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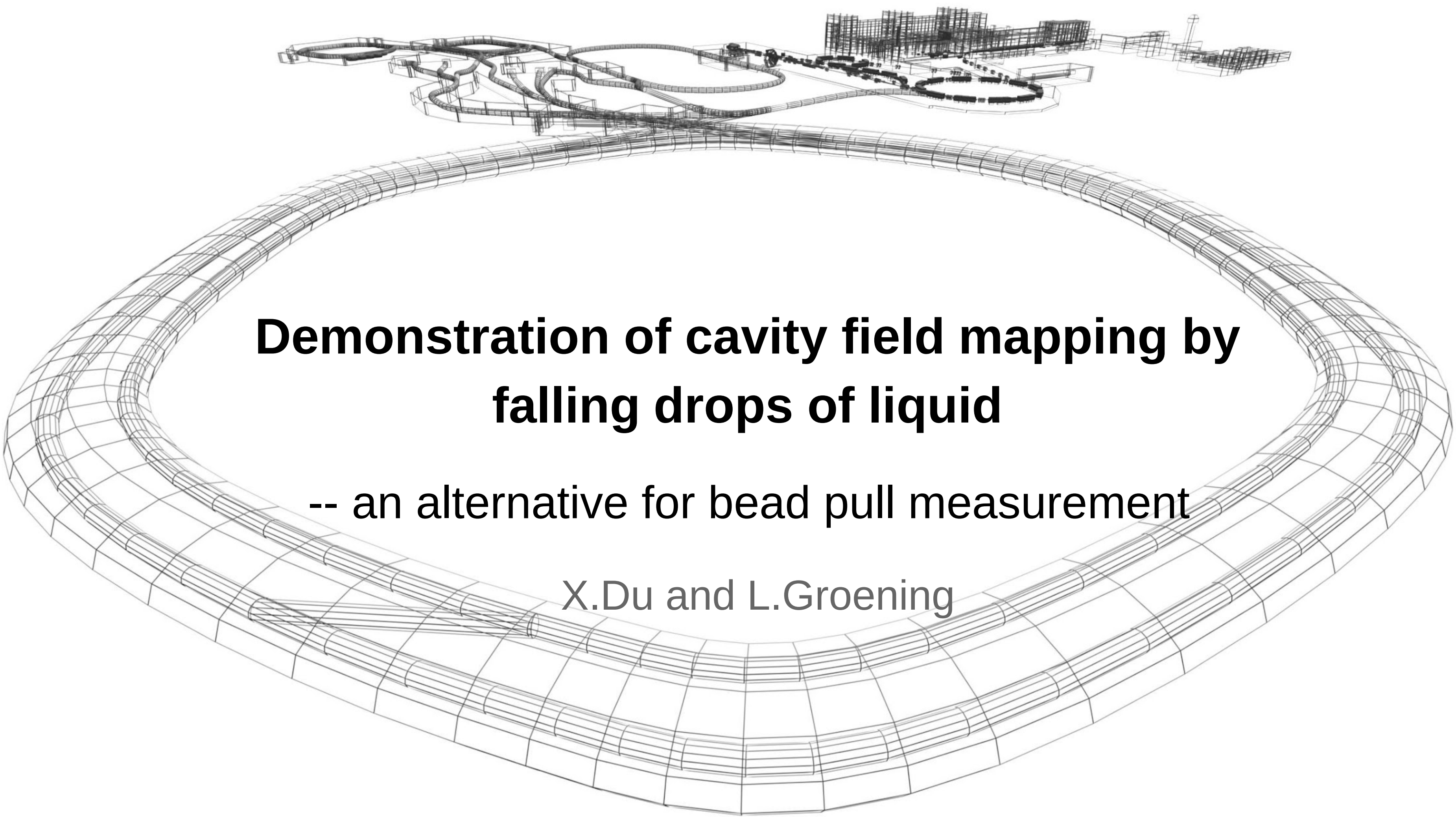

Demonstration of cavity field mapping by falling drops of liquid

-- an alternative for bead pull measurement

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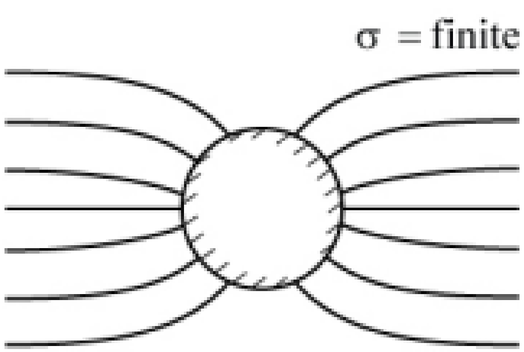
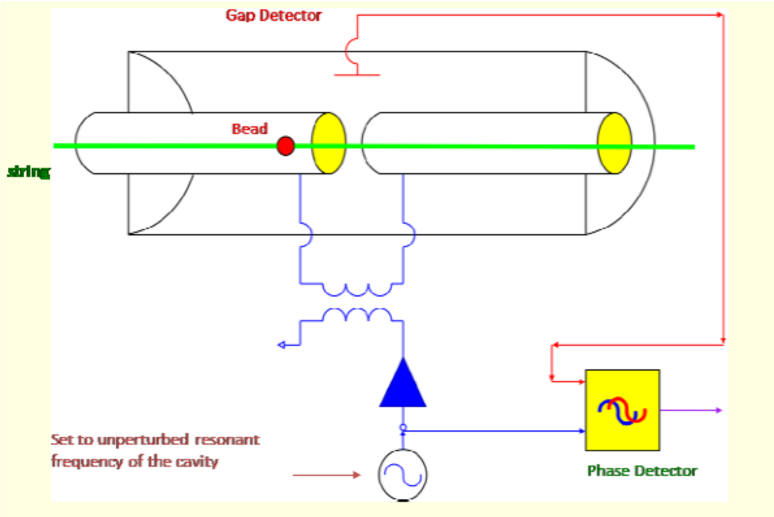
Introduction

perturbation method, bead pull measurement

Bead-Pull is a commonly used Radio Frequency (RF) field measurement technique. RF field measurements play an important role in qualifying any RF cavity. They are used in evaluating the field distribution inside a resonant structures and in tuning them to obtain the required field flatness. The bead is pulled through of the cavity while the electric field measurement in the cavities is done. A step motor and a pulling system guide the motion of the bead through the cavity while a network analyzer is used to take the RF measurements.

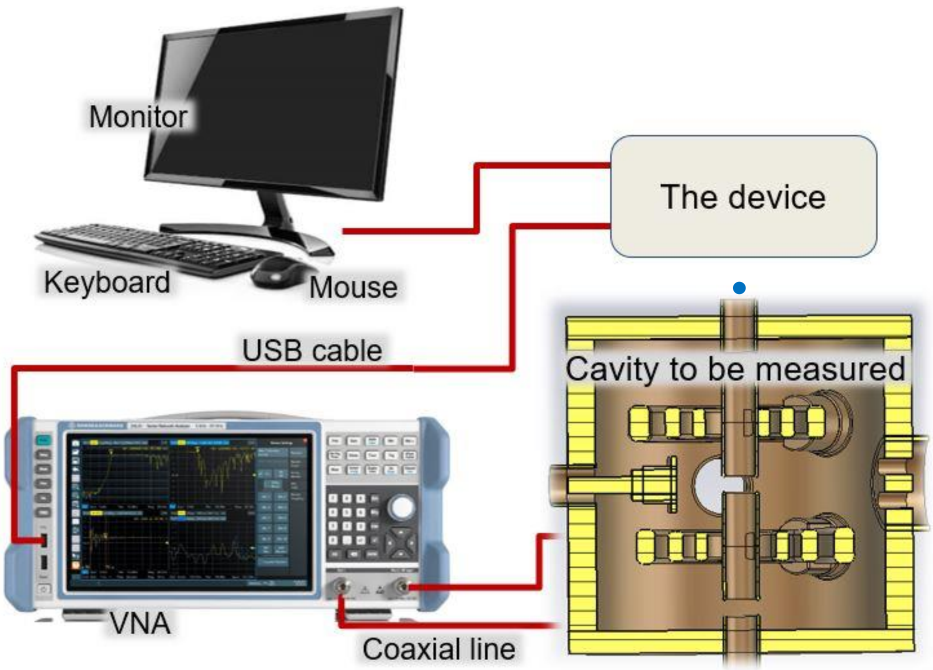


field lines are normal to a perfectly conducting surface at the wall



Conceptual design

Overview



- the cavity is placed such that the measurement path is vertical
- linear motion system for positioning
- bead launching device for droplet or solid bead
- bead detector to trigger the measurement process when the bead reaches entrance of the cavity
- computer to control all components and process data
- VNA for RF-measurements
- The accelerating bead is not a issue, time-height relation can be calculated with formula or measured with high speed camera

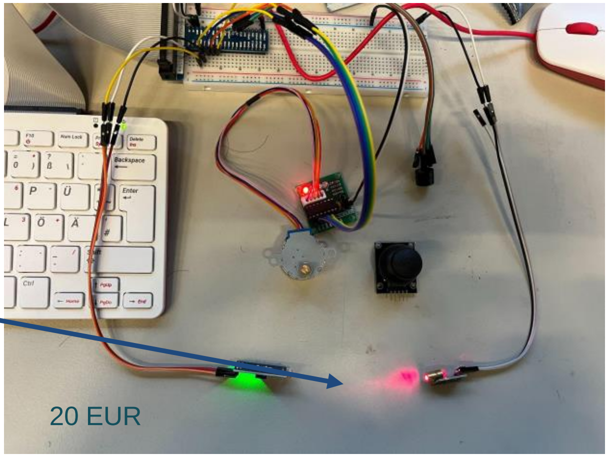
Hardware

Raspberry pi, linear motion system, bead detection system

Raspberry pi 4B

80 €

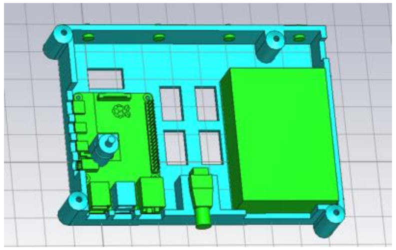
Each time the laser is blocked by the falling bead, measurement is triggered



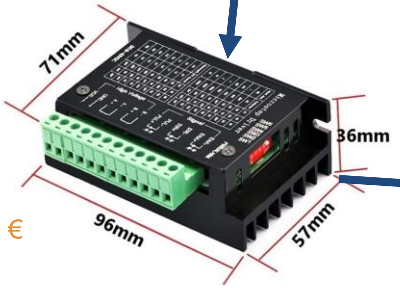
20 EUR

bead detection system
laser (right) and sensor (left)

≈ 20 €



3D printed case

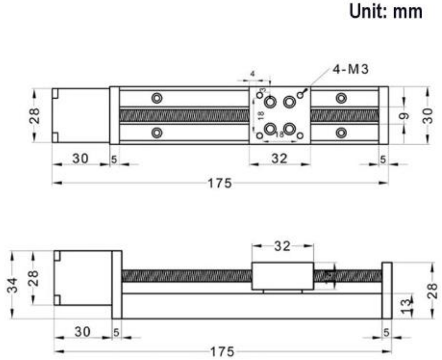


17 €

motor controller

120 €

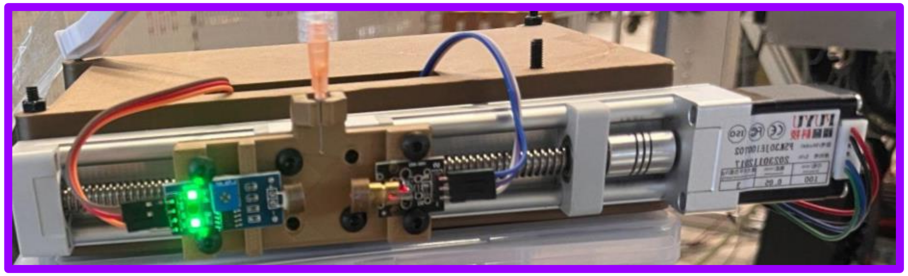
linear motion system

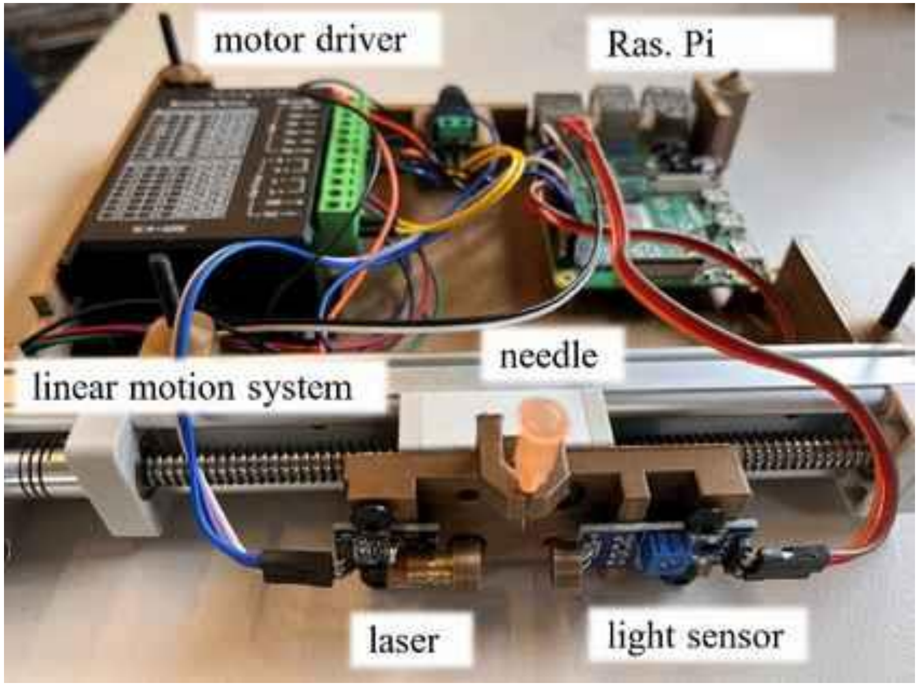


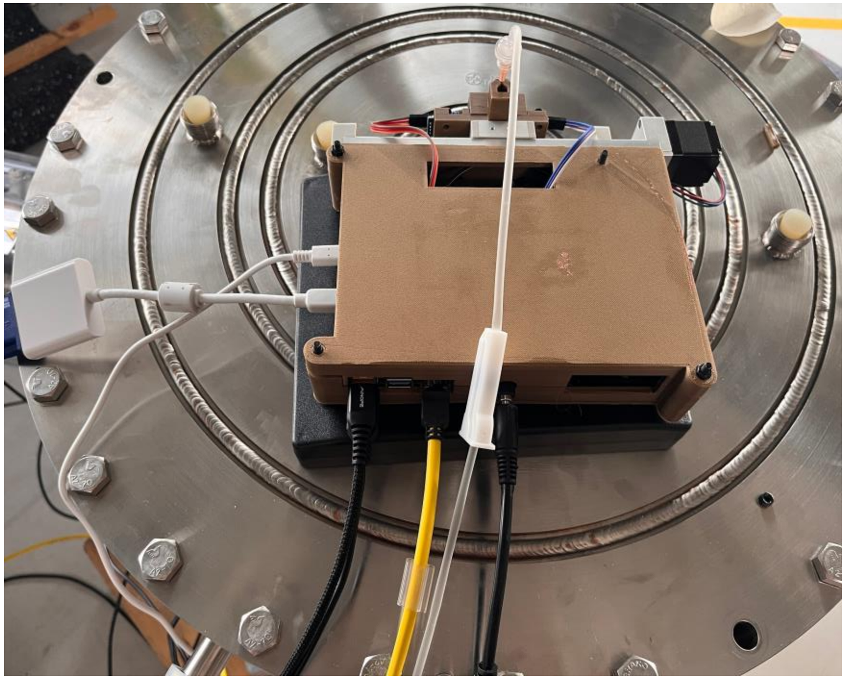
Hardware

The main device (launcher)

A compact, portable device integrates a bead release system, detection mechanism and a mini-computer for rapid and accurate field measurements







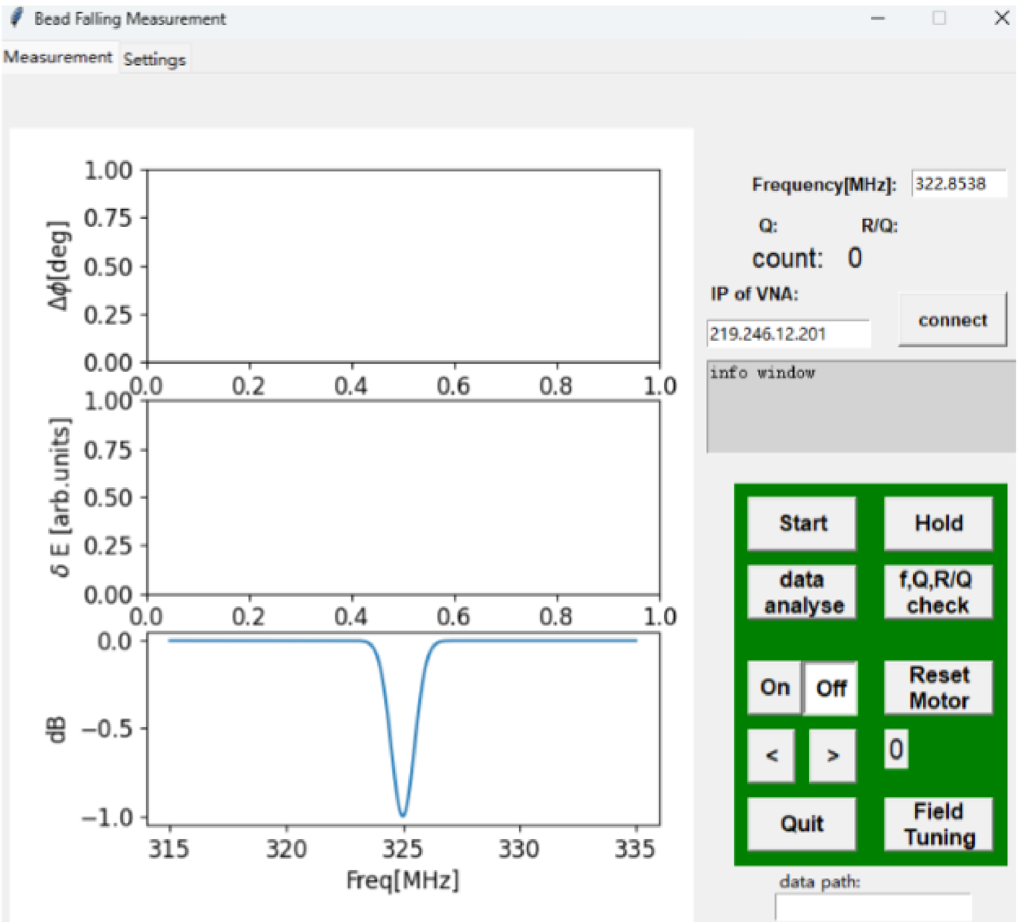
Introduction

Advantages

- The bead could be very small (e.g. 0.5 − 1 mm diameter), such that the perturbation's position can be well-defined. The bead could go through small gaps such as gap between RFQ vane tips
- Different materials can be used for the bead. For example, liquid drops could be used, allowing for fast iterative bead release
- The free falling time duration is less than a second, thus the measurement could be very fast. Real-time field monitoring at about 2 Hz can be achieved. During the field tuning, tuners can be adjusted according to the continuously updated field distribution. The process could be more efficient.
- The path is determined by the position of the launching device, which can be easily controlled. Though, an appropriate device for bead positioning and release is required
- Problems caused by wire and pulley systems are completely eliminated(wire vibration, path distortion, large size......)

Software

UI of the software

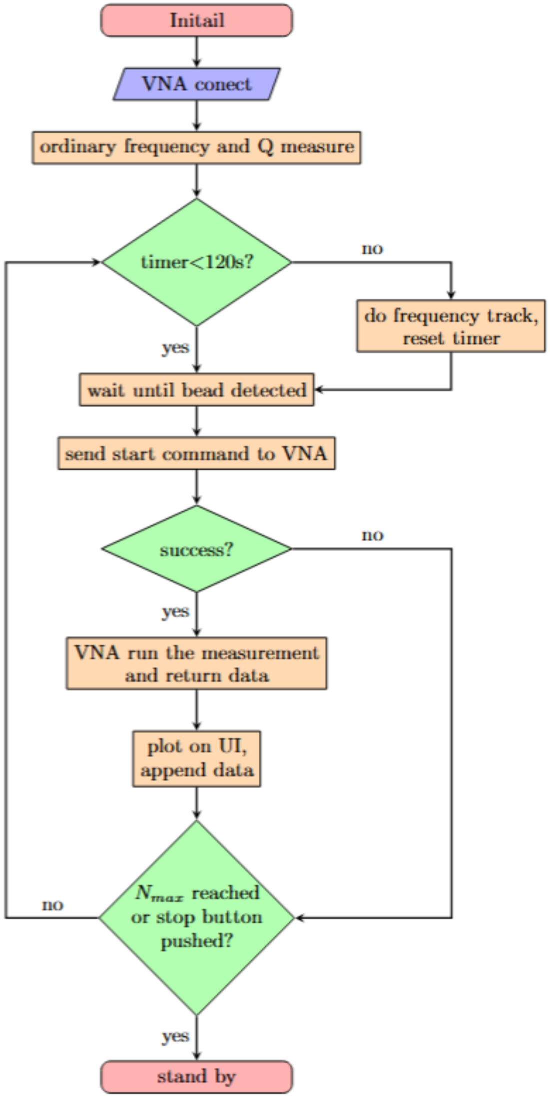


- user interface with buttons, plots and parameter input boxes
- collect measured data from VNA and post-process, convert phase-time relation to field-position
- VNA remote control (when and what to measure)
- manage the measurement process
- control the linear motion system
- receive the trigger signal from bead detection system

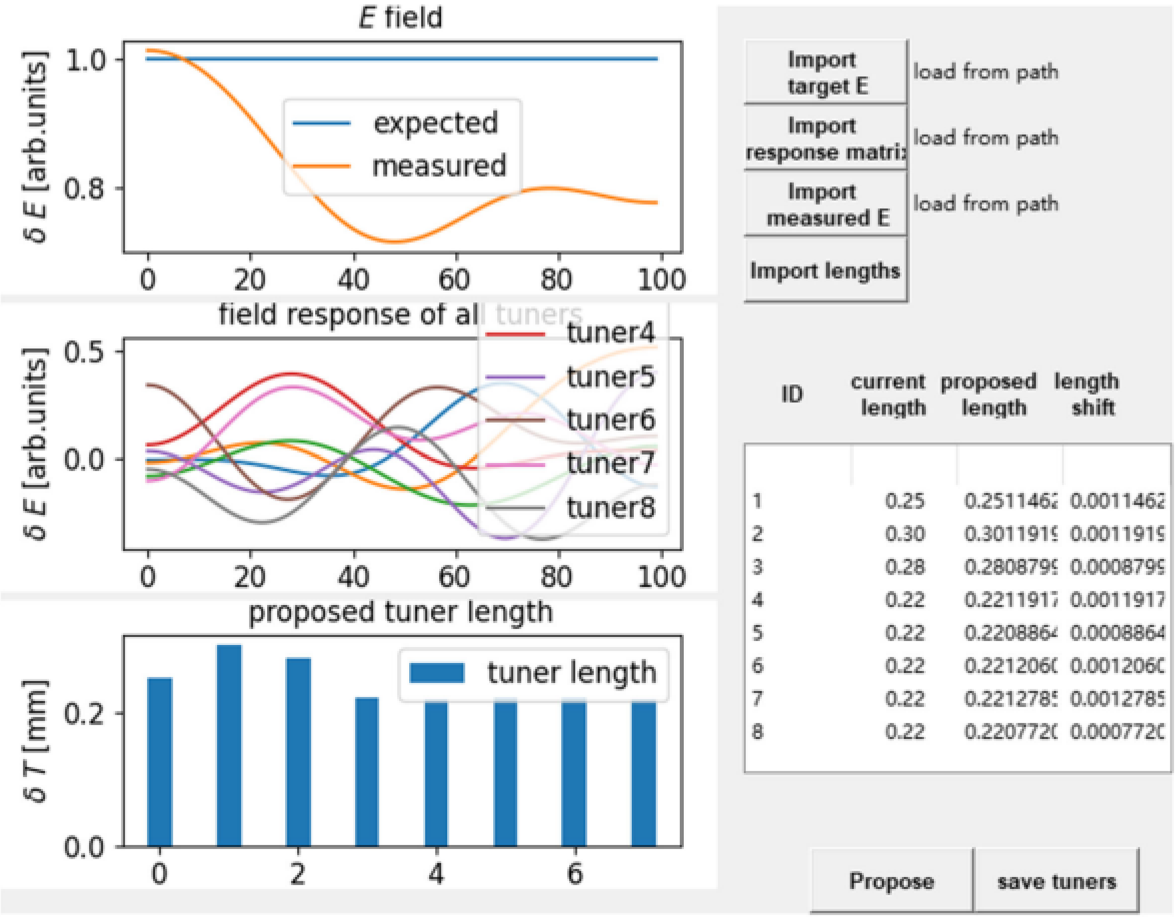
Flow chart

Upon pressing the “start” button, the program begins a repeated cycle of measuring the S21 phase at the specified frequency

Each falling water droplet triggers a measurement, updating the display on the interface and simultaneously accumulating the measurement data into the dataset. This process continues until either the “stop” button is pressed or the specified maximum number of measurements is reached



The tuning algorithm



The algorithm assumes that the difference between the measured distribution and the expected distribution, denoted as δE, can be compensated by the linear combination of all tuners. If the change in field distribution caused by a variation of 1 mm in the length of the jth tuner is represented by $\partial E_i / \partial T_j$, then the required tuner length adjustment δT is determined by the expression

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

Software

Considerations in the software

- system delay (here 77 ms) needs to be considered
- using frequency tracking to overcome frequency shift problem
- properly exclude invalid data produced by un-successful measurement
- original data needs to be de-noised with HOSVD
- reference phase is drifting and needs to be evaluated in each iteration
- during each measurement’s waiting trigger period and the measurement execution period, the Raspberry Pi's CPU should remain as idle as possible to prevent random lag in the measurement
- All parameters are flexible and adjustable, allowing the device to measure different types of resonant cavities

Measurement on Alvarez model cavity

The cavity

1:3 scaled aluminum model of an Alvarez-type cavity, for an extensive upgrade program at the UNILAC. It was used primarily to investigate the stabilization scheme (tilt sensitivity).

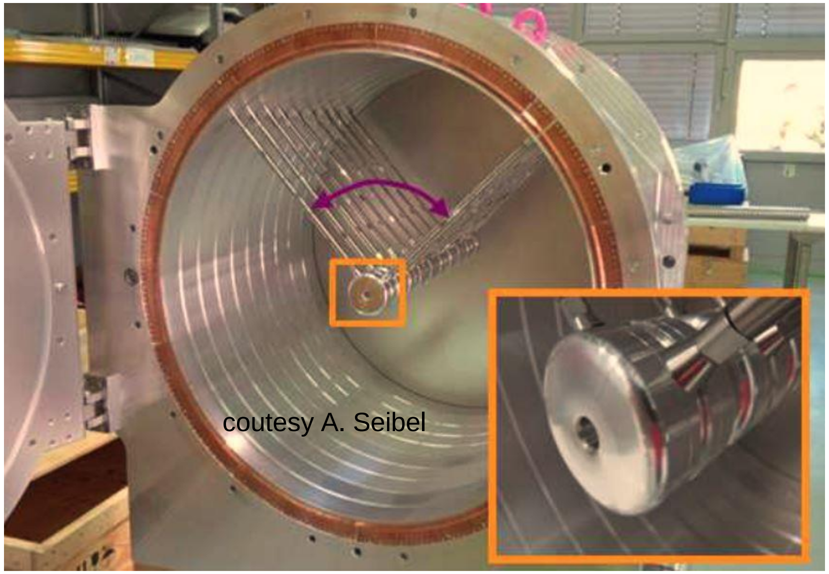
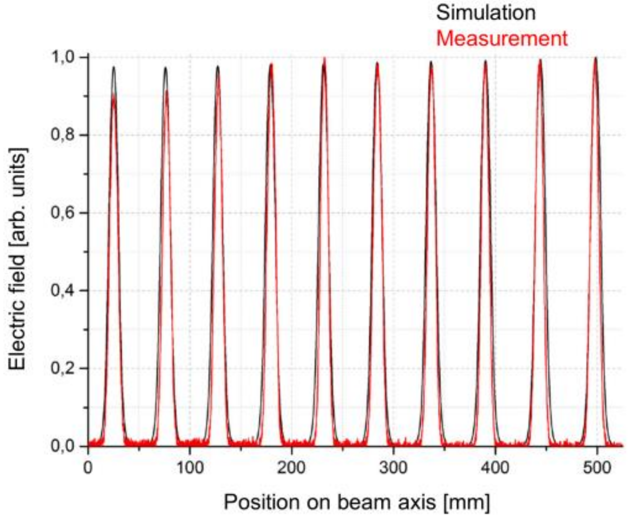


Table 2: Parameters of the 1:3 scaled Alvarez-Model

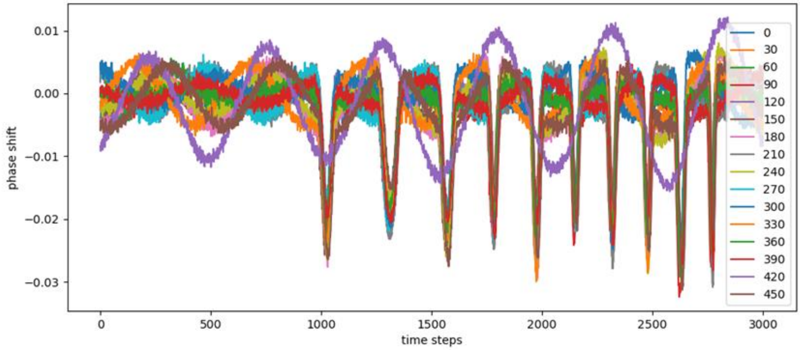
Parameter	Unit	Value
RF-Frequency	MHz	325.224
Gaps	#	10
Gap length	mm	12.7 – 13.5
Drift tubes	#	9
Drift tube length	mm	38.1 – 40.8
Drift tube diameter	mm	60.0
Aperture	mm	10.0
Tank diameter	mm	634.5
Tank length	mm	525.7
Q - Factor		45000



Measurement on Alvarez model cavity

Measured data

Due to the noisy “test hall”, the measured data is full of noise. Besides, the Q-value of the aluminum cavity is low. Thus, the signal-to-noise-ratio is too low. Multiple repeated measurements are necessary



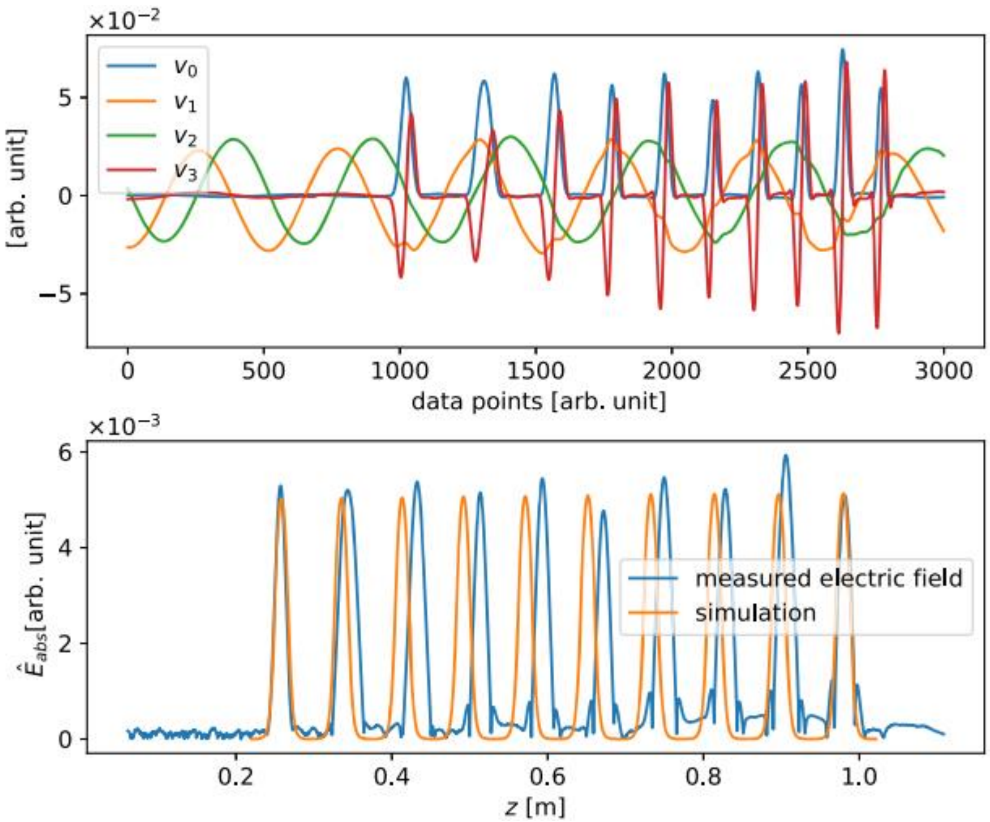
noisy measured data (phase shift),
with signal to noise ratio of ≈ 2.0

Singular Value Decomposition (SVD) is a powerful mathematical tool used in various fields. It has several practical and theoretical applications:
data compression, noise reduction, solving linear systems, principal component analysis (PCA) ...

The measured data set from the perturbation method is stacked into 1d arrays with noise, being suitable to be treated with SVD

Measurement on Alvarez model cavity

-Treatment for heavily noised data of the model cavity



The z-offset between measurement and simulation clearly indicates the deflection (or sagging) of the drift tube due to its weight

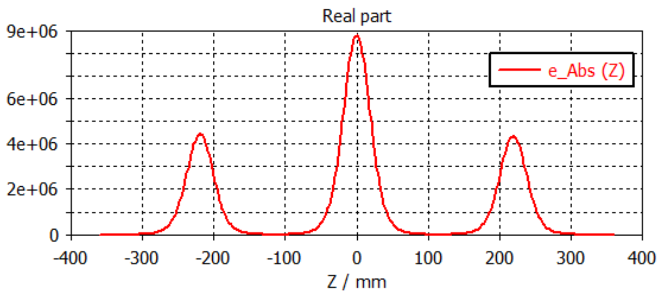
The real-field distribution is considered as a linear combination of the first four singular vectors with specific weights. By using a small segment (0–900 out of 3000) of the measurement data for 0-field area as a reference, the four weights can be found, thus yielding the final measurement field distribution. Assuming this segment flattens as expected, the solution can be found with a overdetermined linear equation. The ratio of the four weights is 45.9 / 0.11 / 0.93 / 7.69. Despite the initial data being heavily laden with noise, attributed to the soft coupler, we successfully discerned the field distribution.

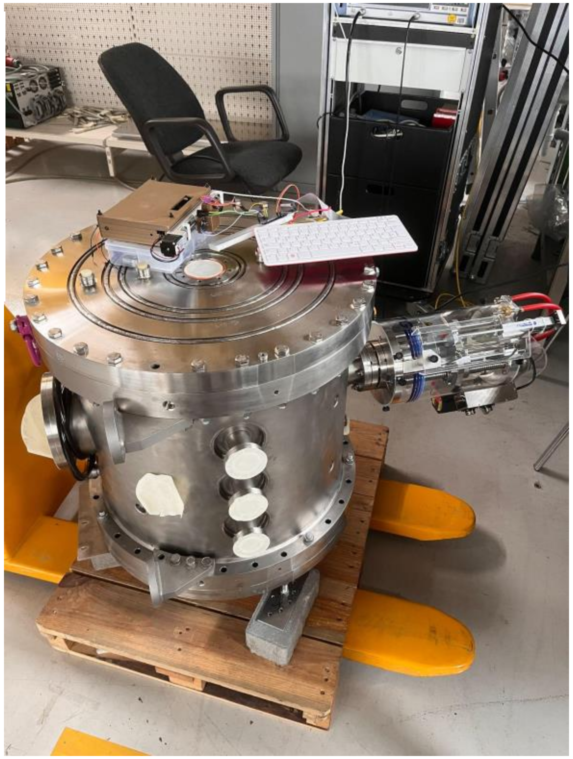
Measurement on buncher cavity

The cavity

This buncher cavity is used for bunch compression prior to the UNILAC post-stripper

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

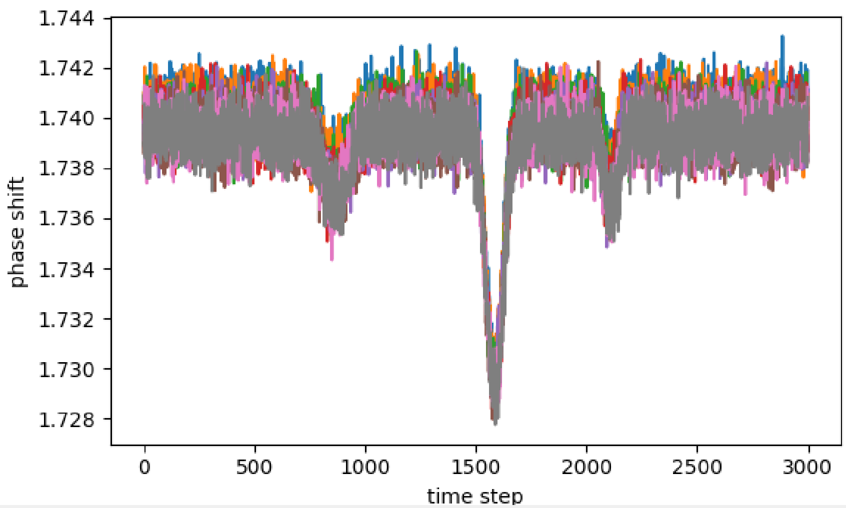




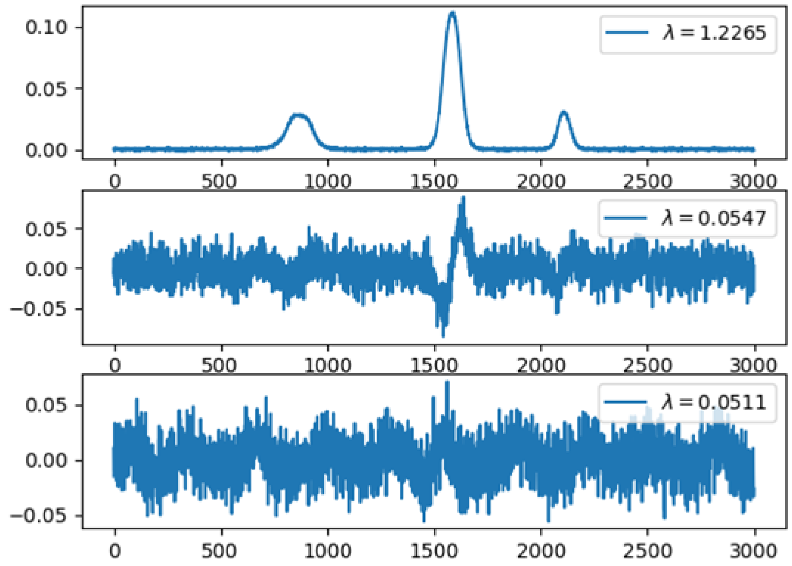
Measurement on buncher cavity

Measured data

Due to low Q-value (1000) of this buncher with long spirals, in the measured data, the magnitude of noise in the measurement data is close to the magnitude of the signal itself. Though fast iterative measurements allow to collect big mount of data within short time



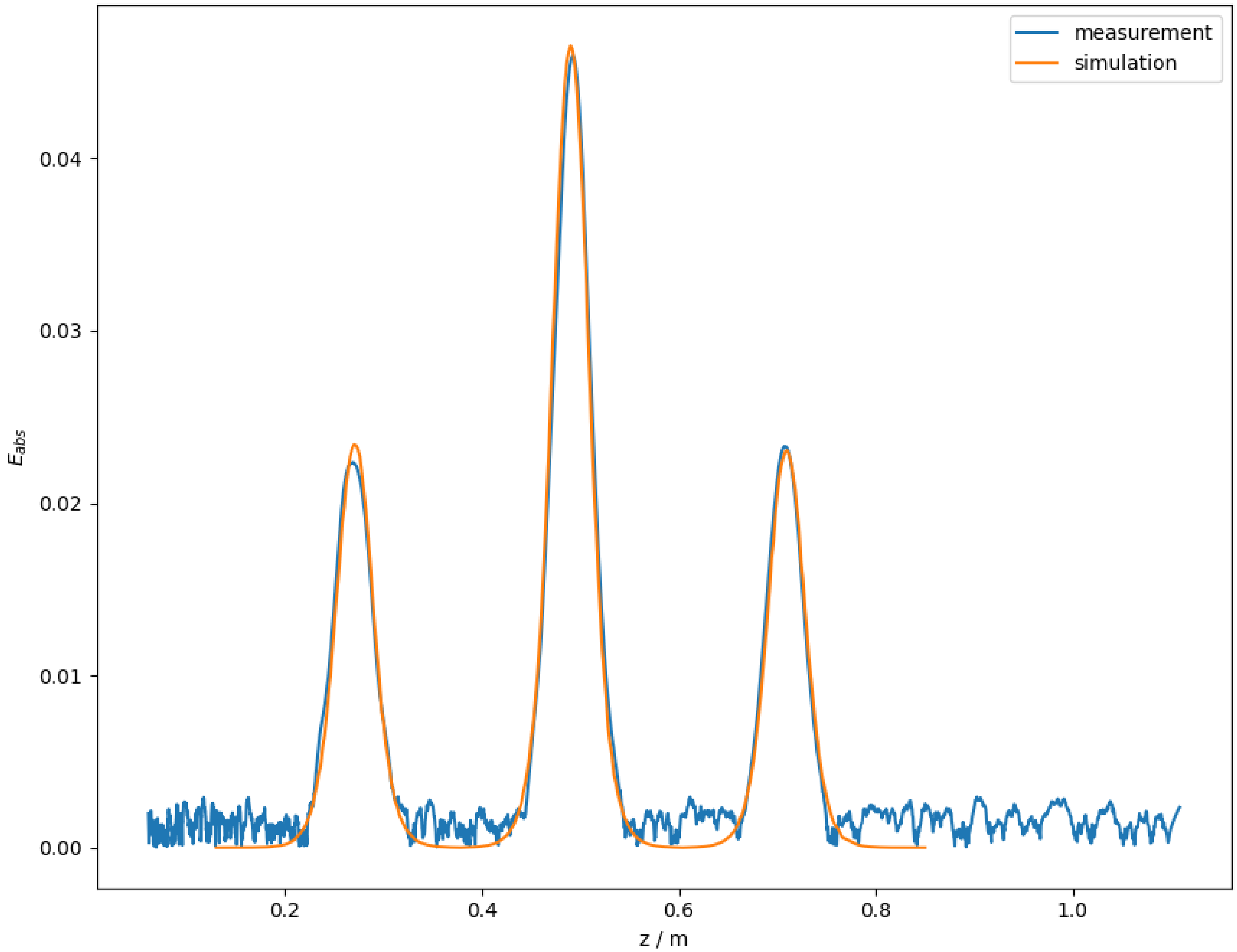
aligned original data



treated with SVD to separate field essence and noise

Measurement on buncher BB3

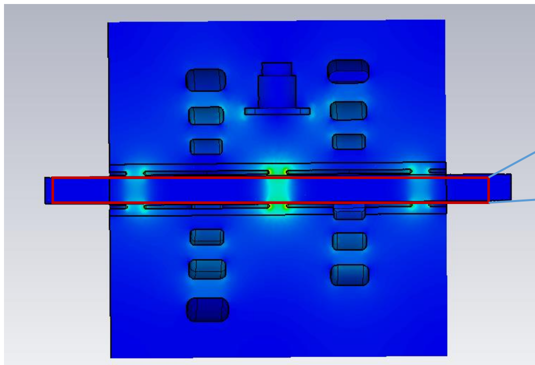
compare 1d

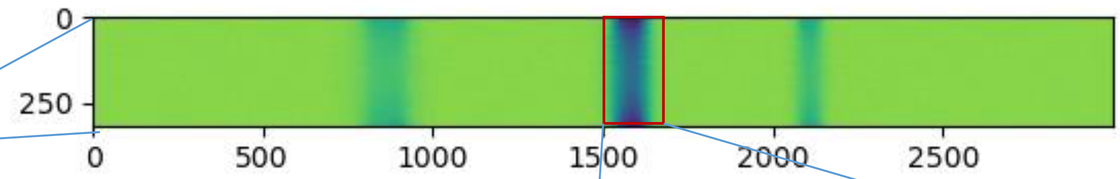


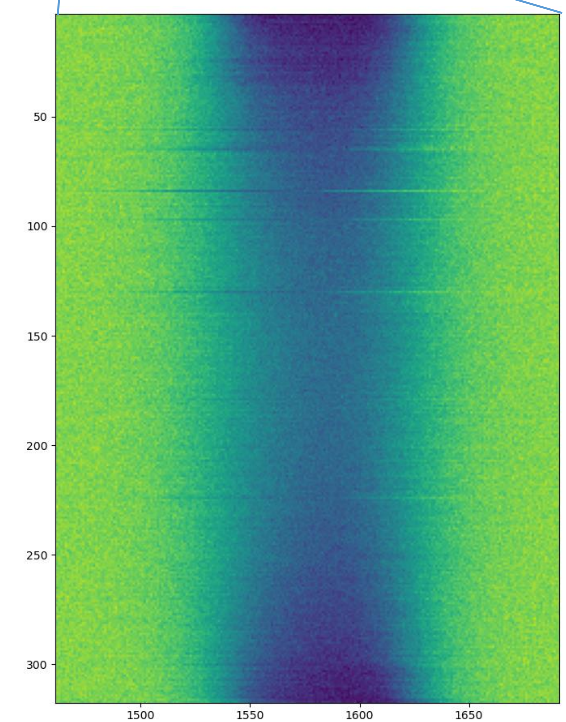
field strength measured by falling bead (blue) compared with simulated field strength (orange).

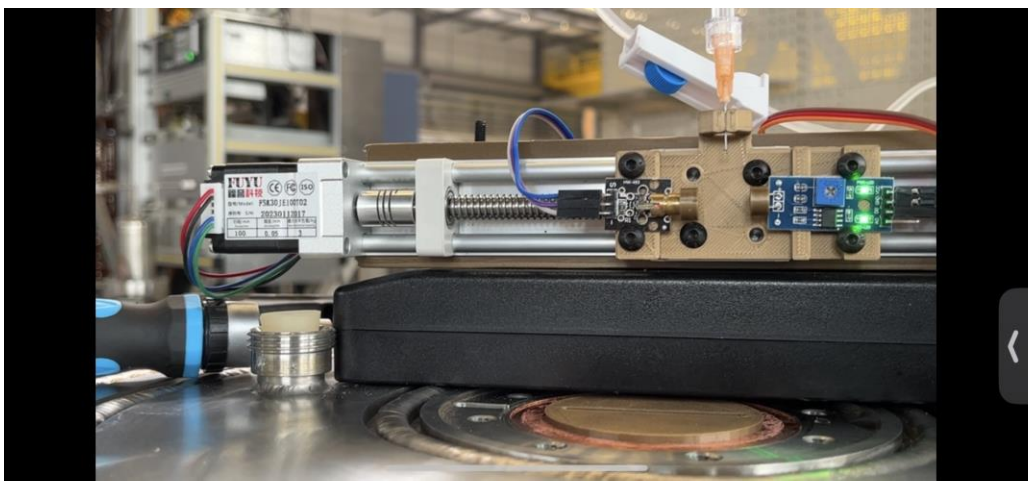
Measurement on buncher cavity

The 2d measurement









The 2d field mapping is performed by moving the needle horizontally during the iterative measurements. At each step, a 1d field along beam axis is measured

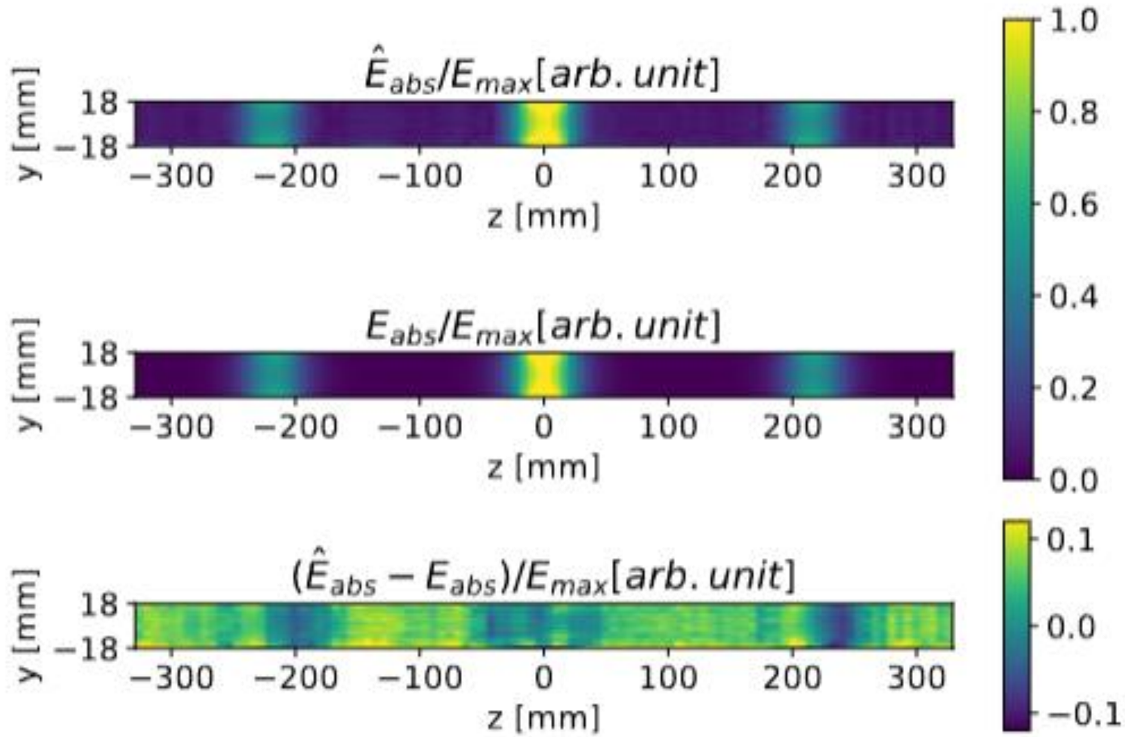
Measurement on buncher cavity

The 2d measurement

measurement

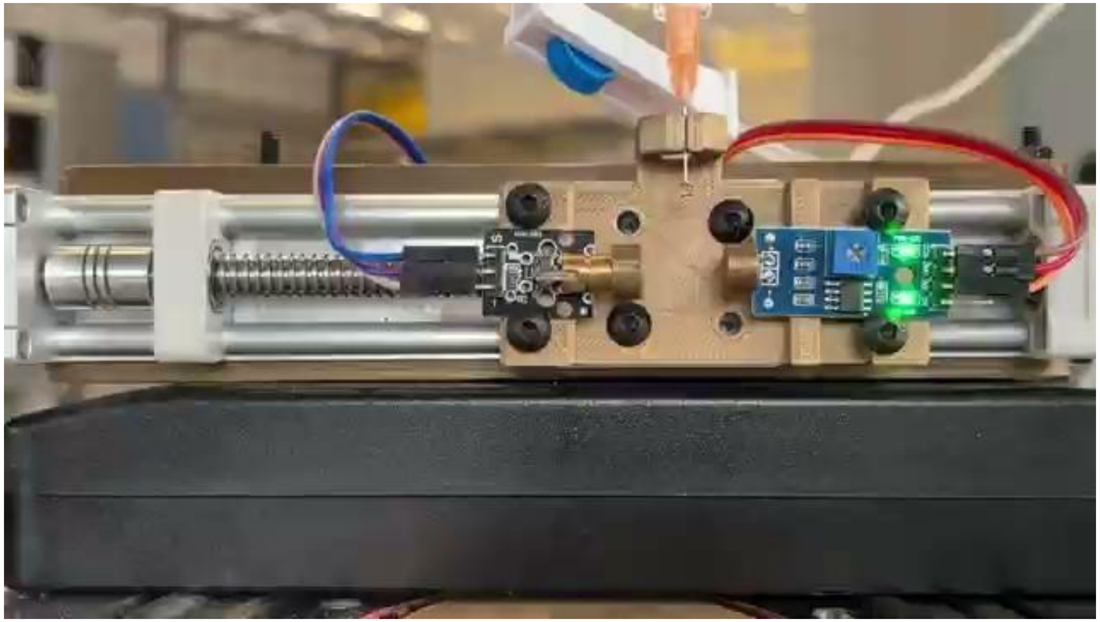
simulation

compare



2d measurement compared with simulation

The 2d measurement process video



droplet falling

16X video, Ctrl+click