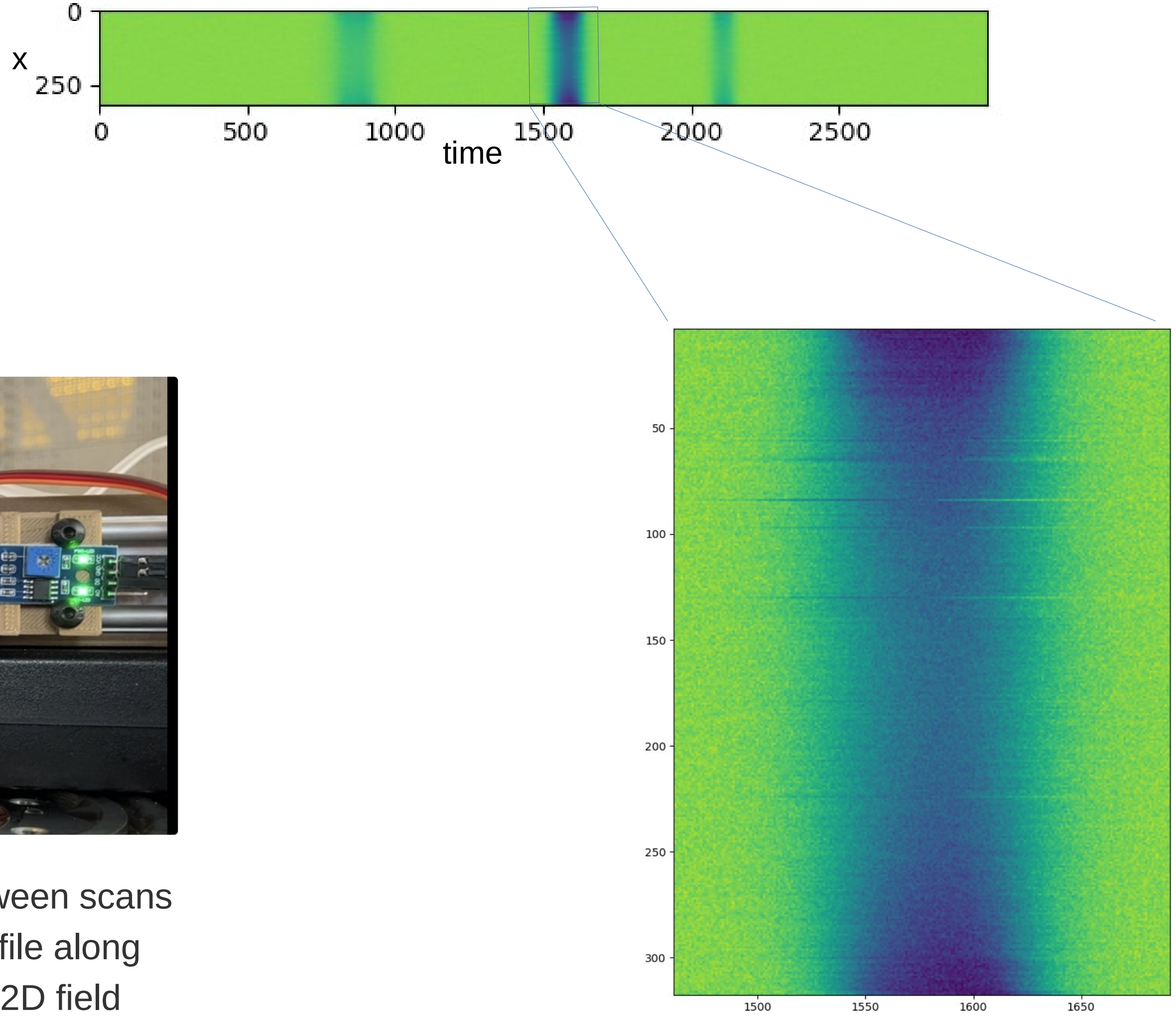
Measurement on the BB3 buncher cavity

Repeated 1D scans assemble a 2D field map



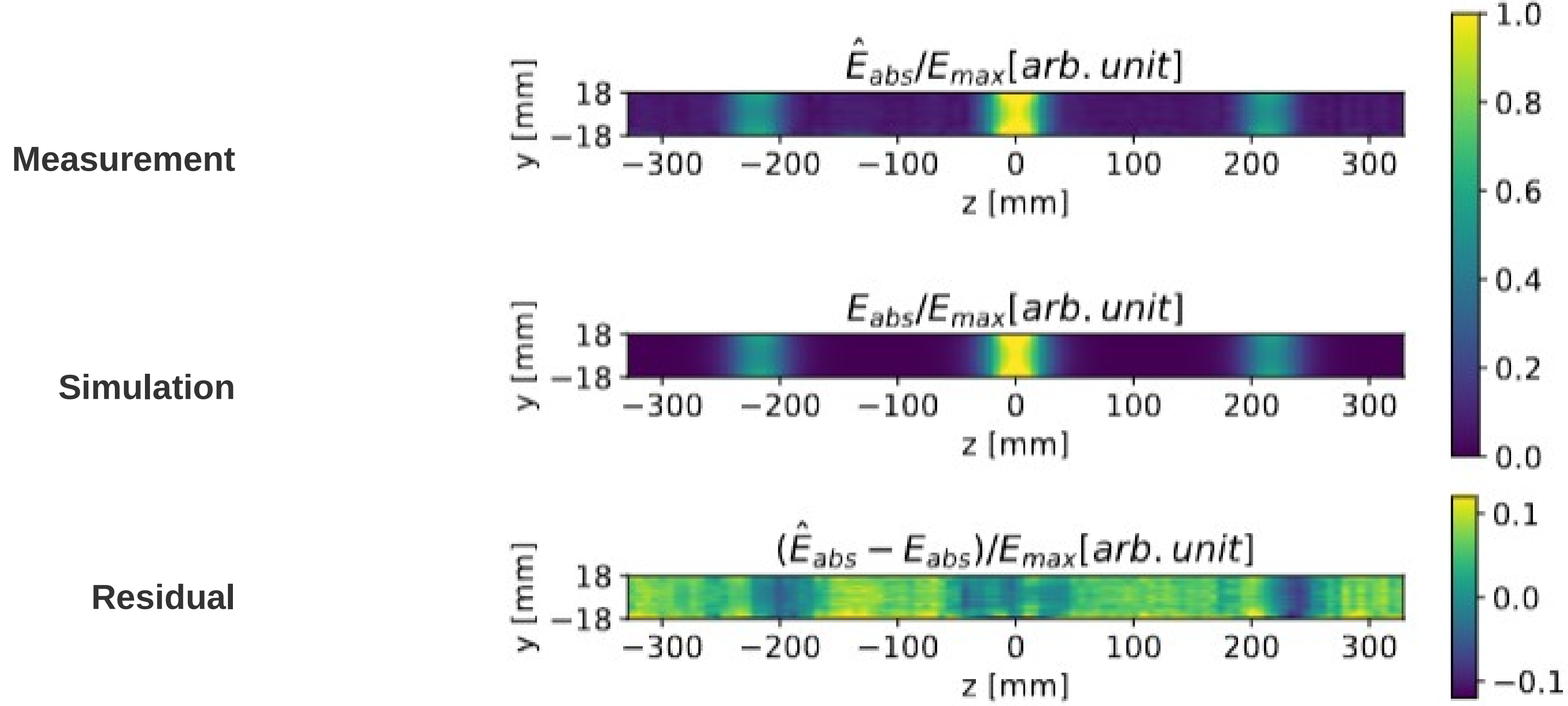


The launcher translates the needle horizontally between scans
At each transverse position, one fall yields a 1D profile along the beam axis; combining the profiles produces the 2D field map



Measurement on the BB3 buncher cavity

The 2D measurement reproduces the simulated three-gap structure



After independent normalization to the central peak, the residual map quantifies the difference between measurement and simulation

Acknowledgements

Thank you for your attention

Thank you!

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X. Du and L. Groening, Radio-frequency cavity field measurements through free falling bead,
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