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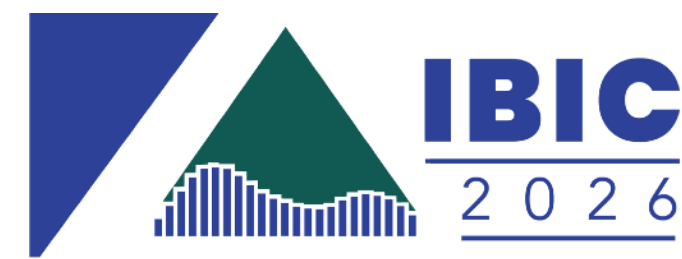


Development and characterization of a high-resolution re-entrant cBPM system at the ATF Linac

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Contributed Oral Presentation at IBIC2026, 31/08/2026



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Introduction

Development of a **re-entrant cBPM** for future colliders.
To guide and stabilise the beam, we require high-resolution **beam position monitors (BPM)** with spacial resolution $< 1 \mu\text{m}$.

Project in **collaboration with KEK and CIEMAT**: development of the cryostat for a BPM and a super-conducting quadrupole.

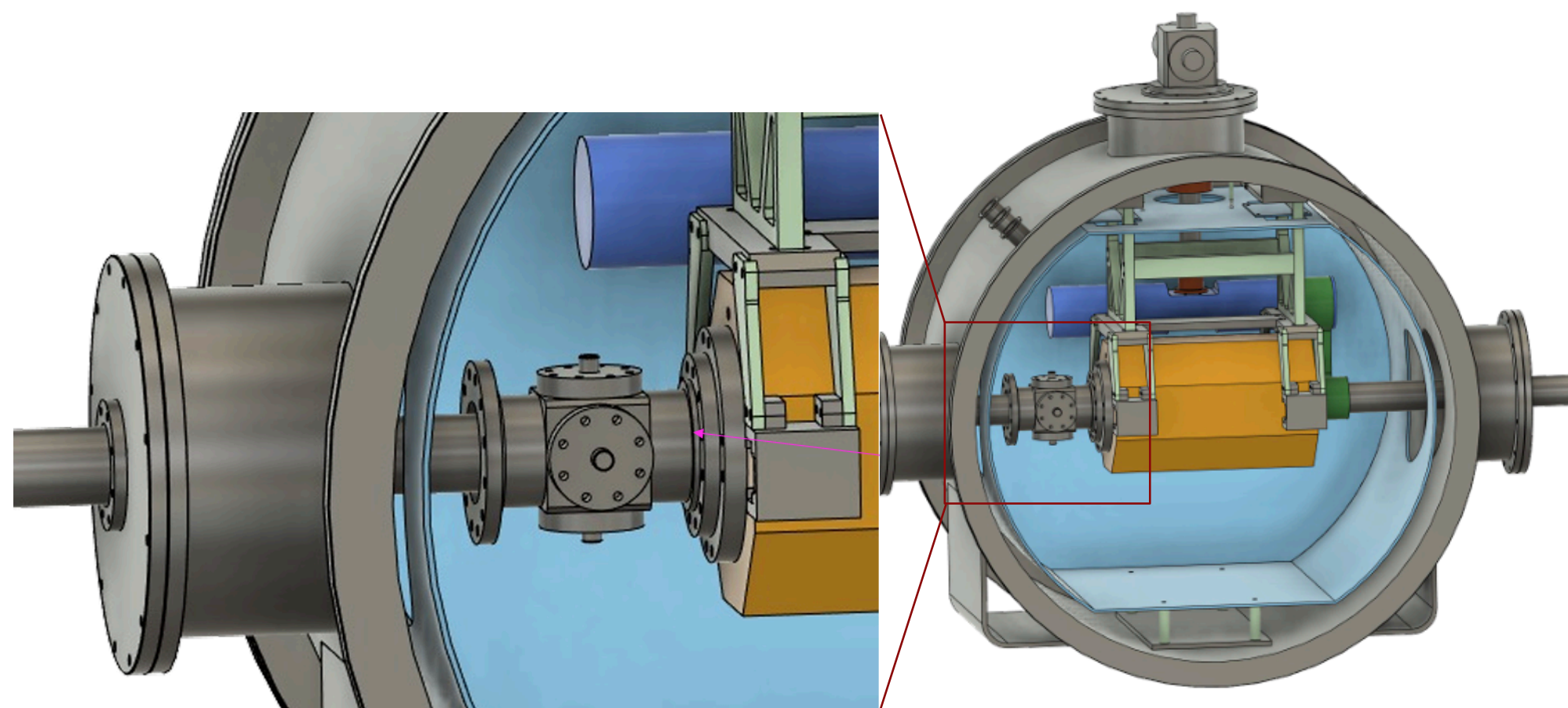
The designed BPM was initially tested at ATF (KEK).

Mechanical requirements:

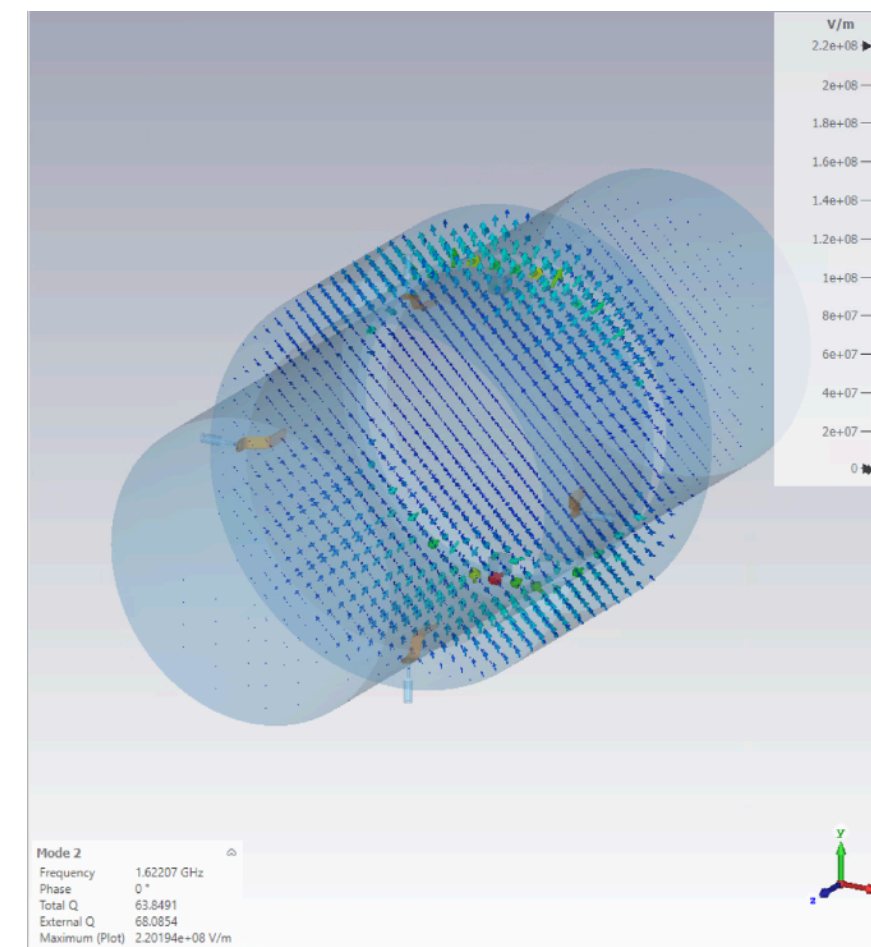
Mechanical fit of the BPM and the SC quadrupole magnet.
Cryogenic and UV conditions have to be met.

Measurement requirements:

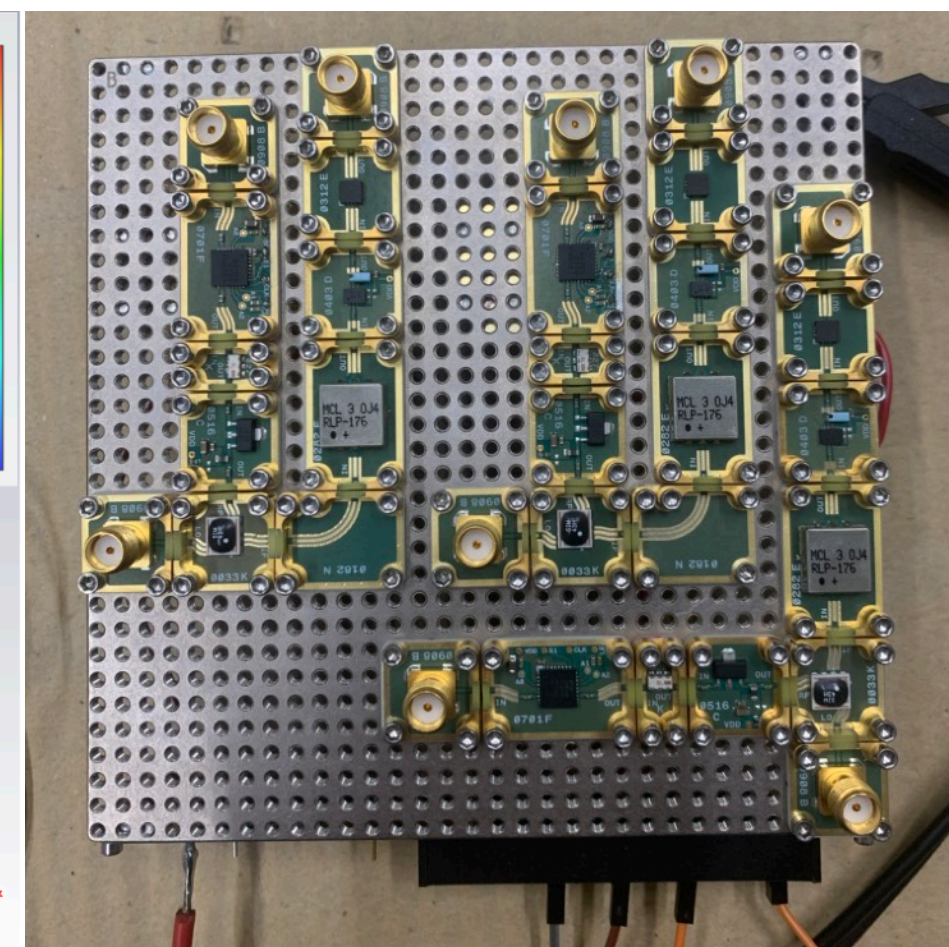
Spatial resolution $< 1 \mu\text{m}$.
Temporal resolution $< 369 \text{ ns}$.



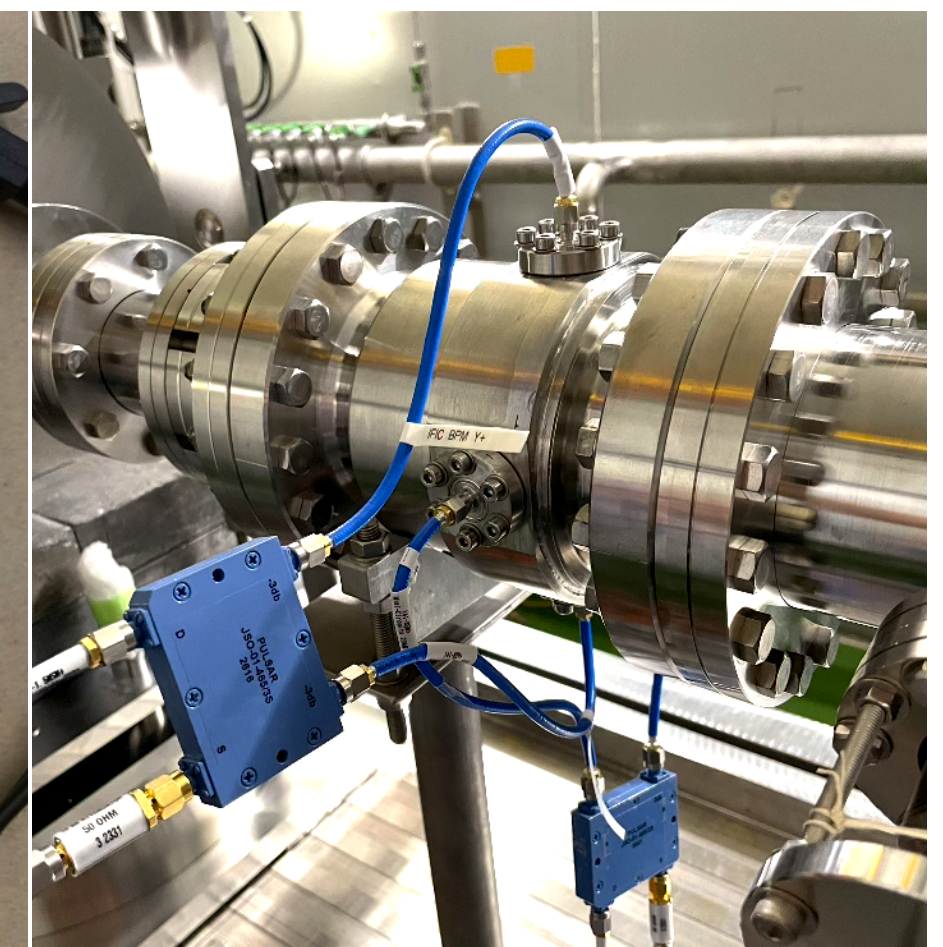
• Design of the BPM



• Design of DAQ



• Beam test



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at IBIC2026 31/08/2026

Introduction

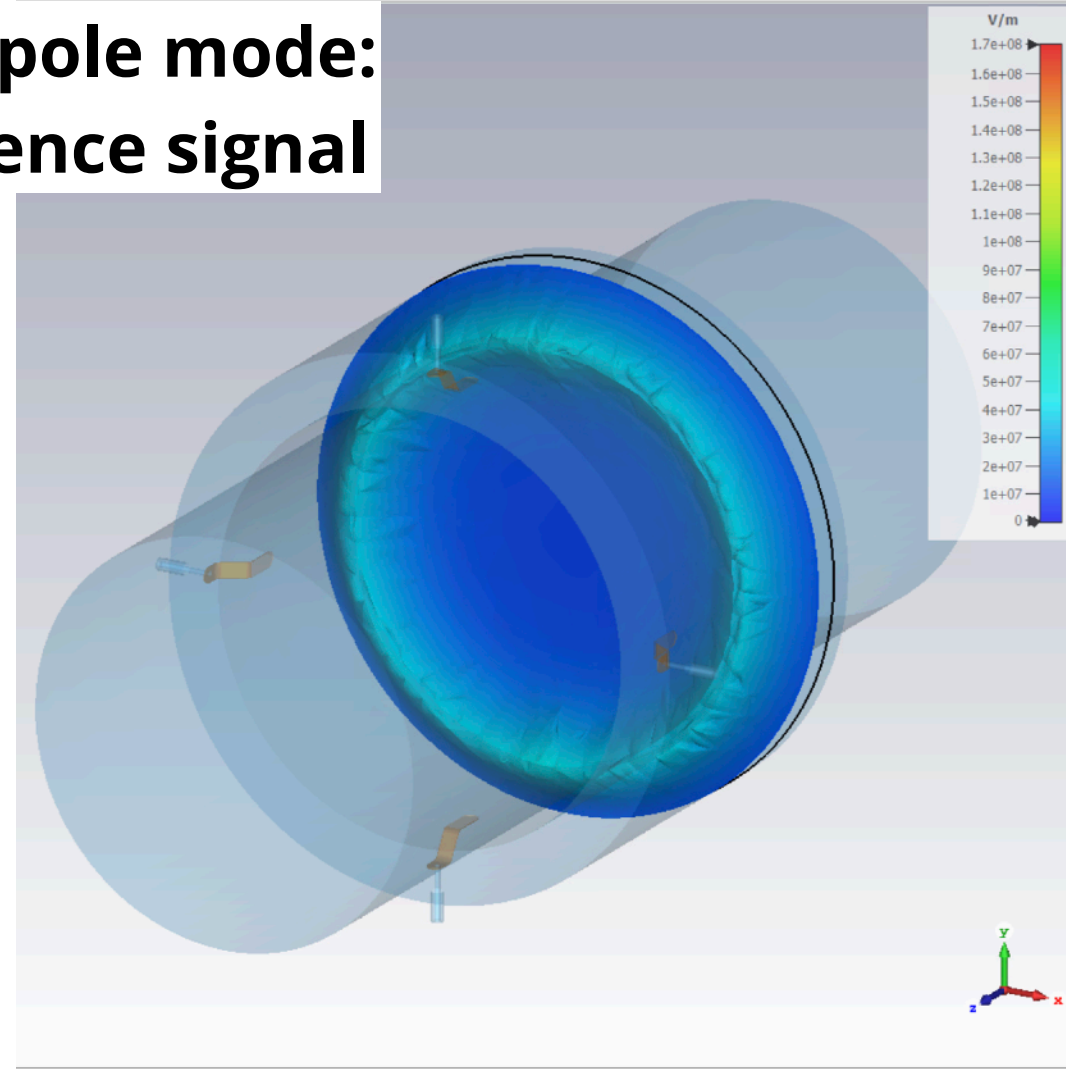
- I. cBPM theory and prototype design
 - A) Resonant BPMs
 - B) CST electromagnetic simulations
 - C) Manufacturing and measured RF characteristics
- II. DAQ and experimental procedure
 - A) Readout system
 - B) Beam tests at the ATF Linac
- III. Preliminary characterisation results
 - A) Calibration results
 - B) Resolution estimation
 - C) Measurement system and model limitations

Conclusion

I. cBPM theory and prototype design

A) Resonant-BPMs

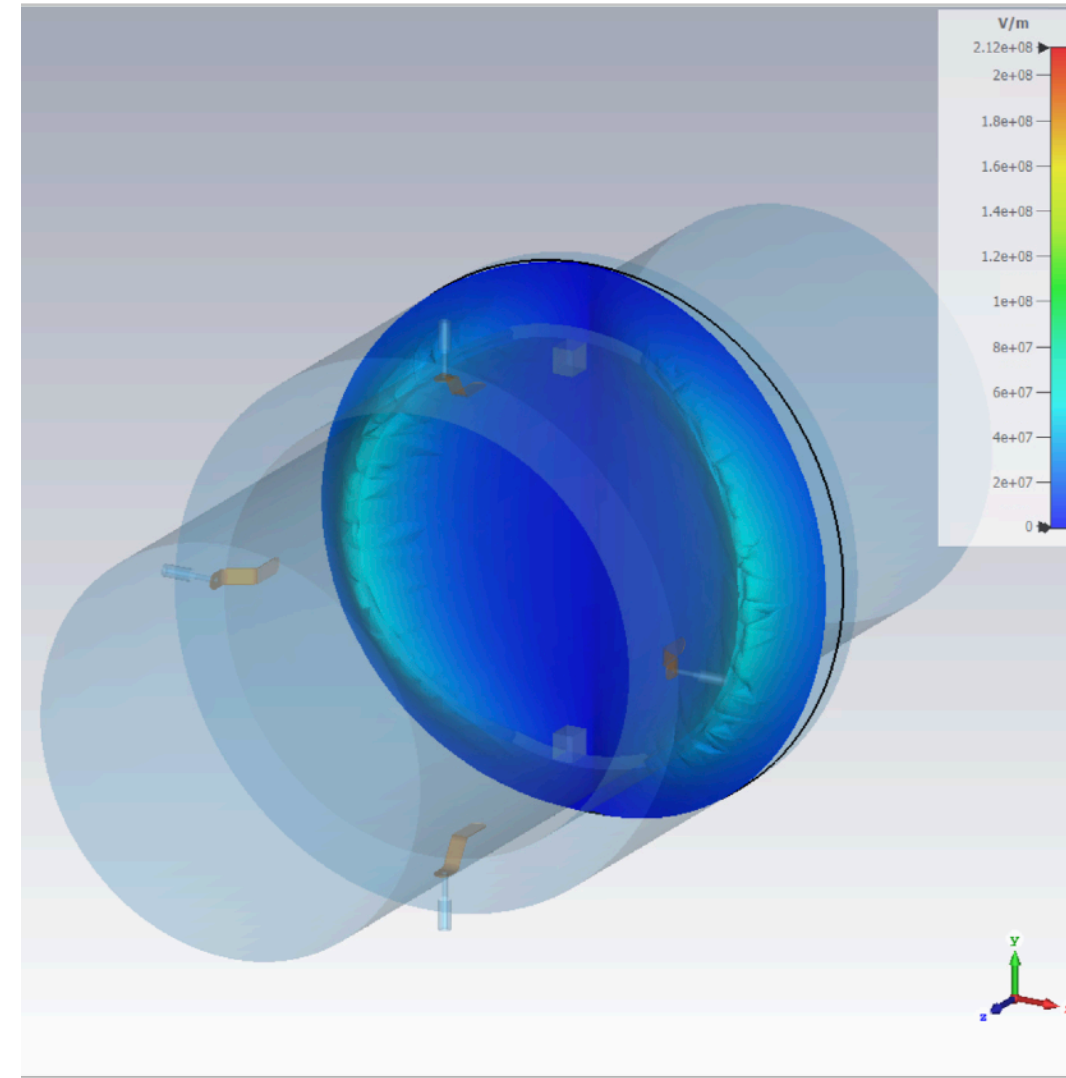
**Monopole mode:
Reference signal**



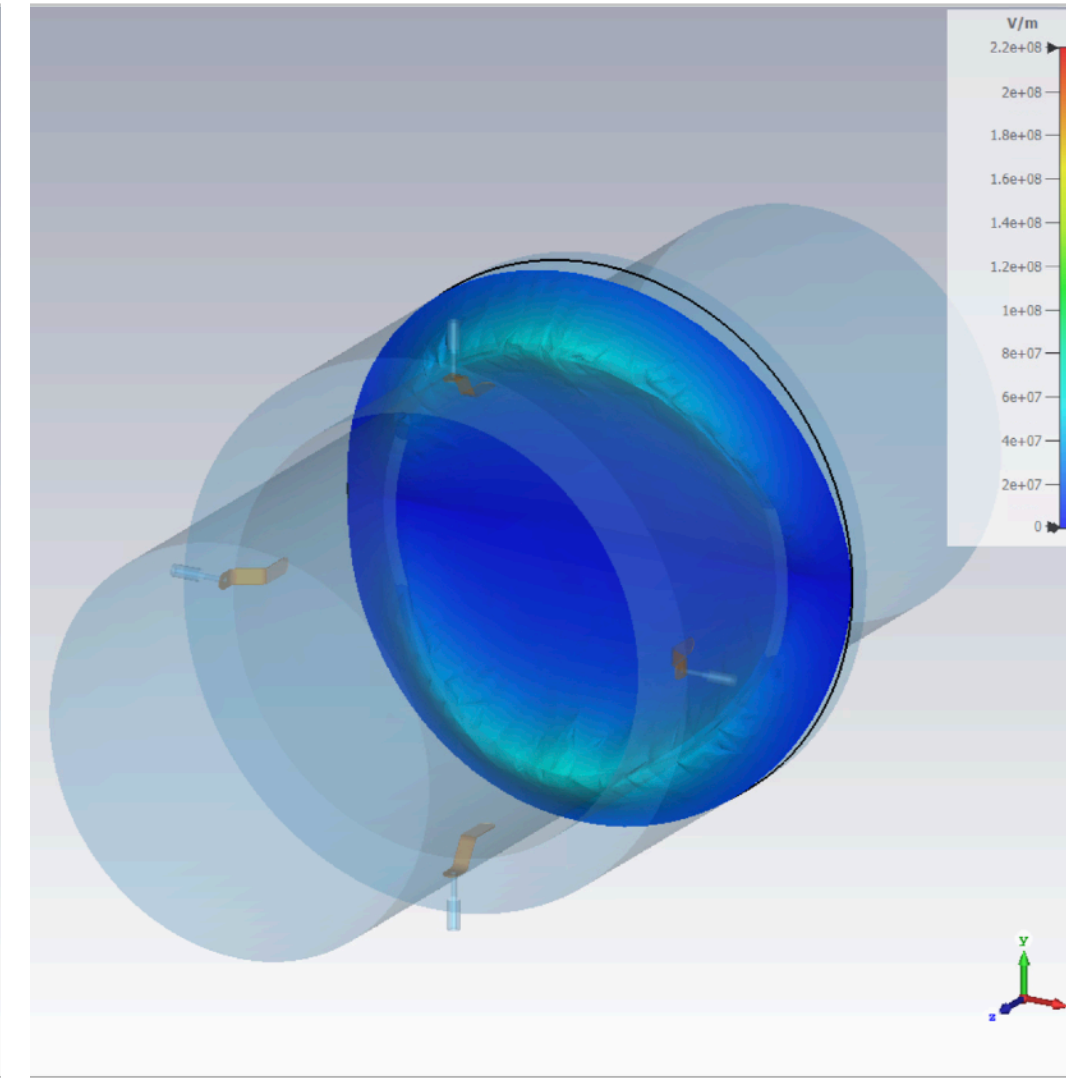
Proportional
to the beam
charge q_{bunch} .

Dipole mode:

Position signal on x



Position signal on y



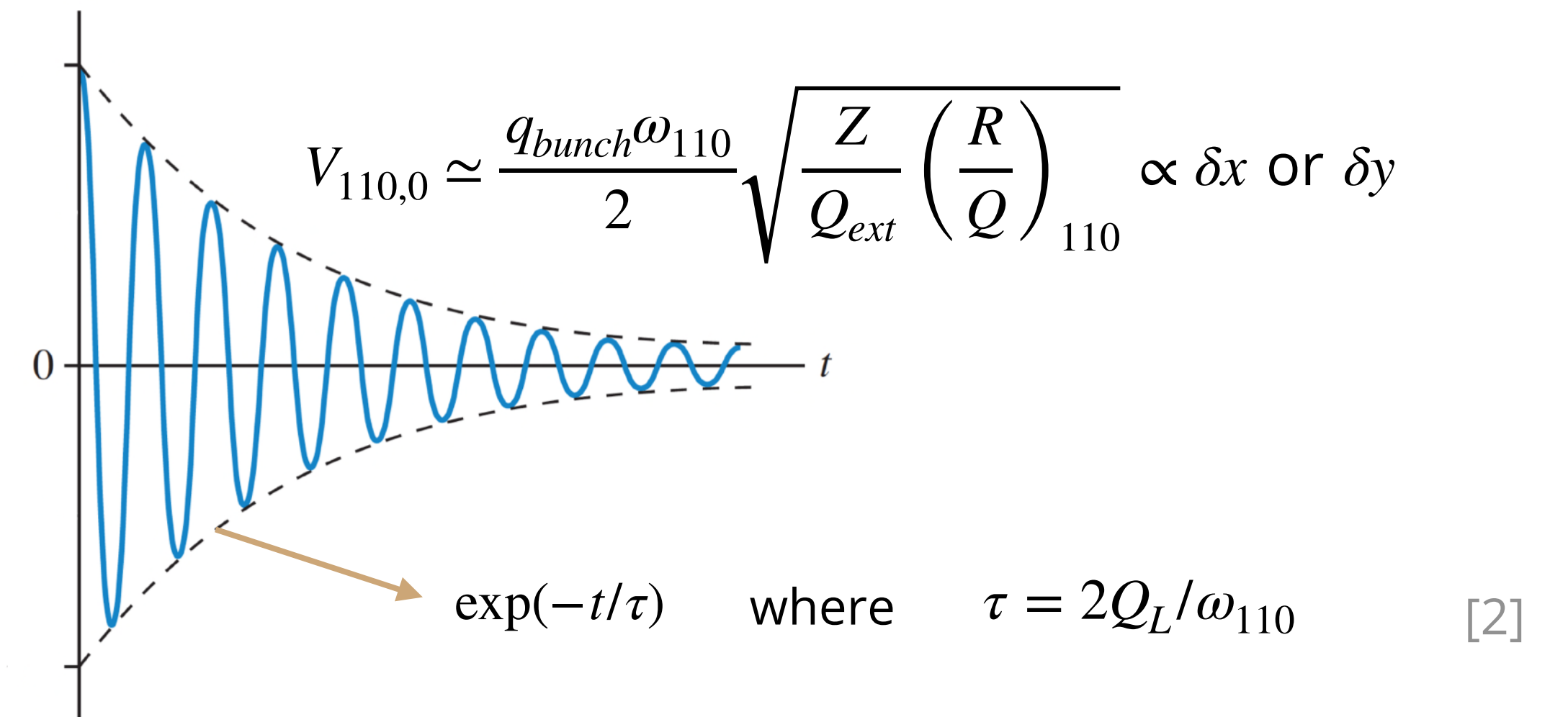
Proportional to the
beam charge q_{bunch}
and the beam
position δx or δy . [1]

→Output signal on the time domain:

The position signal oscillates at the dipole mode resonance frequency and decays exponentially with decay constant τ .

$$V_{position}(t) = V_{110,0} \sin(\omega_{110}t + \varphi) \exp(-t/\tau)$$

Need to measure the amplitude and the phase to determine the beam position .



I. cBPM theory and prototype design

B) CST electromagnetic simulations

- **Resonance frequency** f_m : Operation frequency of the BPM (two modes) → Mainly determined by the electronics and size of the BPM.

Because of filters and LO specifications: $1.610 < f_{dip} < 1.638$ GHz

- **Loaded quality factor** Q_L : Determines the coupling of the cavity with the exterior but also the length of the waveforms in time.

To have the right length of signals: $10\text{ns} < \tau < 100\text{ ns} \Rightarrow 10\text{ ns} \times \pi f_m < Q_L < 100\text{ ns} \times \pi f_m$

- **Normalized shunt impedance** $(R/Q)_m$: Evaluates the effect from the beam in the cavity. This factor determines the sensitivity of the observed output signals.

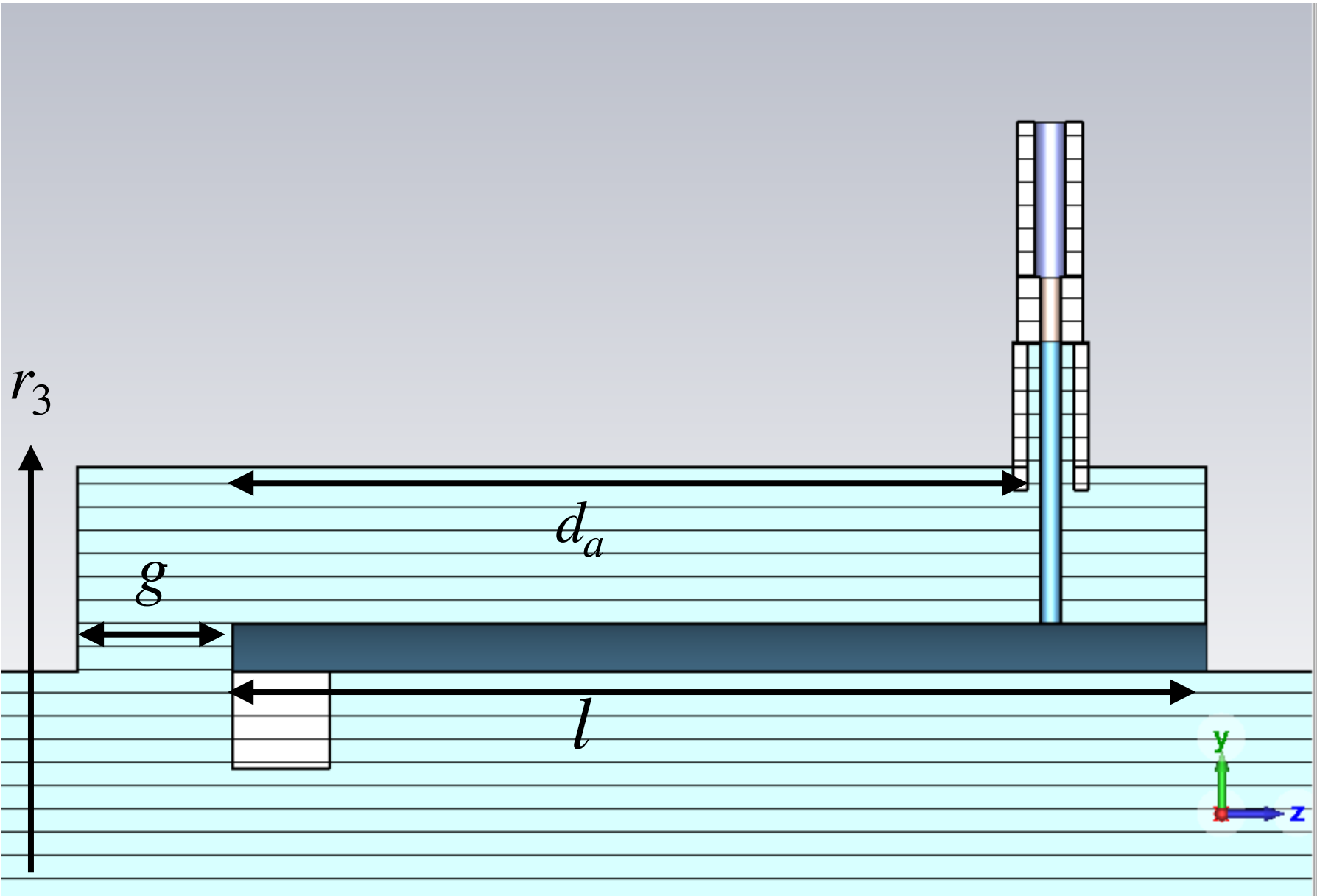
$(R/Q)_{monop}$ should be minimised $(R/Q)_{dip} > 0.27\ \Omega$ (at 5 mm from the pipe center) → increases the sensitivity of the measurements

- **S-parameter** S_{21} (at the dipole mode frequency): Determines the coupling between orthogonal ports. A high coupling will produce a reading on one axis when there is beam shifted on the orthogonal axis, known as **cross-talk**.

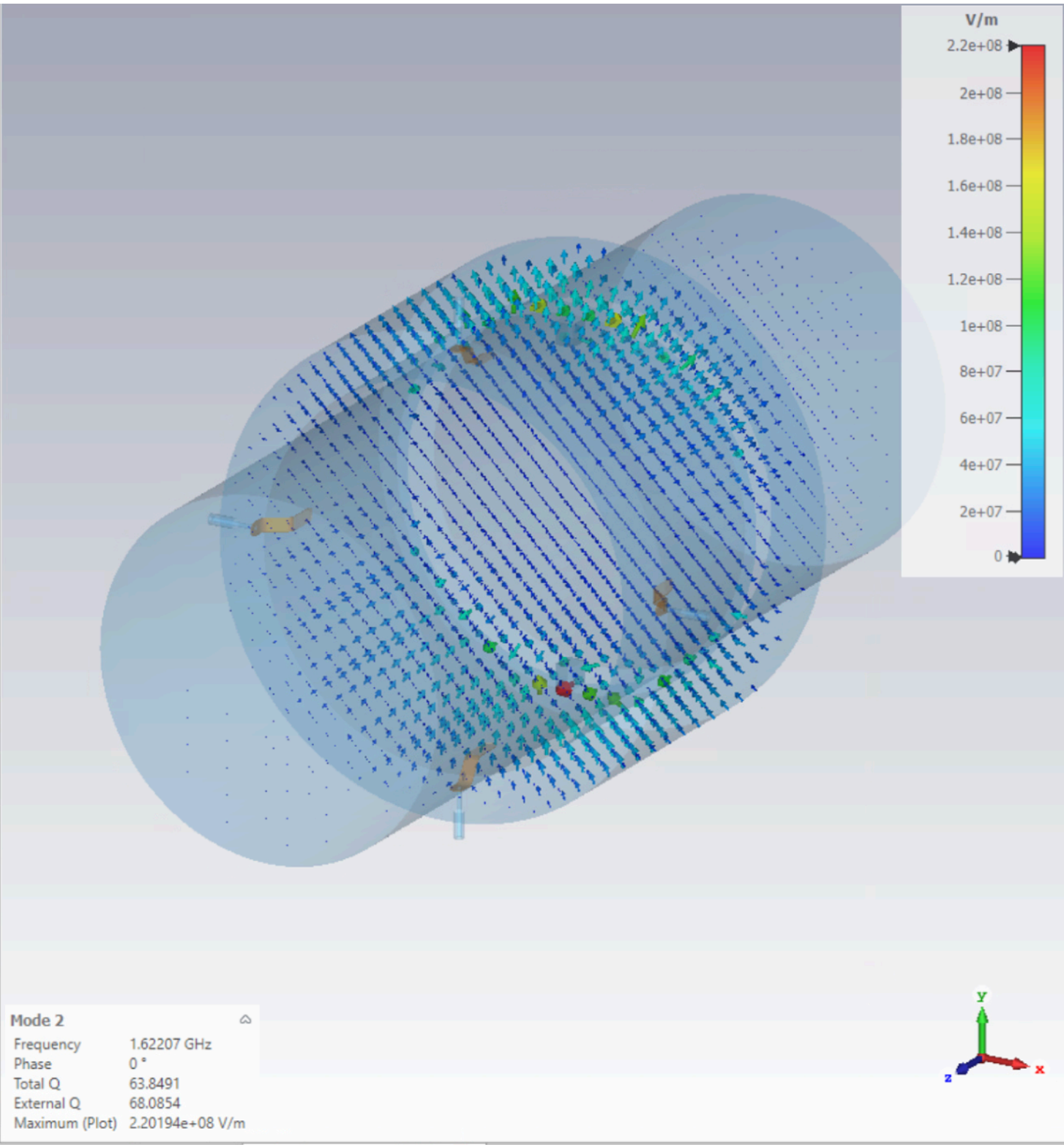
To keep the cross-talk to a minimum: $|S_{21}(f_{dip})| < -30\text{ dB}$

I. cBPM theory and prototype design

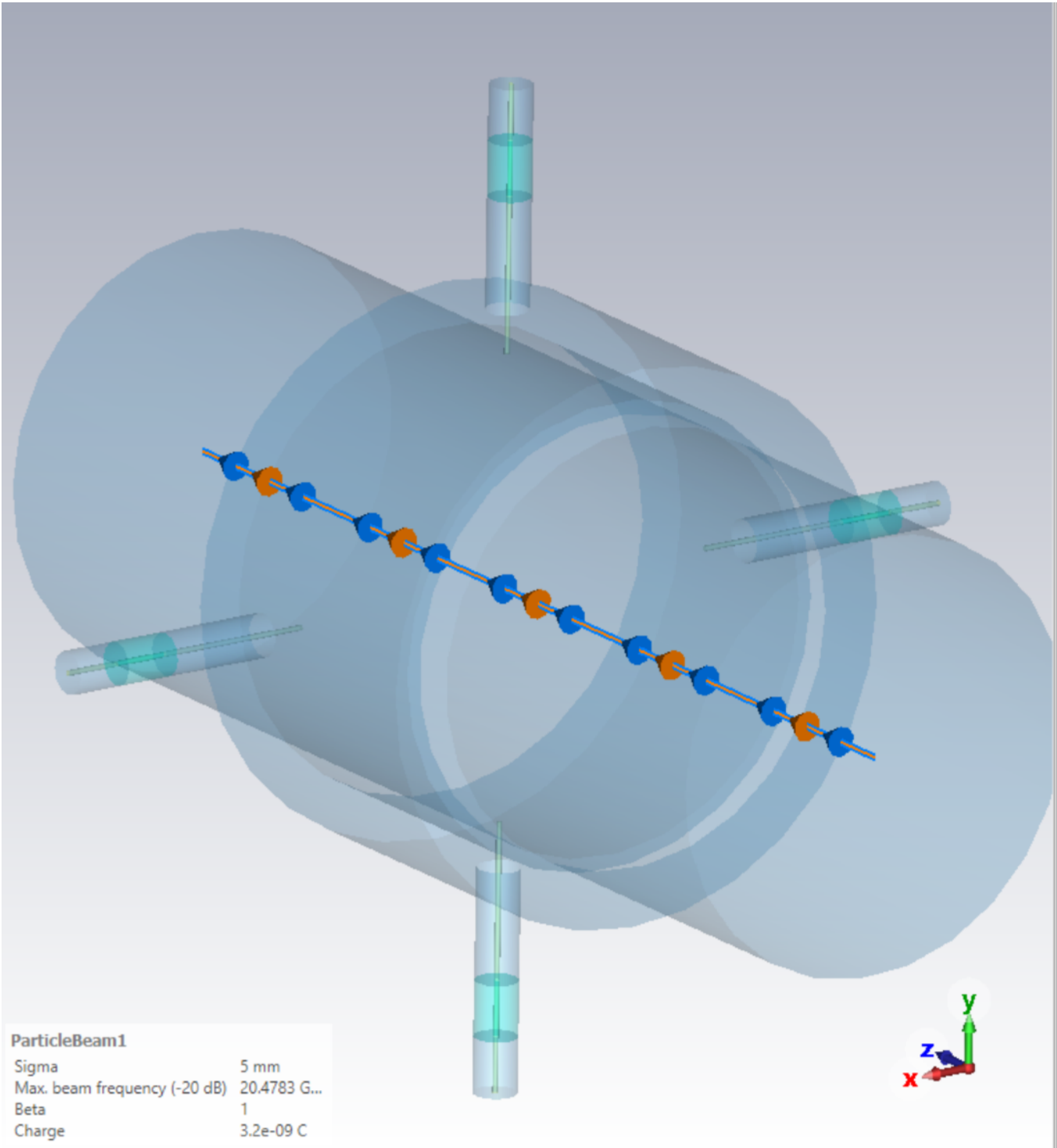
B) CST electromagnetic simulations



eigenmode solver

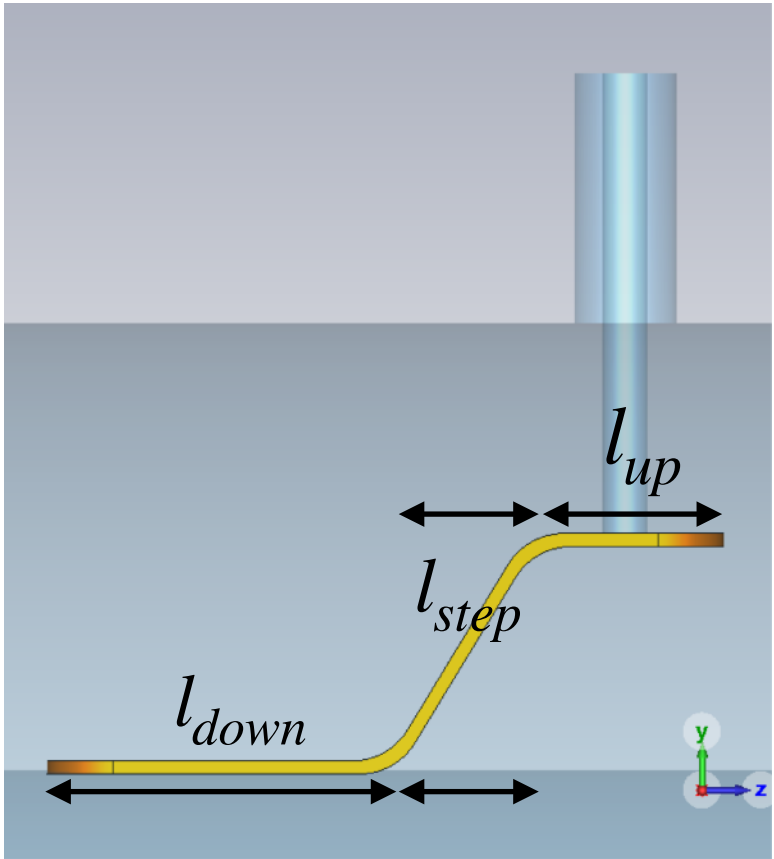


frequency solver



Adaptation of the re-entrant cBPM to the commercial feedthrough.

[3]



Allows to evaluate:
 f_m $Q_{L,m}$ $(R/Q)_m$

Allows to evaluate:
S-parameters

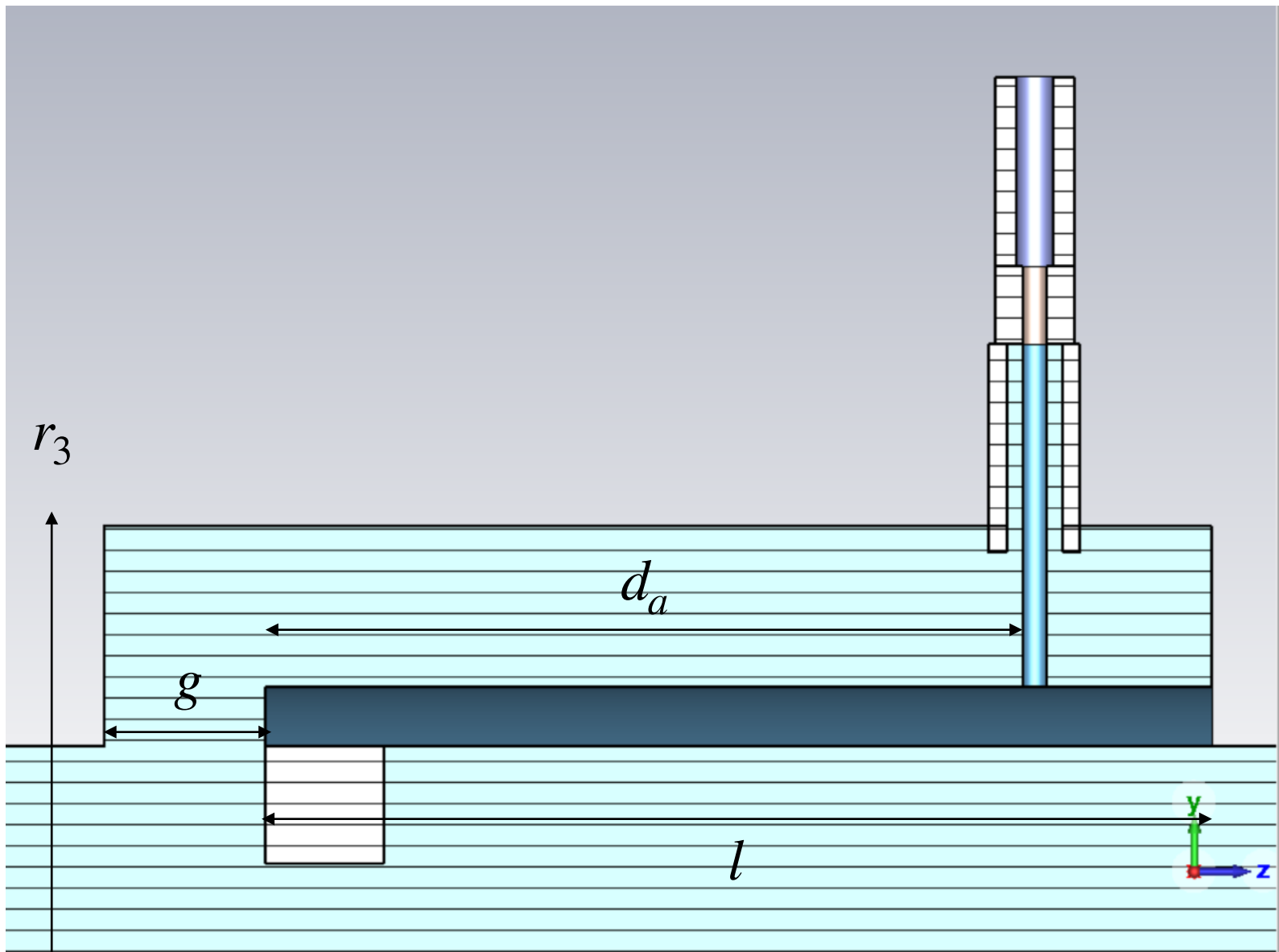
➔ Parametric studies and the CST optimization tool allowed to reach an optimal design.

I. cBPM theory and prototype design

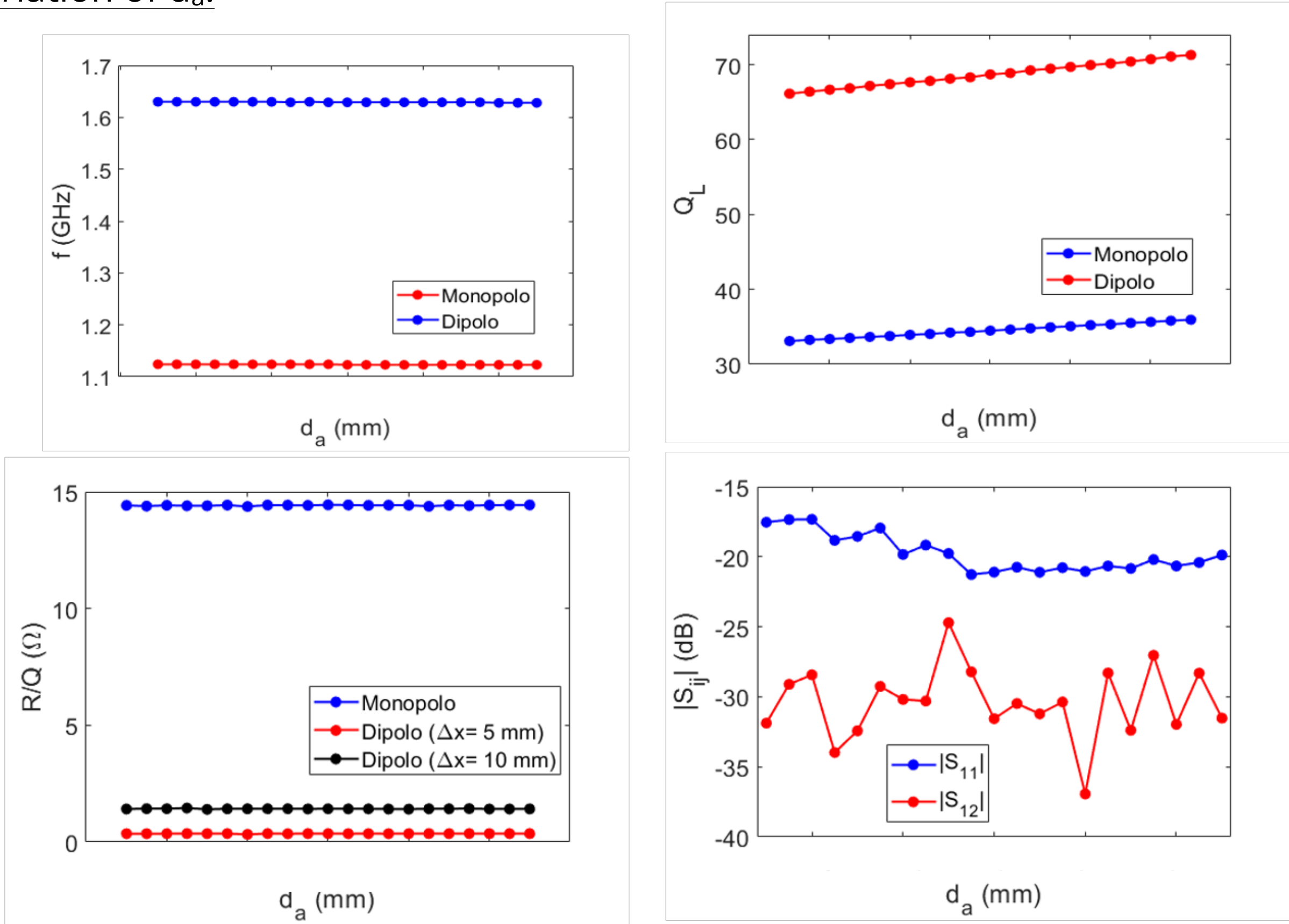
C) Manufacturing and measured RF characteristics

Tolerances analysis:

In order to build the proposed model, we have conducted tolerance studies to determine the precision required at construction.



Influence of individual parameters: with increments of 25 μm .
Variation of d_a :



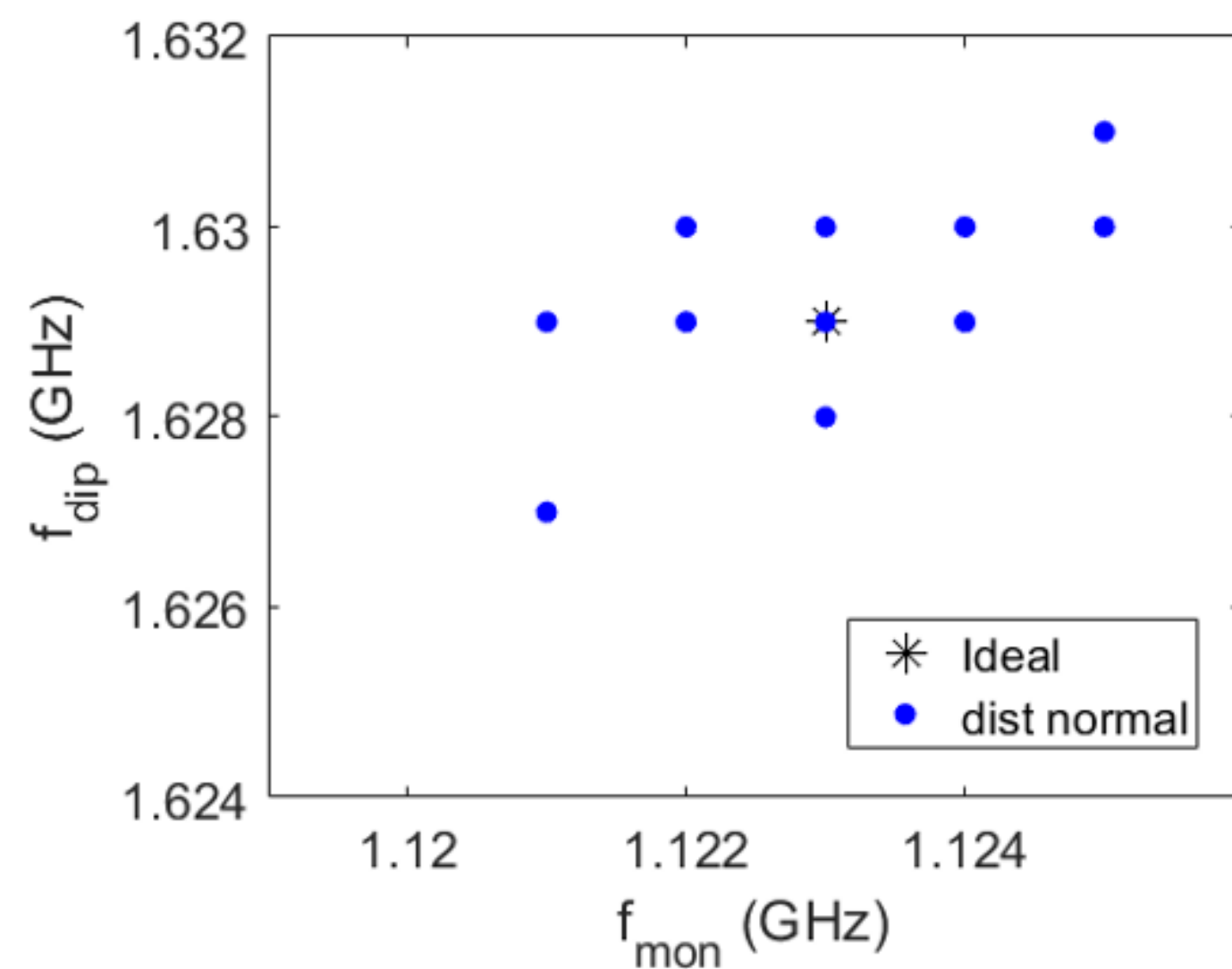
The same analysis was performed with other dimensions.

I. cBPM theory and prototype design

C) Manufacturing and measured RF characteristics

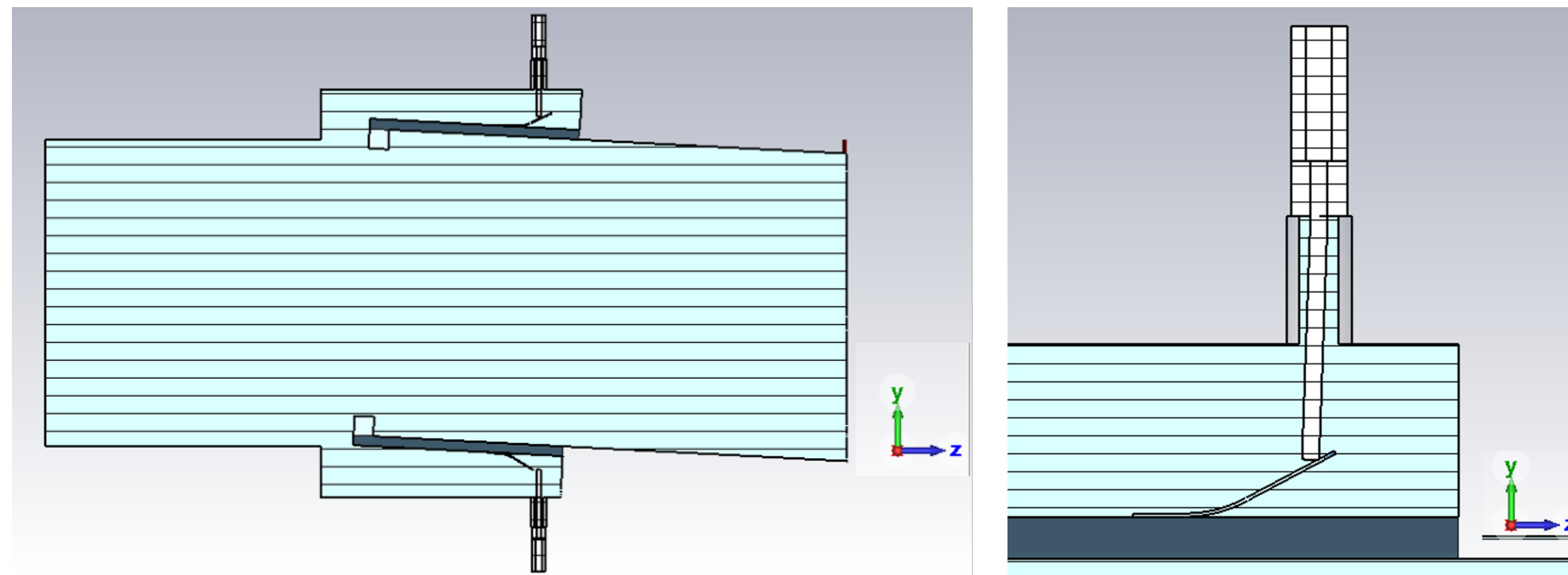
Tolerances analysis:

Multi-parametric variation: manufacturing tolerances with $\sigma = 50 \mu\text{m}$
20 cases with different variations in all parameters simultaneously.



Other tolerances studies:

Eccentricity of the cavity, misalignment when welding parts, effect of crooked feedthroughs, among others...



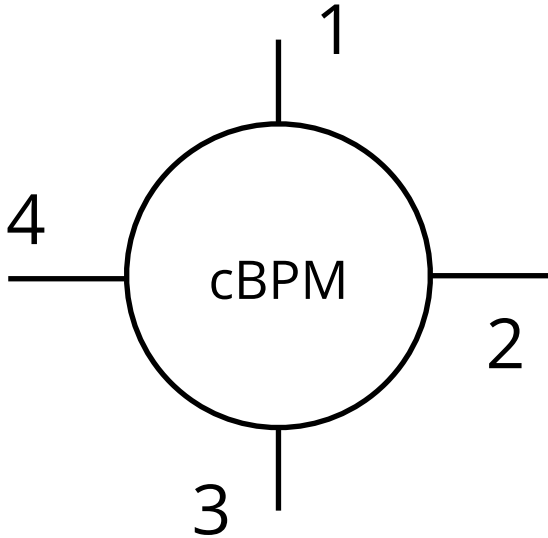
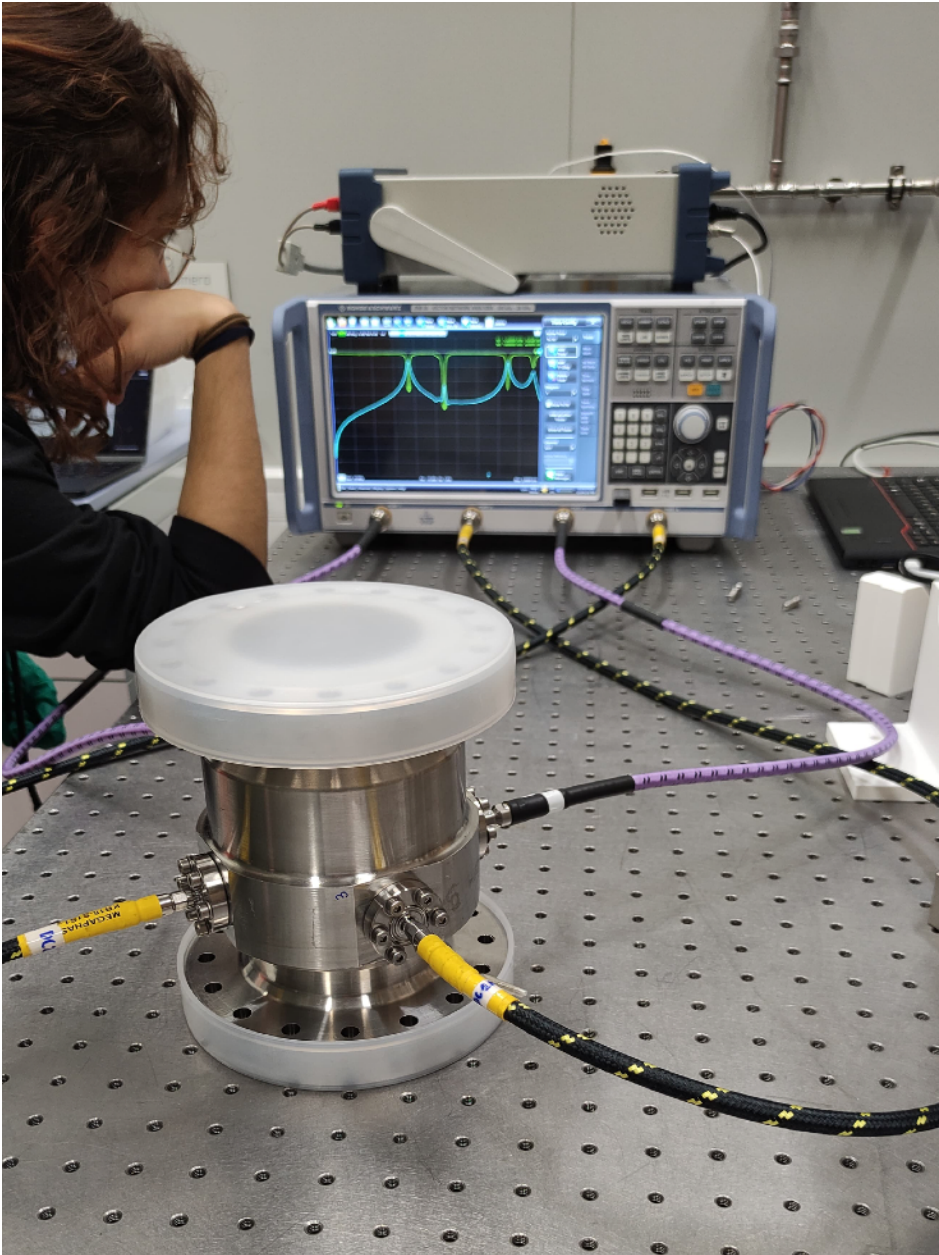
With small lengths and angles variations, there was no significant alteration on the RF parameters of the BPM.

After evaluating the tolerance study and weighing the cost-benefit trade-off, it was decided to manufacture the BPM with **tolerances of 50 μm for the critical dimensions.**

I. cBPM theory and prototype design

C) Manufacturing and measured RF characteristics

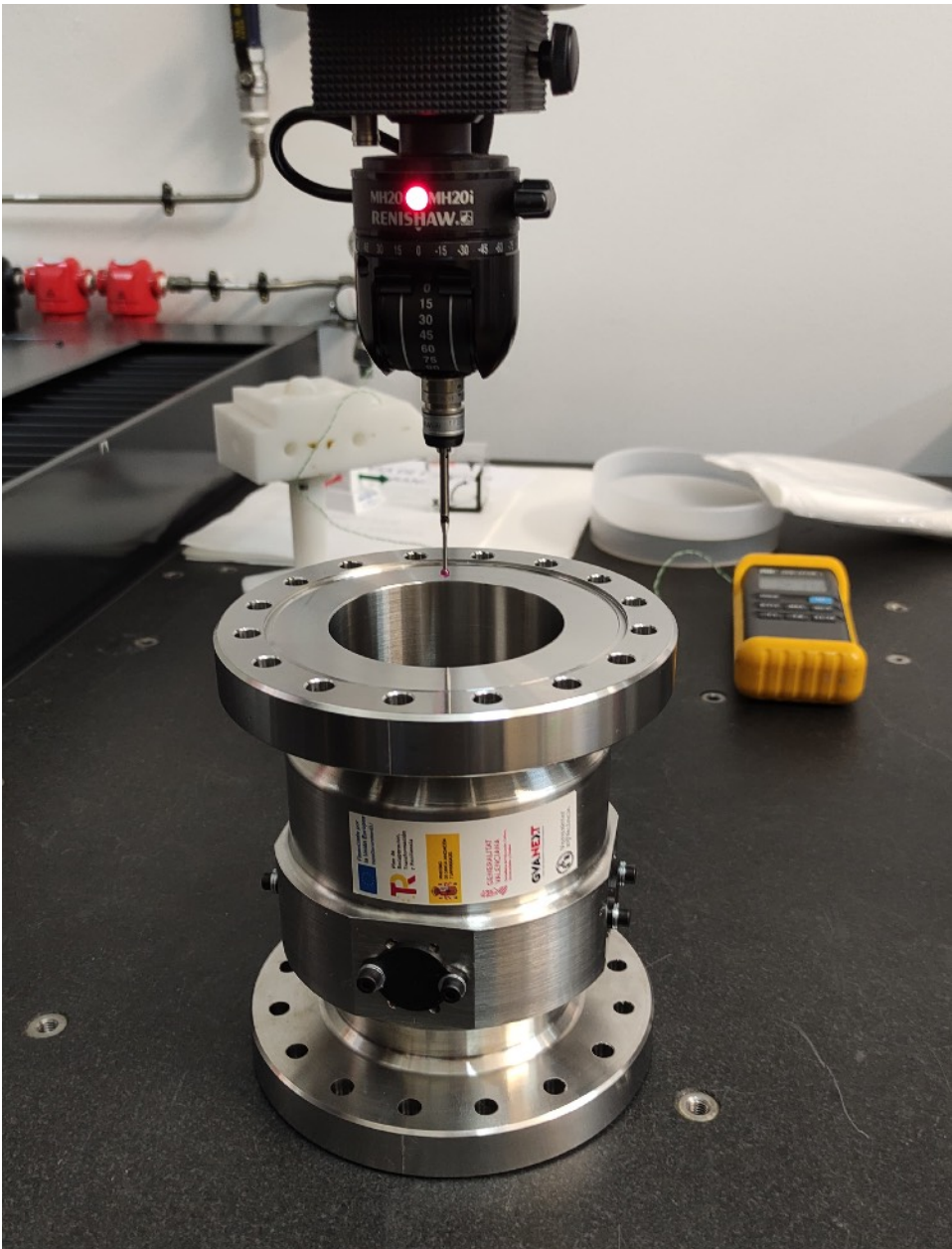
Vector Network Analyzer (VNA):



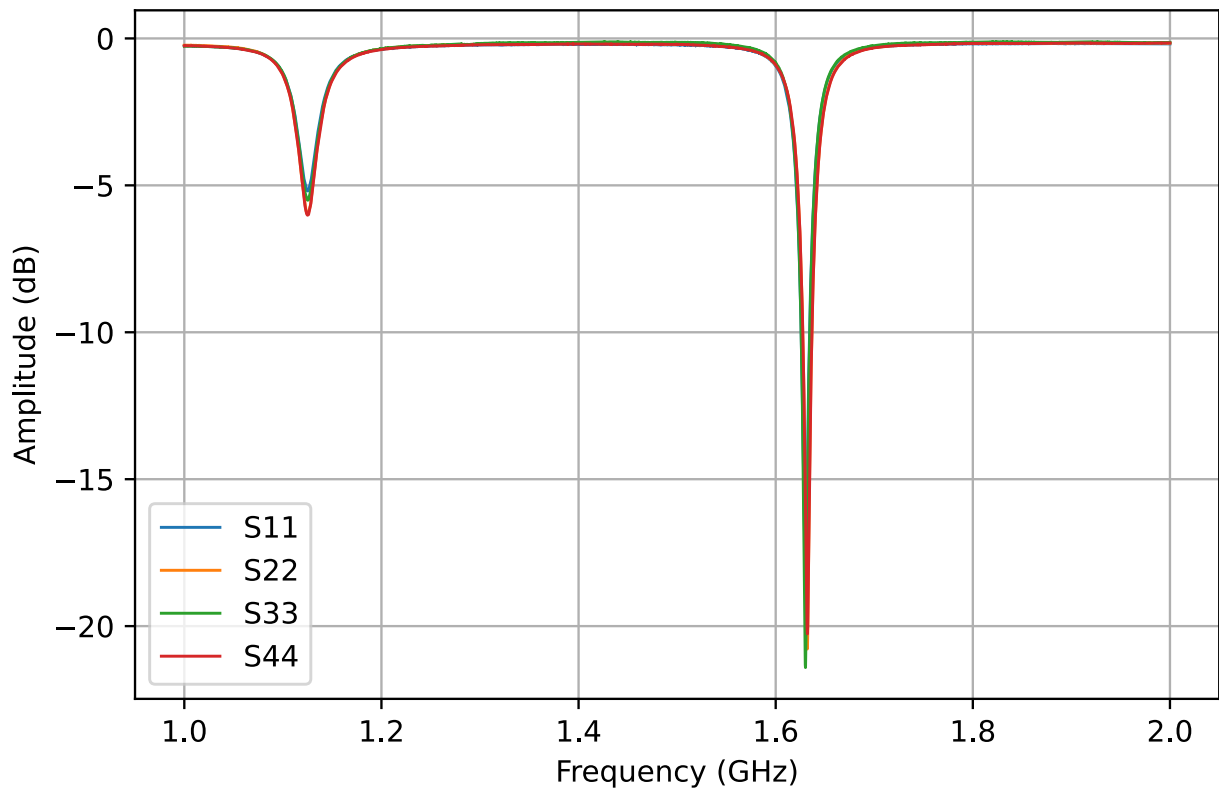
Vacuum test: Approved.

Metrology:

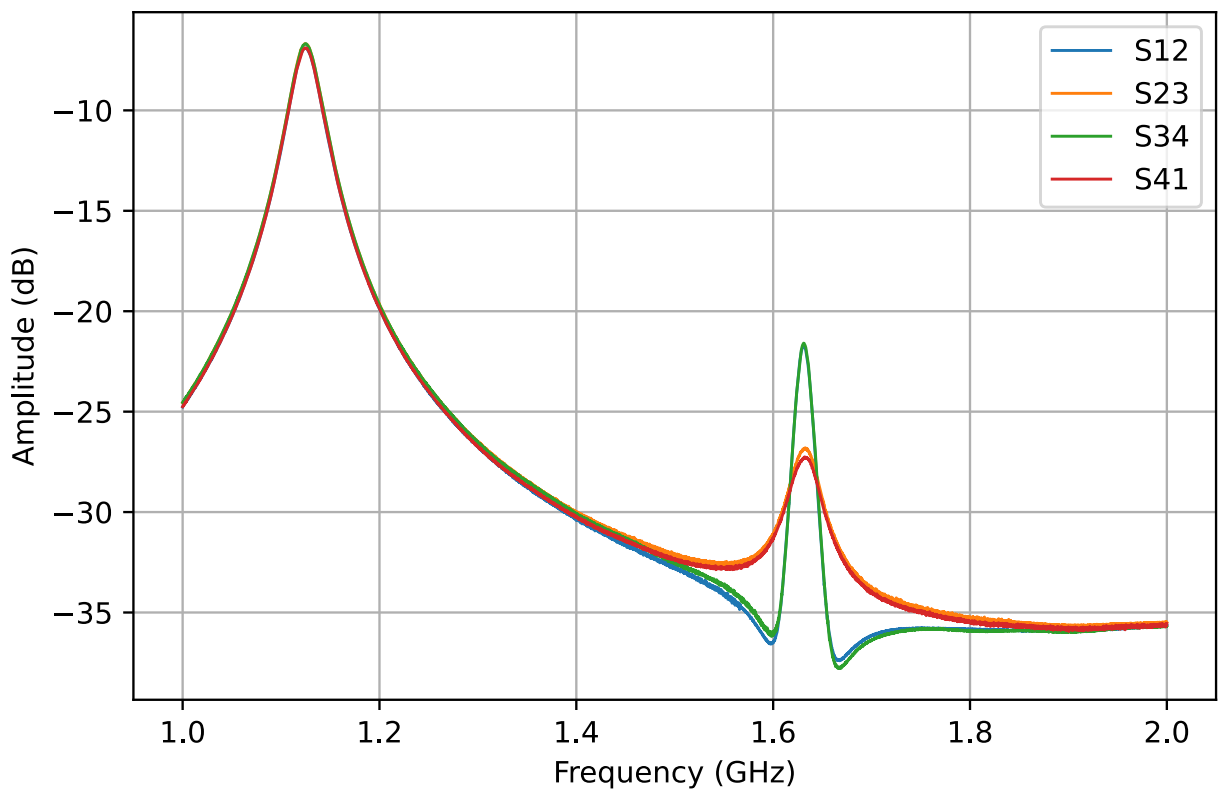
All BPM dimensions were according to specifications.
Tolerances were according to specifications.



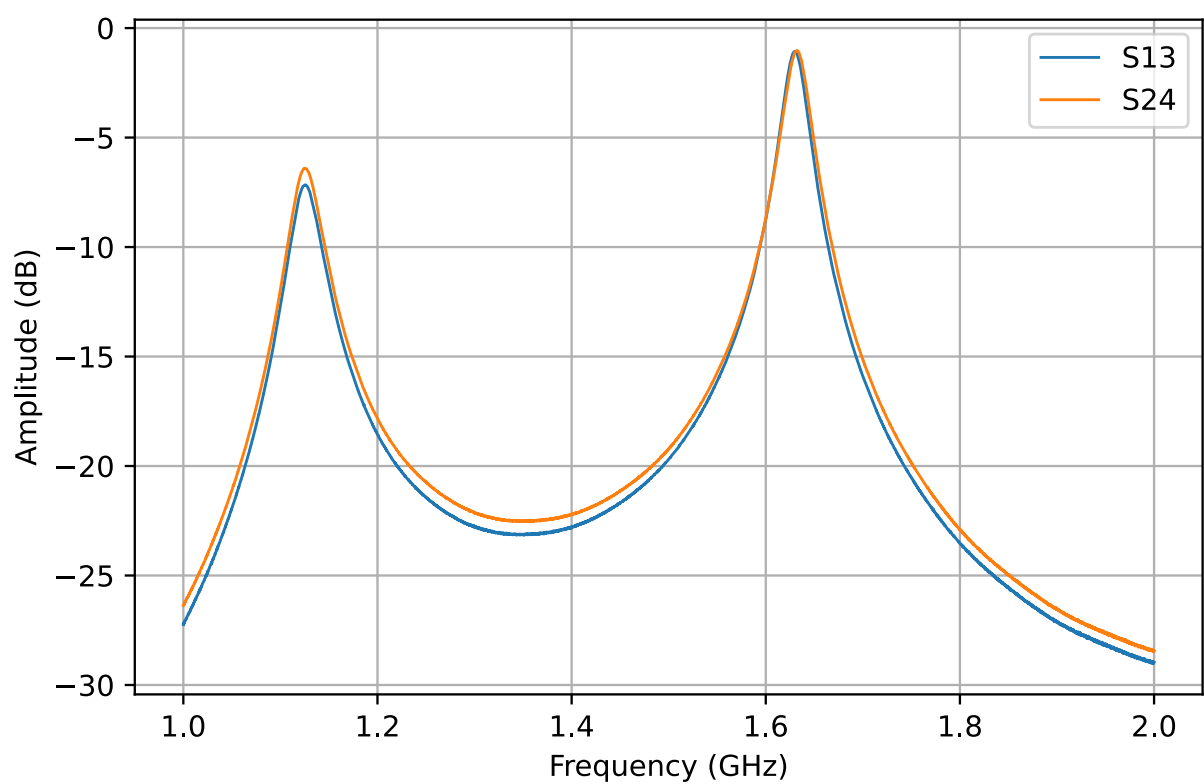
Reflection:
At the same port



Cross-talk:
Between the 4 consecutive ports



Transmission:
Between the opposite ports



I. cBPM theory and prototype design

C) Manufacturing and measured RF characteristics

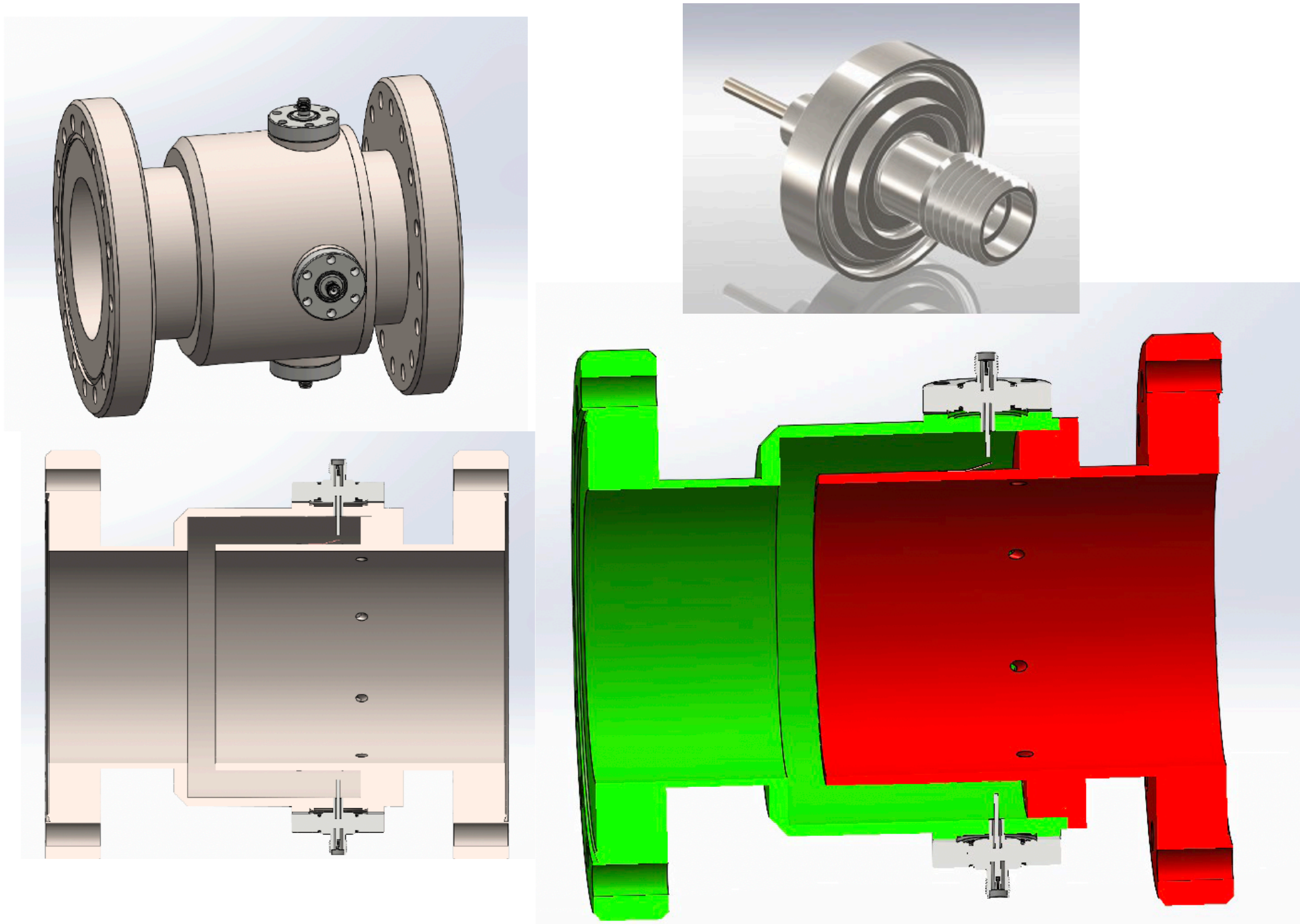
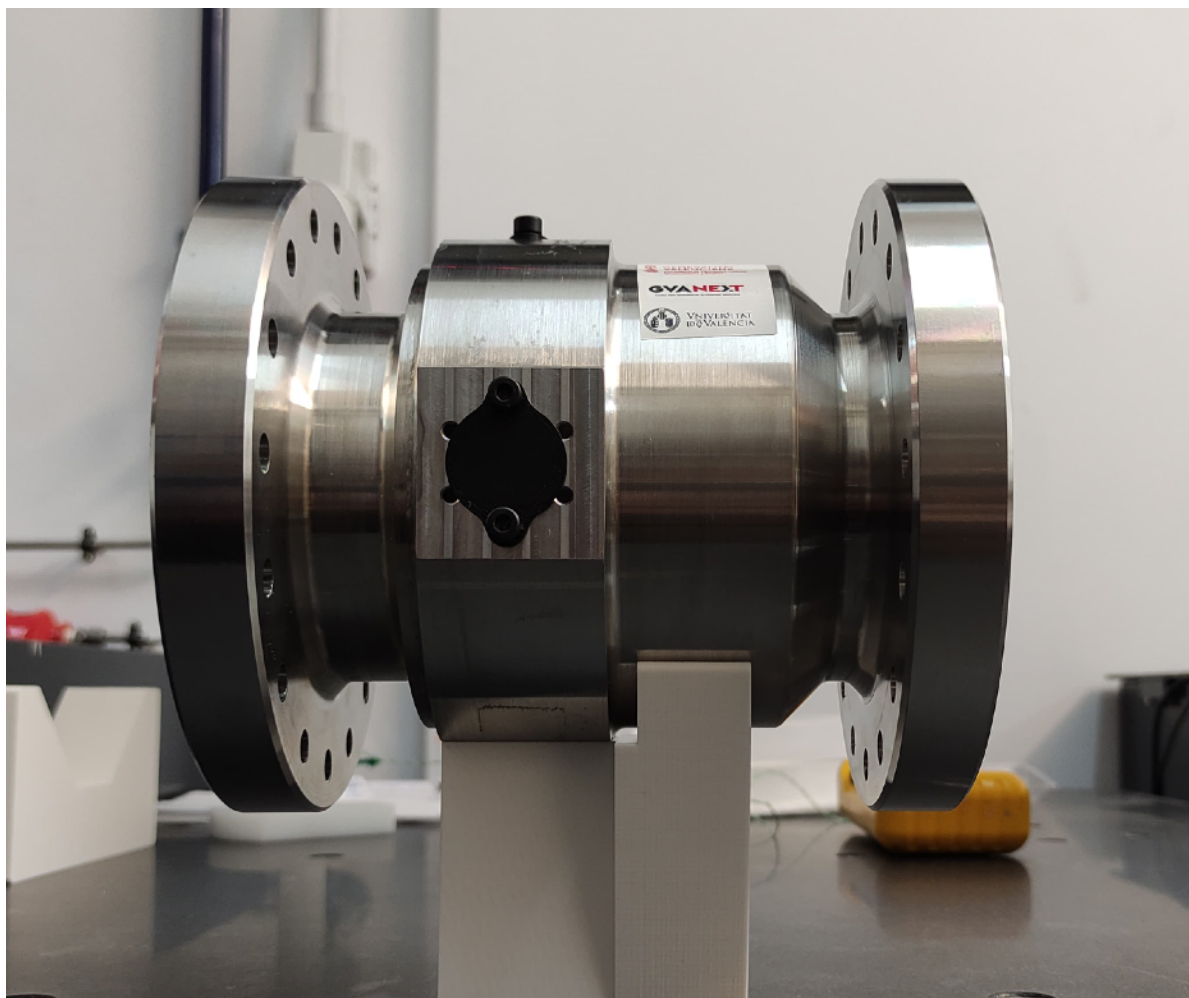


Table 1: cBPM RF characteristics from CST simulations and VNA measurements.

	f (GHz)	Q_L	$R/Q(\Omega)$ @ 5 mm	S_{11} (dB)	S_{12} (dB)
Monopole mode					
Sim.	1.118	34.91	14.50	-5.48	-6.52
Meas.	1.125	46.98	-	-5.70	-6.89
Dipole mode					
Sim.	1.620	64.09	0.350	-20.2	-30.8
Meas.	1.631	57.84	-	-20.76	-24.30



Construction was carried out in collaboration with Spanish company Neptury Technologies.

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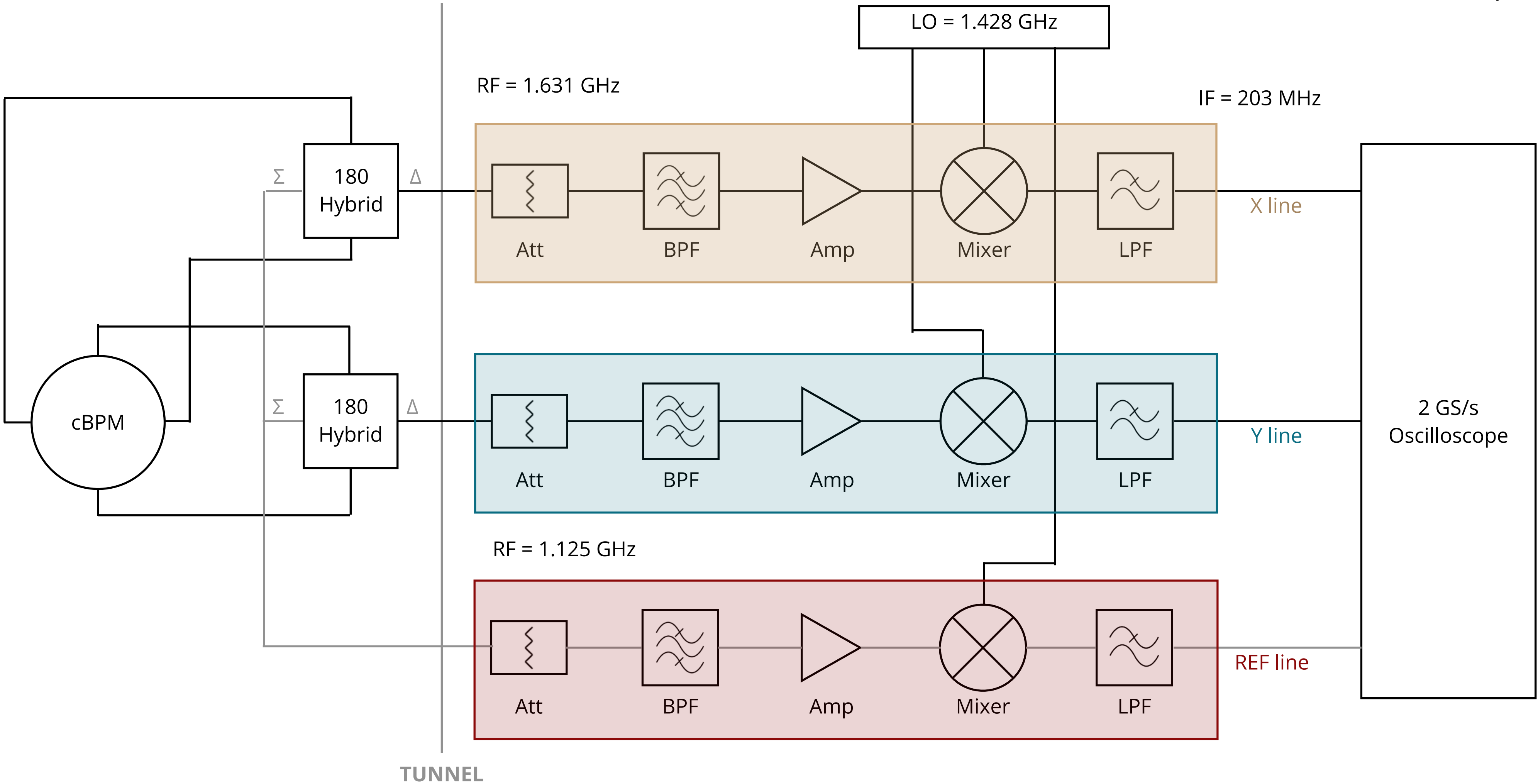
Introduction

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Conclusion

II. DAQ and experimental procedure

A) Readout system



3 identical lines of down-conversion to ~200 MHz:
-two for **x** and **y** signals (with RF = 1.631 GHz).
-one for **reference** signal (with RF = 1.125 GHz)
(the tail of the monopole mode is taken).

Reference signal is taken from the same BPM and the same LO is used for the 3 signals.

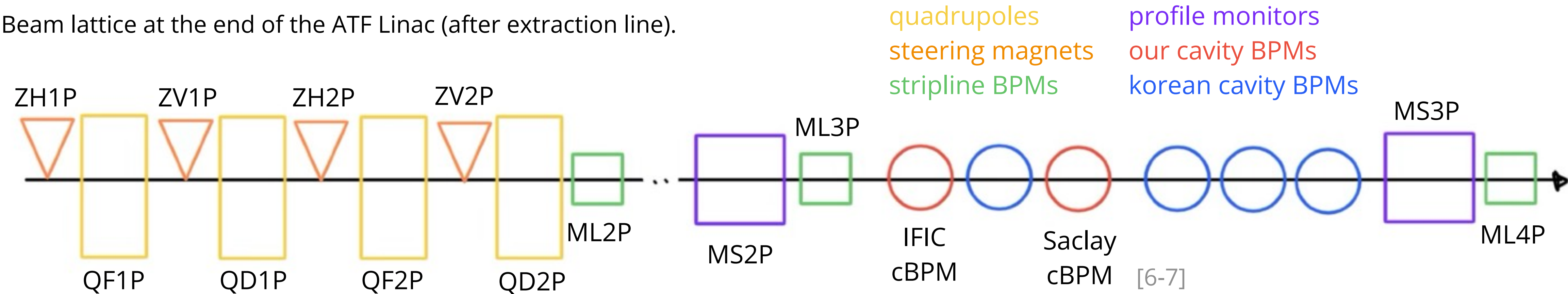
A digital down-conversion (DDC) algorithm is employed to extract the amplitude and phase of both signals.

[4-5]

II. DAQ and experimental procedure

B) Beam tests at the ATF Linac

Beam lattice at the end of the ATF Linac (after extraction line).



Calibration:

The horizontal and vertical steering magnets (ZH2P and ZV2P) were used to induce a range of beam offsets in the X and Y planes for calibration.

The cBPM measurements were converted to estimated beam positions using linear interpolation of stripline BPM readings from ML3P and ML4P, along with upstream and downstream profile monitors (MS2P and MS3P).

Resolution:

A set of $P = 1000$ pulses was acquired at a fixed beam position, and simultaneous measurements from 19 stripline BPMs and the CEA-Saclay cBPM were used to remove coherent beam motion, and evaluate the system noise.

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at IBIC2026 31/08/2026

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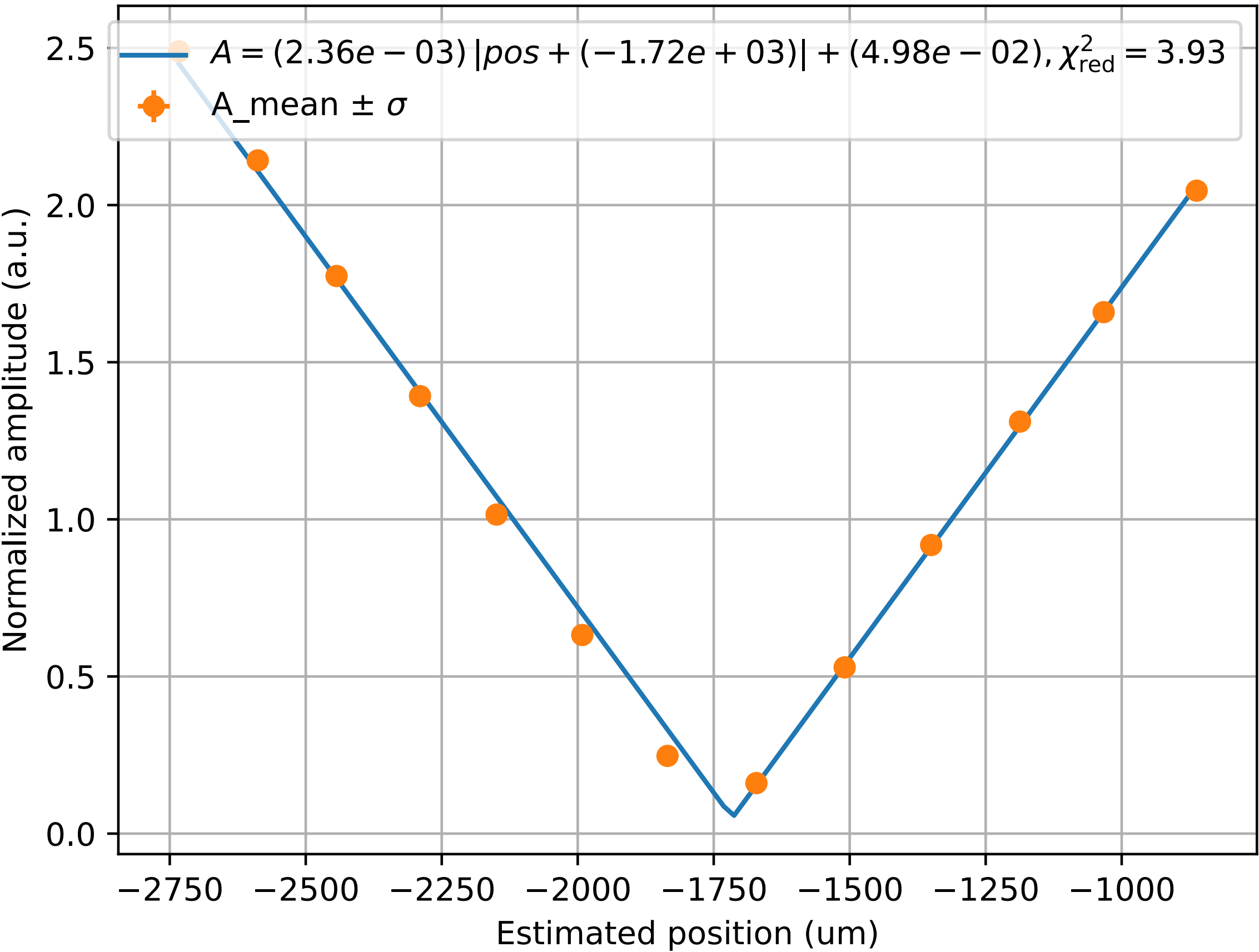
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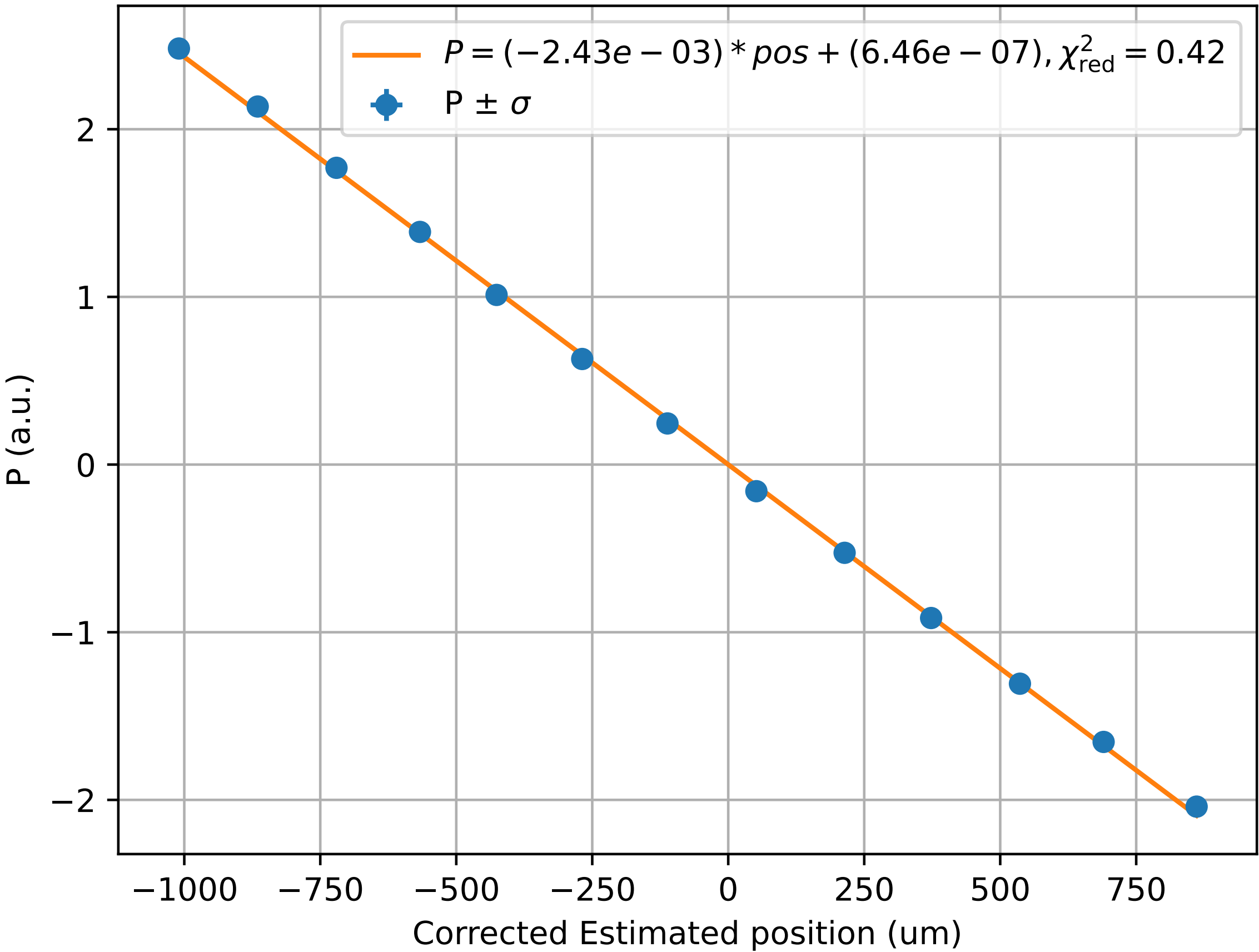
III. Preliminary characterisation results

A) Calibration results

A systematic offset was observed due to mechanical misalignments during the cBPM installation.



A small dynamic range was employed for this calibration, of around 2 mm to maximise the bit per volt from the oscilloscope and improve the conditions of the resolution measurement.



III. Preliminary characterisation results

B) Resolution estimation

Taking a long set of data in a single beam position:

$P = 1000$ is the number of pulses

$M = 20$ is the number of BPMs used

Model Independent Analysis: [8]

$$\text{cBPM measured values} \longrightarrow \begin{pmatrix} d_{k0} \\ d_{k1} \\ \vdots \\ d_{kP} \end{pmatrix} = \begin{pmatrix} d_{00} & d_{10} & \dots & d_{i \neq k, 0} & \dots & d_{M0} \\ d_{01} & d_{11} & \dots & d_{i \neq k, 1} & \dots & d_{M1} \\ \vdots & \vdots & & \vdots & & \vdots \\ d_{0P} & d_{1P} & \dots & d_{i \neq k, P} & \dots & d_{MP} \end{pmatrix} \cdot \begin{pmatrix} v_0 \\ v_1 \\ \vdots \\ v_M \end{pmatrix} \longleftarrow \text{correlation coefficients}$$

$\mathbf{d} = \mathbf{D} \cdot \mathbf{v}$

$\uparrow$
stripline BPM measured values

To find the correlation coefficients: $\mathbf{v} = \mathbf{D}^{-1} \cdot \mathbf{d}$ where the inverse of $\mathbf{D}$ is calculated using the SVD method: $SVD(\mathbf{D}) = \mathbf{U} \mathbf{S} \mathbf{V}^T$

The residuals between measured position and estimated position are calculated as

$$\mathbf{R} = \mathbf{d} - \mathbf{D} \cdot \mathbf{v}$$

And the resolution is estimated with the rms of the residuals:

$$\sigma = \sqrt{\frac{\sum_i^P R_i^2}{P}}$$

$$\begin{aligned} \mathbf{D}^{-1} &= \mathbf{V}^T \mathbf{S}^{-1} \mathbf{U}^T \\ &= \mathbf{V} \begin{pmatrix} 1/\sigma_1 & & \\ & \ddots & \\ & & 1/\sigma_M \end{pmatrix} \mathbf{U}^T \end{aligned}$$

BPMs taken: up-stream: ML1L ML15L, ML1P, ML2P, ML3P ; down-stream: ML4P

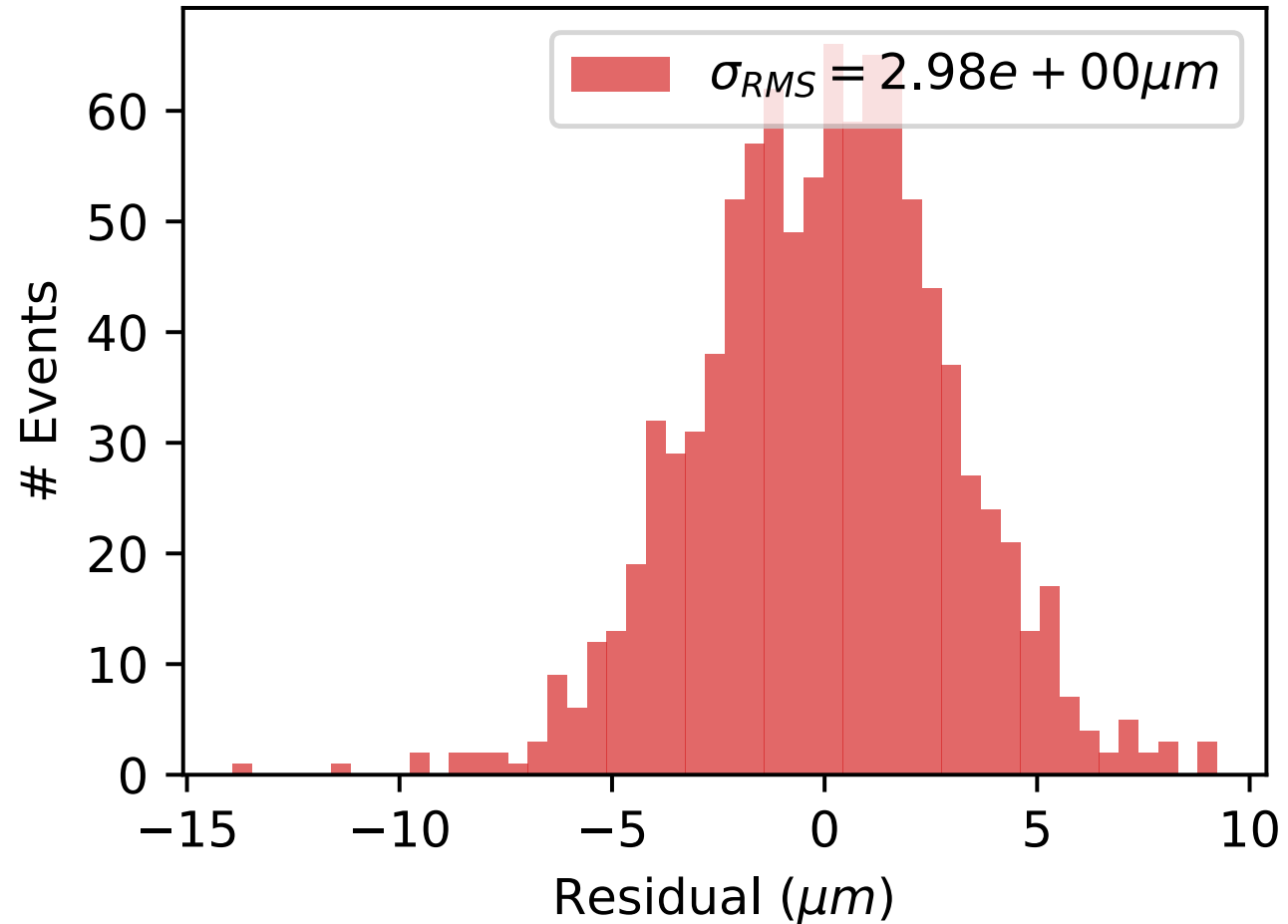
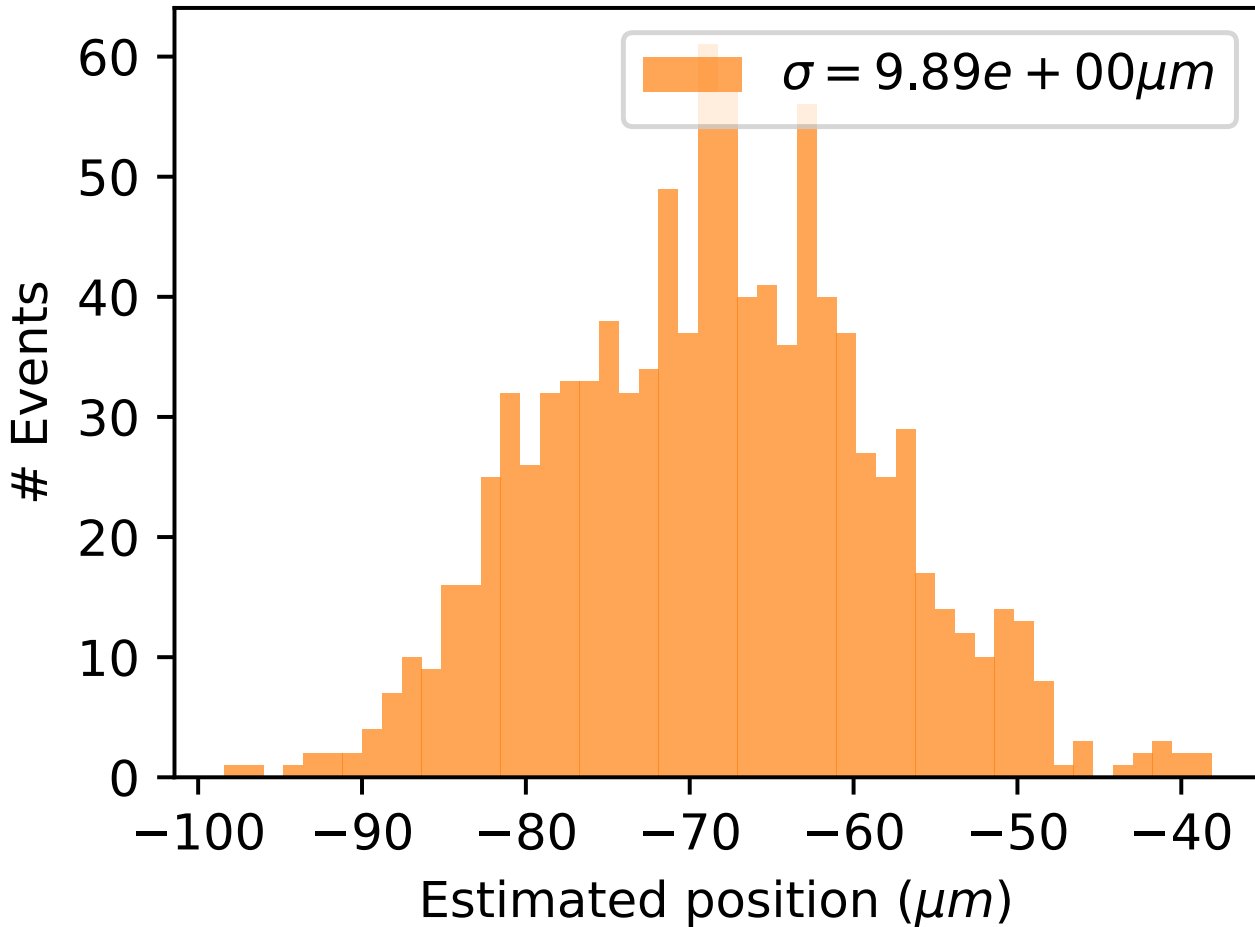
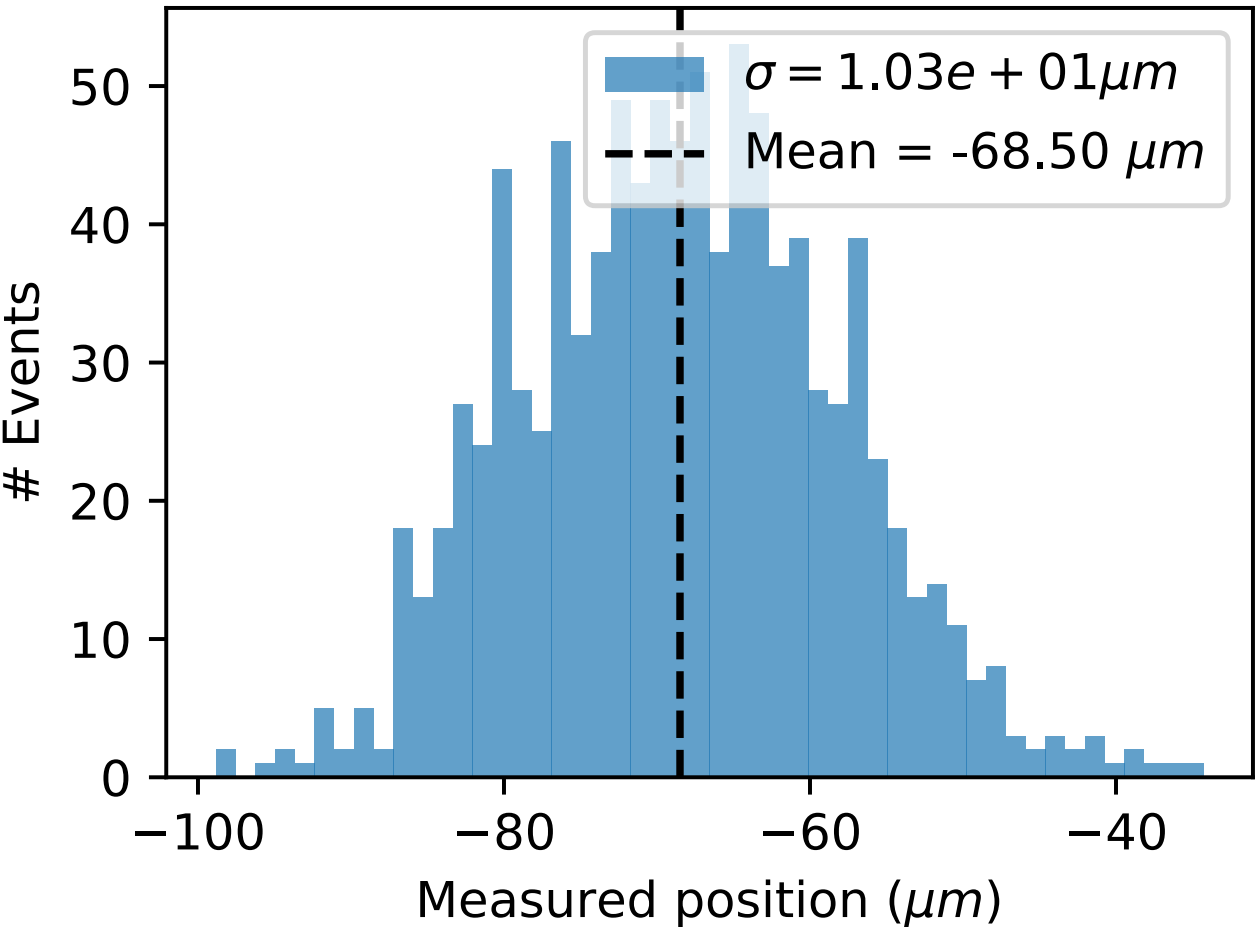
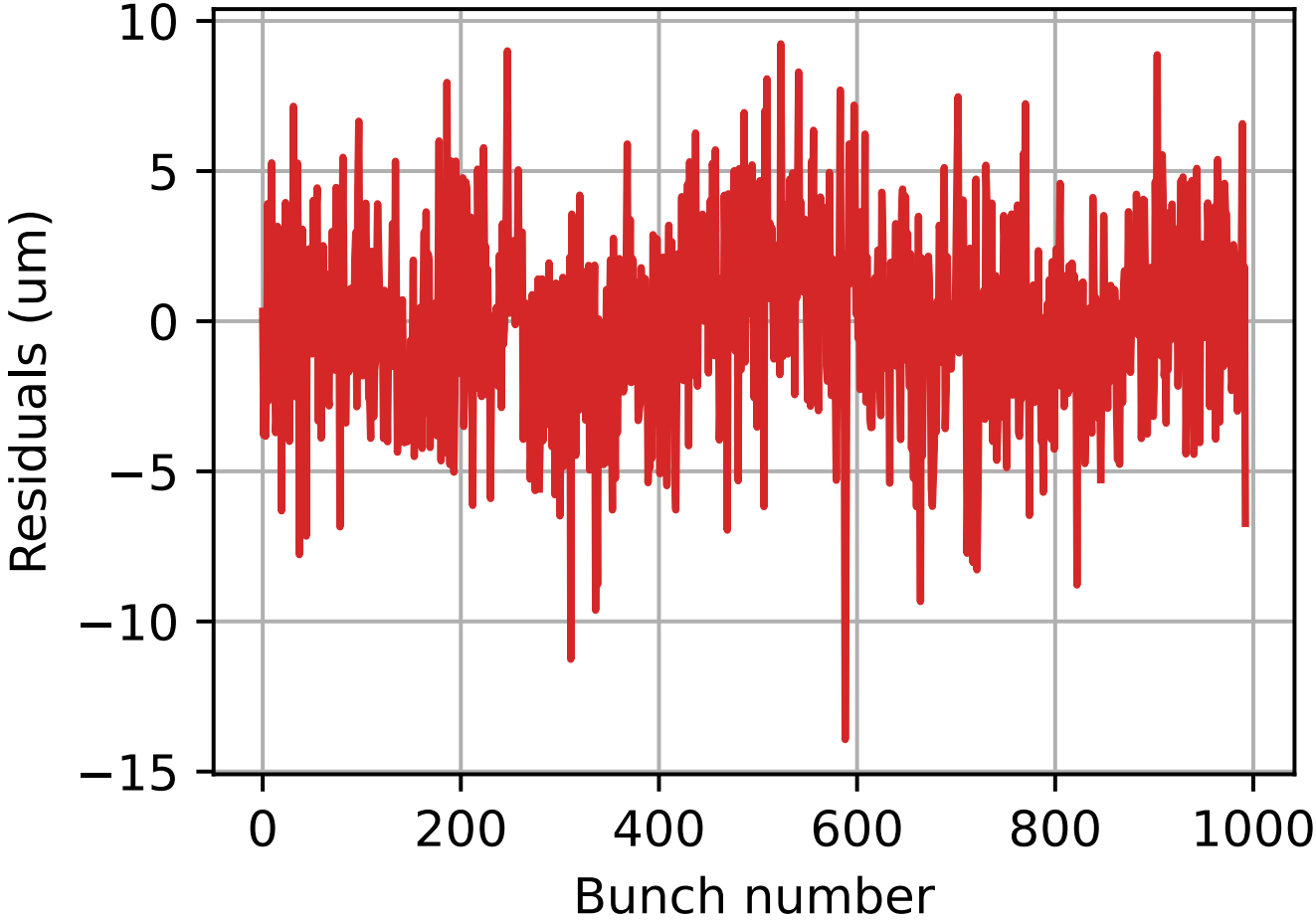
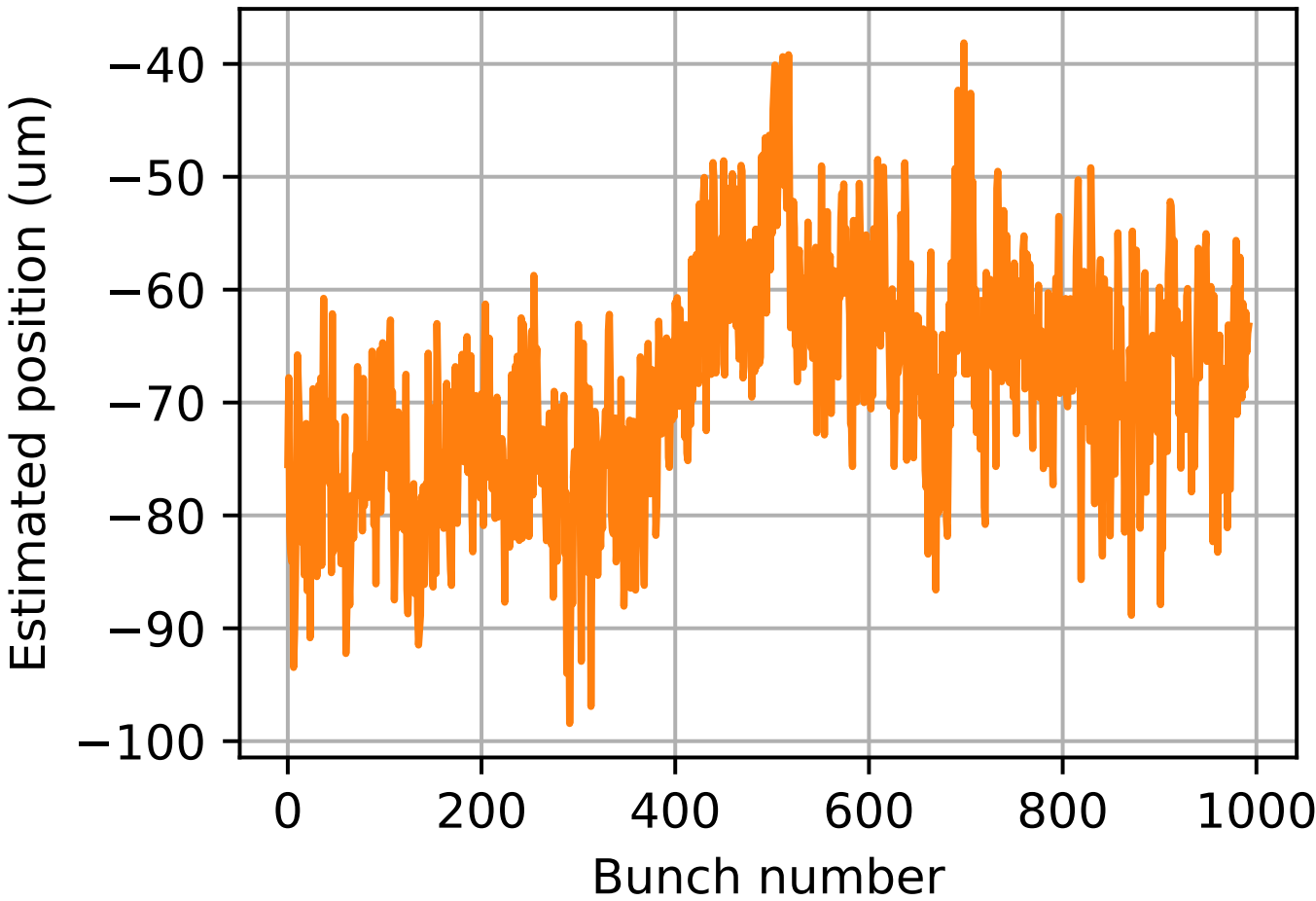
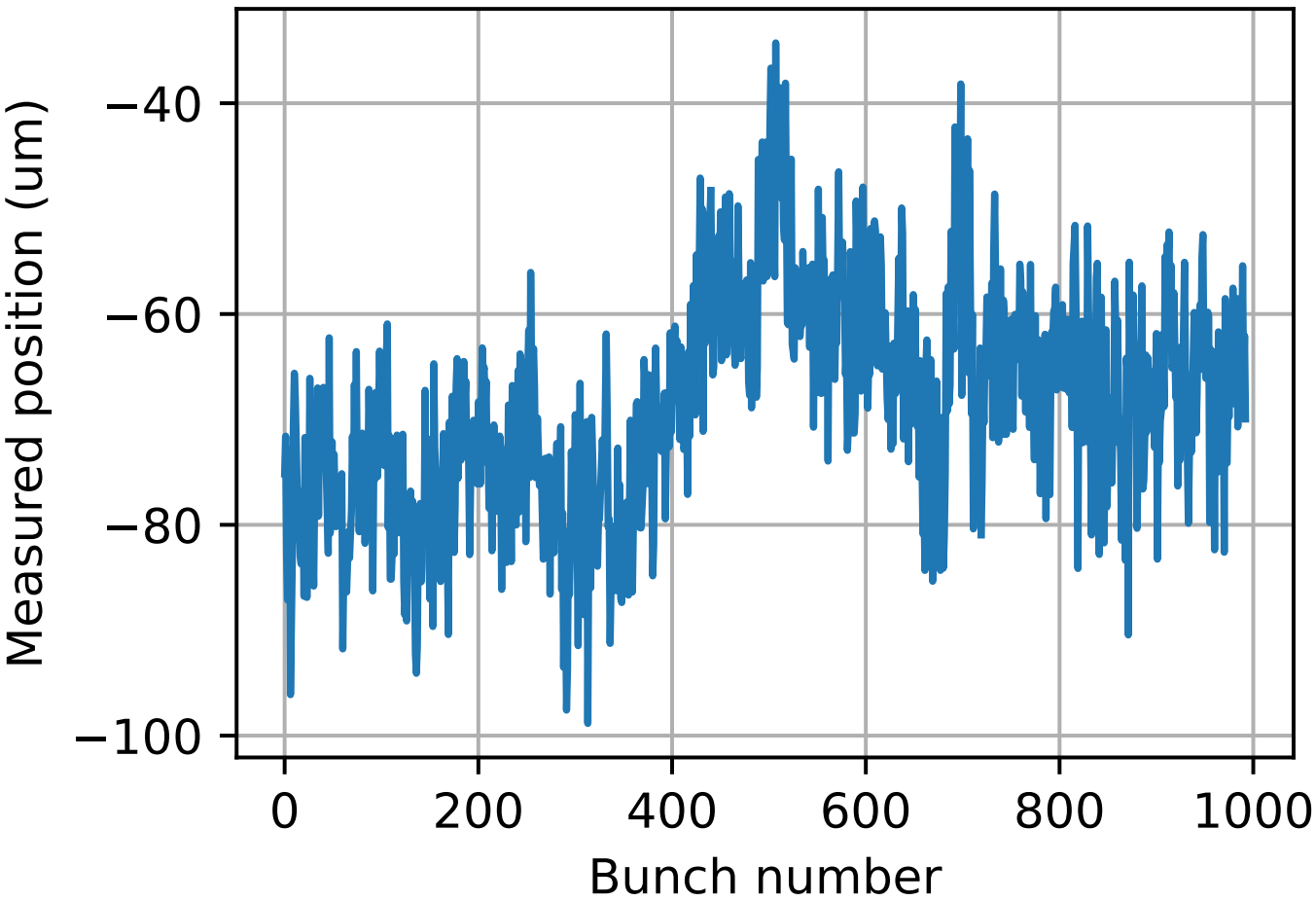
III. Preliminary characterisation results

B) Resolution estimation

$\mathbf{R} = \mathbf{d} - \mathbf{D} \cdot \mathbf{v}$

Taking a long set of data in a single beam position:

$P = 1000$ is the number of pulses
 $M = 20$ is the number of BPMs used
bunch charge = 0.74 nC/bunch



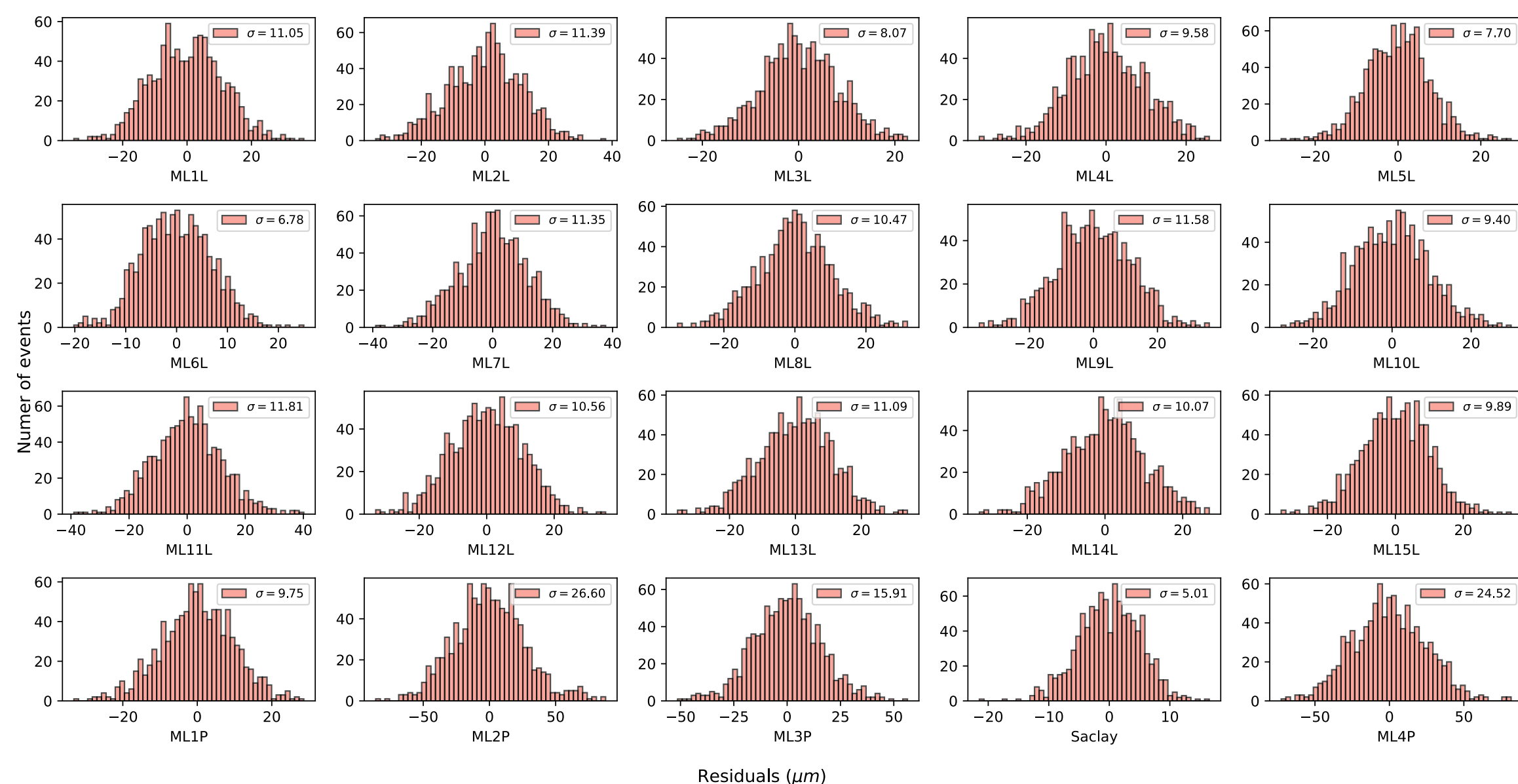
2.98 μm

III. Preliminary characterisation results

C) Measurement system and model limitations

Contribution of the resolution of other BPMs:

The previous method is employed for all BPMs:



Stripline BPMs showed resolutions between 7 μm and 25 μm , while the CEA-Saclay cBPM has shown to have a resolution of 3 μm under these beam conditions.

Uncertainties on the correlation coefficients from MIA:

- Analytically:**

from the square root of the diagonal elements of the covariance matrix $Cov(\mathbf{v})$, where

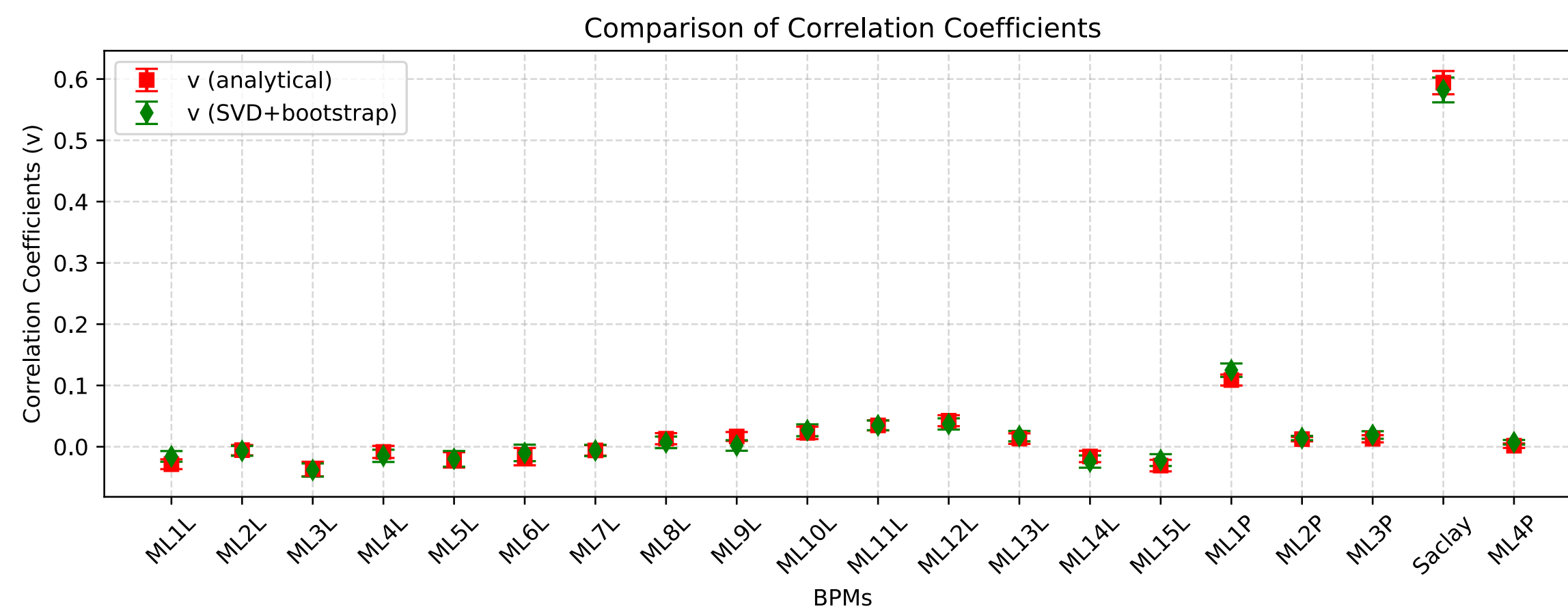
$$Cov(\mathbf{v}) = \sigma_{\hat{d}}^2 [\mathbf{D}^T \mathbf{D}]^{-1} = \frac{\|\mathbf{R}\|^2}{P-1} [\mathbf{D}^T \mathbf{D}]^{-1}$$

assuming measurement noise in the cBPM is uncorrelated across pulses.

- Via Bootstrap method:**

resampling pulses from $\mathbf{d}$ and $\mathbf{D}$ with replacement and recalculating $\mathbf{v} = \mathbf{D}^{-1} \cdot \mathbf{d}$

[9]



III. Preliminary characterisation results

C) Measurement system and model limitations

Influence of BPMs resolution and correlation coefficient errors on the resolution estimation:

$$\mathbf{d} = \mathbf{D} \cdot \mathbf{v}$$

$$\begin{pmatrix} d_{k0} \\ d_{k1} \\ \vdots \\ d_{kP} \end{pmatrix} = \begin{pmatrix} d_{00} & d_{10} & \dots & d_{i \neq k, 0} & \dots & d_{M0} \\ d_{01} & d_{11} & \dots & d_{i \neq k, 1} & \dots & d_{M1} \\ \vdots & \vdots & & \vdots & & \vdots \\ d_{0P} & d_{1P} & \dots & d_{i \neq k, P} & \dots & d_{MP} \end{pmatrix} \cdot \begin{pmatrix} v_0 \\ v_1 \\ \vdots \\ v_M \end{pmatrix}$$

To find the correlation coefficients: $\mathbf{v} = \mathbf{D}^{-1} \cdot \mathbf{d} \rightarrow$ done **for all events**

➔ **For a given bunch i and a simulation l :** We simulate the noise with $\sigma_{strip,i}$ and σ_{v_i} in $\mathbf{E}_{l,i}$ which is added to $\mathbf{D}_i$ and $\mathbf{v}_i$:

The simulated estimation position is: $\mathbf{D}_{sim,l,i} \cdot \mathbf{v}_{sim,l,i}$ where $\mathbf{D}_{sim,l,i} = \mathbf{D}_i + \mathbf{E}_{D,l,i}$ and $\mathbf{v}_{sim,l,i} = \mathbf{v}_i + \mathbf{E}_{v,l,i}$

The simulated residuals between measured position and estimated position are calculated as: $\mathbf{R}_{sim,l,i} = \mathbf{d}_i - \mathbf{D}_{sim,l,i} \cdot \mathbf{v}_{sim,l,i}$

We observe the standard deviation of the residuals for a given bunch i across all L simulations:

$\sigma_{residuals,i}(\mathbf{R}_{sim,l,i}) \Rightarrow$ Performing simulations over several bunches, $\bar{\sigma}_{residuals}$ determines the expected resolution error.

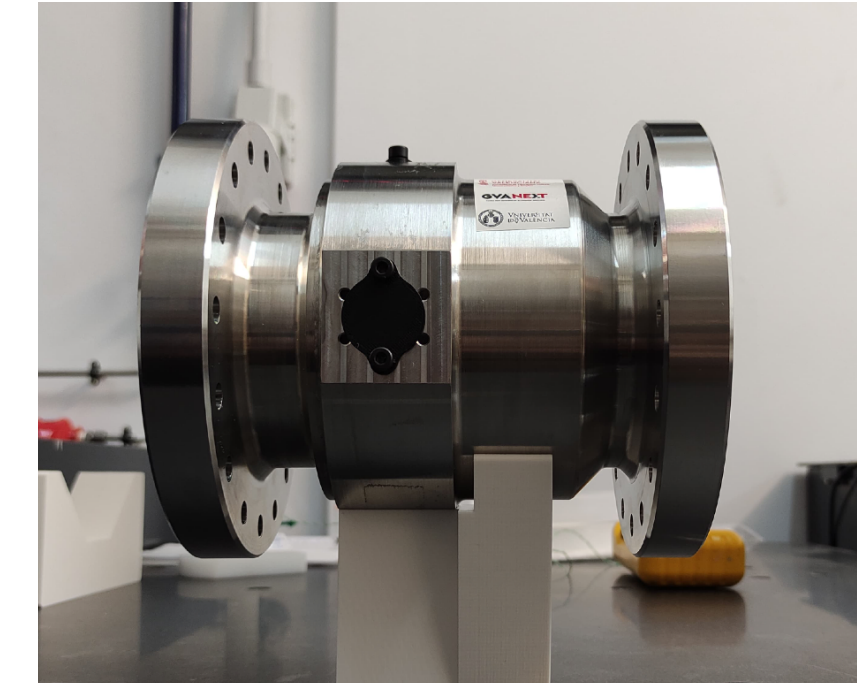
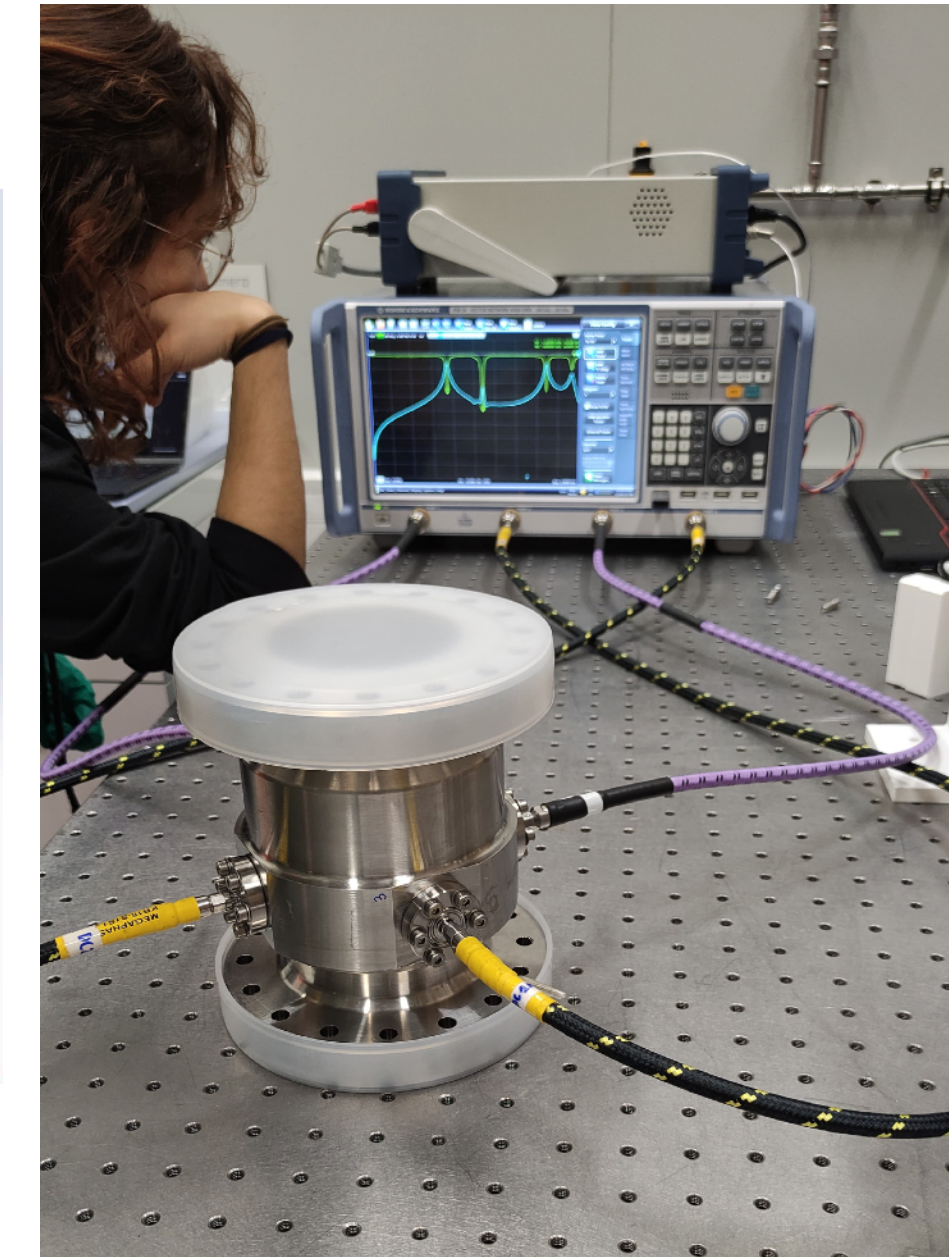
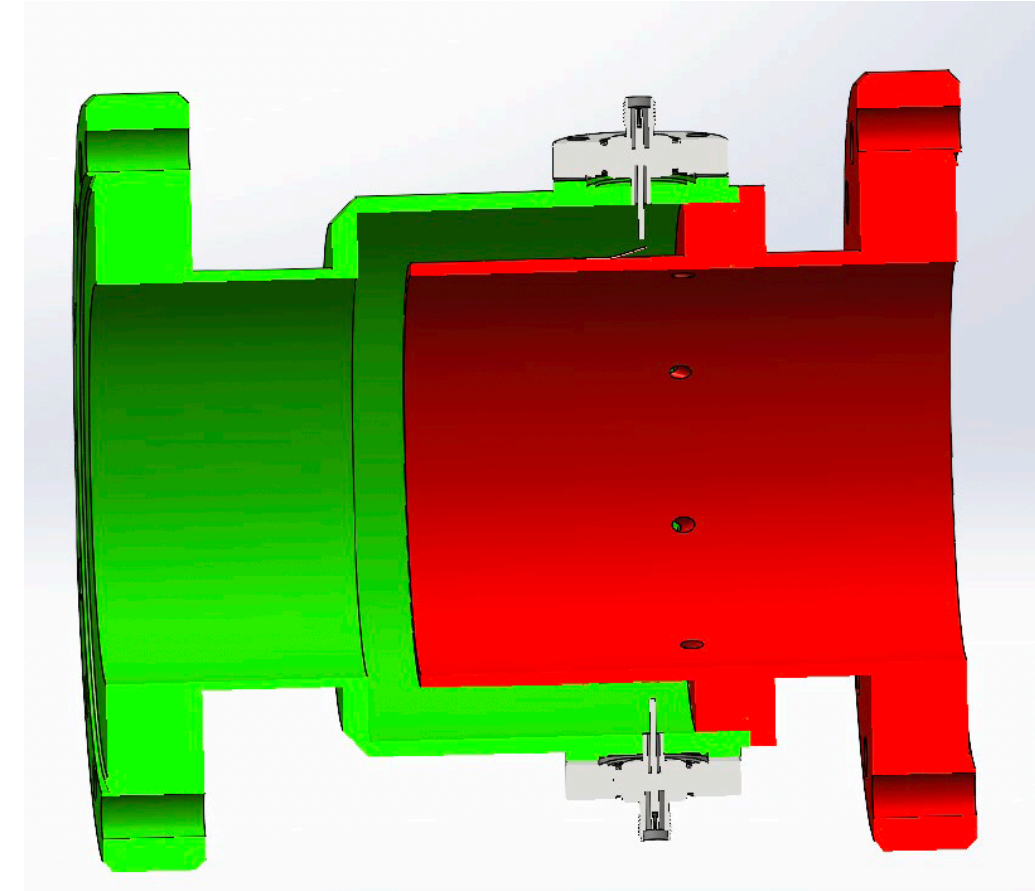
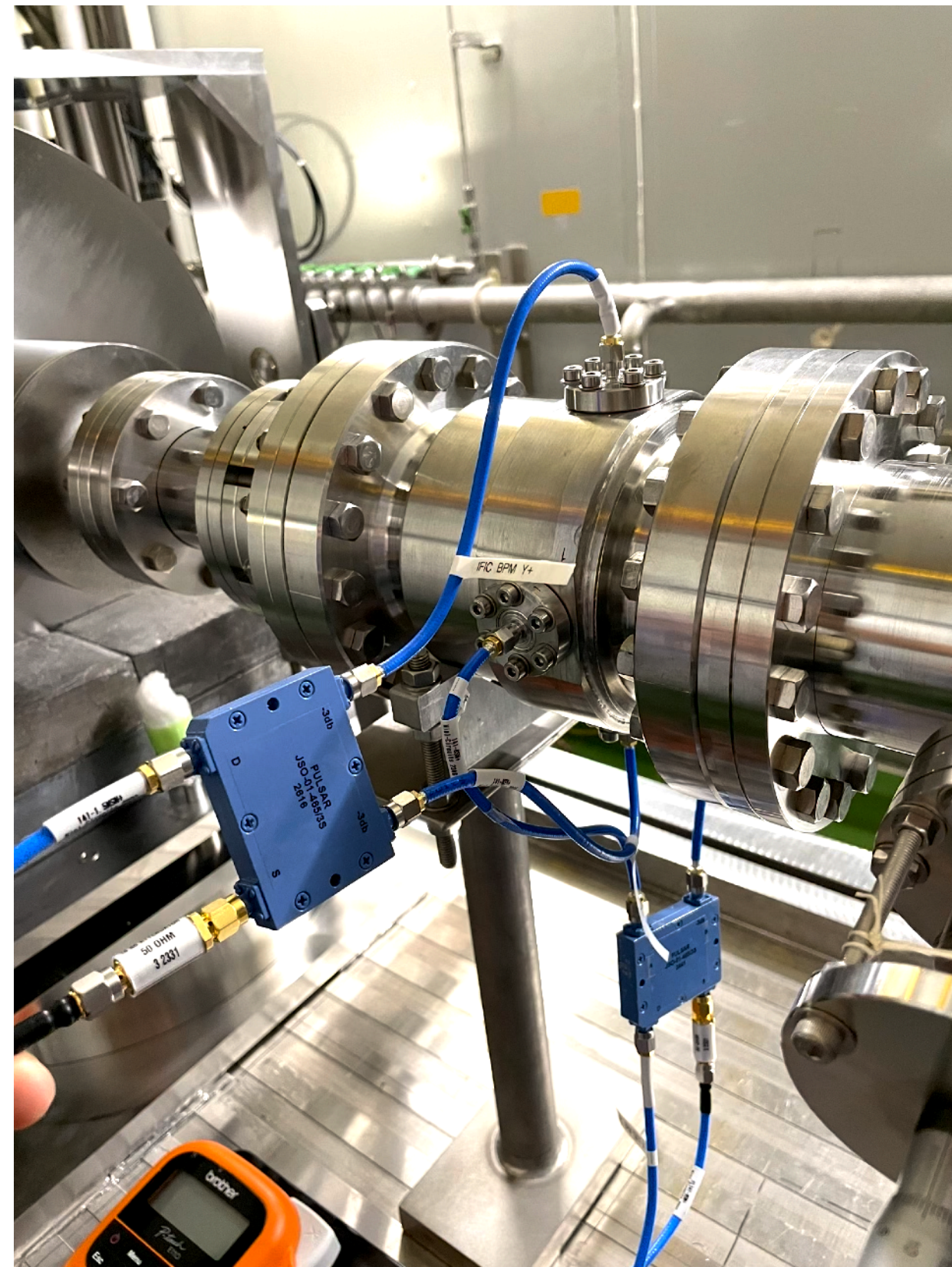
Estimated lower limit resolution:

Table 2: Resolution error contributions breakdown from pseudo-experiments method (in μm).

	Meas. res	Resolution error		
	σ	$\sigma_{err,BPMs}$	$\sigma_{err,v}$	σ_{err}
Striplines only	4.17	3.30	0.78	3.44
with Saclay cBPM	2.98	2.34	0.59	2.46

Conclusion

Designed, built and tested a 1.631 GHz re-entrant cBPM using commercial stainless steel feedthroughs suitable for cryogenic operation.



- ➔ System achieved $\sim 2.98 \mu\text{m}$ Y-axis resolution (at 0.74 nC/bunch) with a 2 mm linear dynamic range.
- ➔ Current stripline BPMs resolution limits the measurements: higher-precision monitors are needed to prove sub-micron capability for future colliders.
- ➔ A cryogenic test will be carried out in collaboration with STF (KEK) to further validate the new prototype.

References

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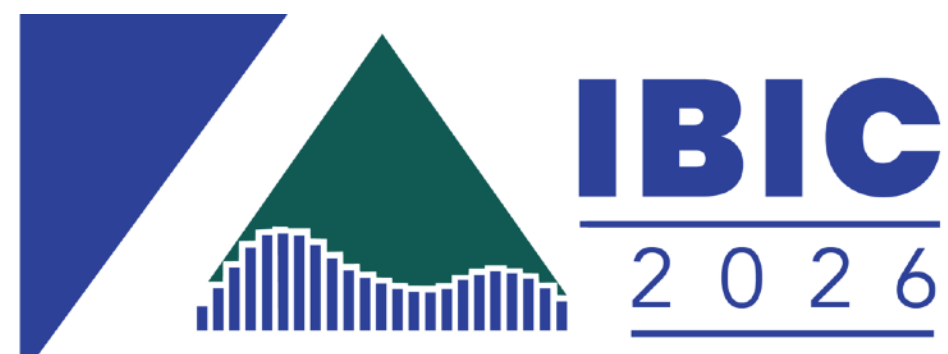


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15TH INTERNATIONAL
BEAM INSTRUMENTATION
CONFERENCE

Whistler
Conference
Centre

August 30th to
September 3rd
Whistler BC, Canada

Thank you for your attention

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