

L-band cavity BPM tests and its application to CEPC

2025 European Edition of the International Workshop on the Circular Electron-Positron Collider

Jun 16 2025, Barcelona, Spain

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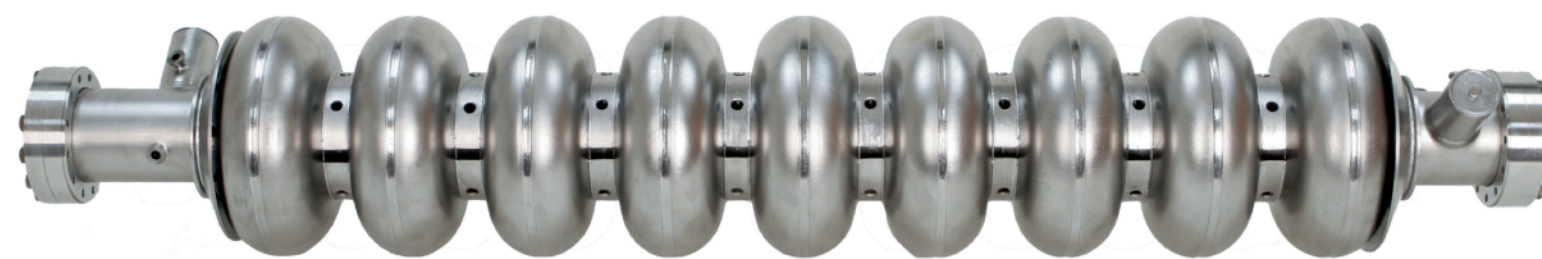
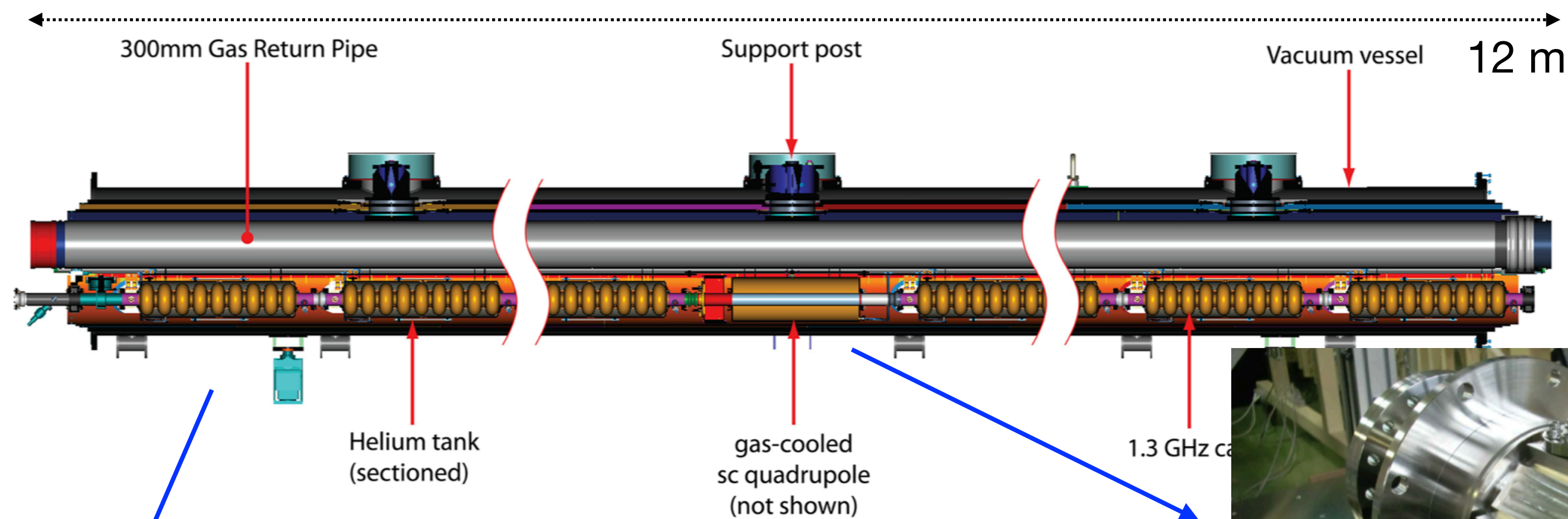


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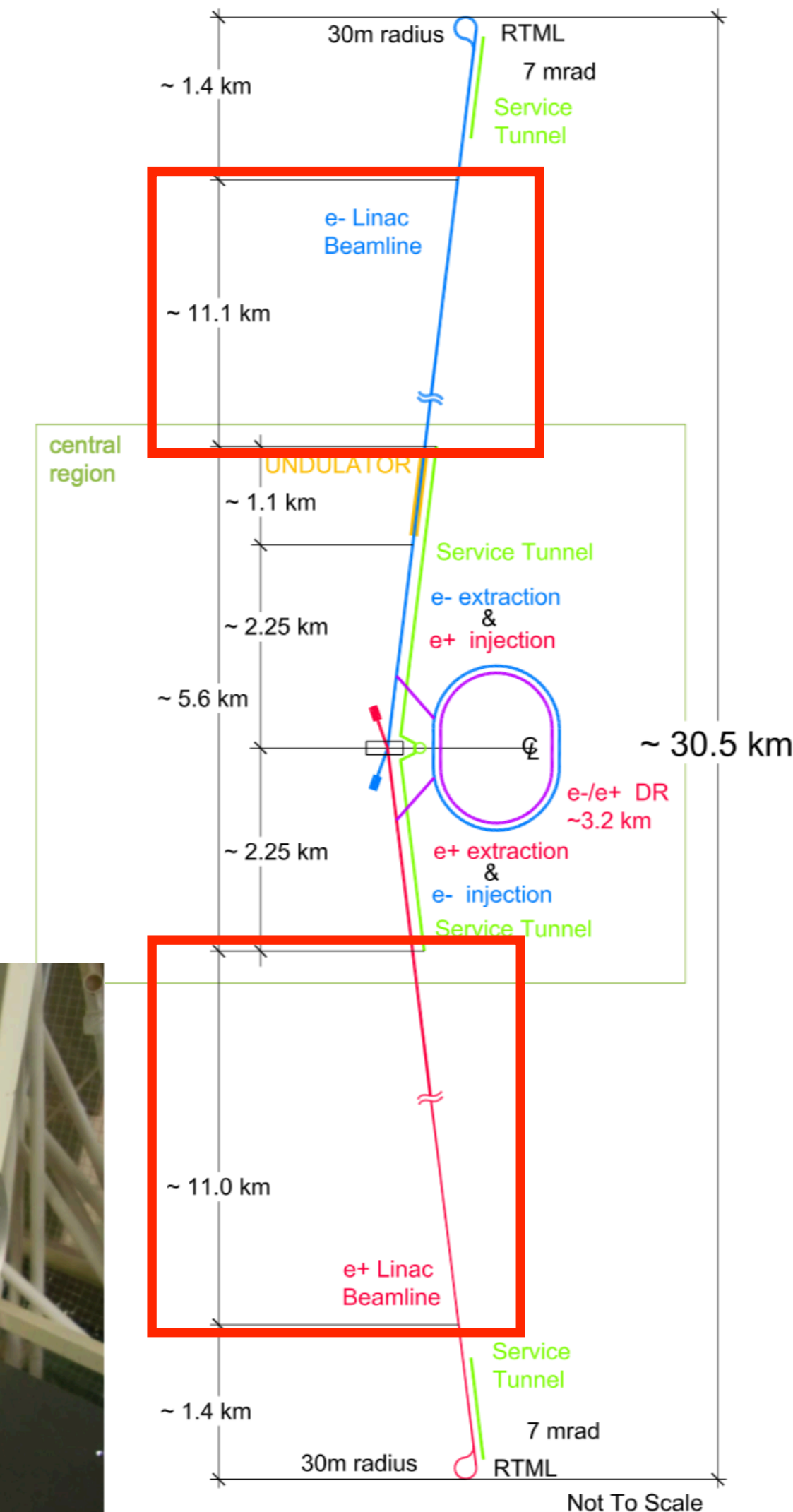
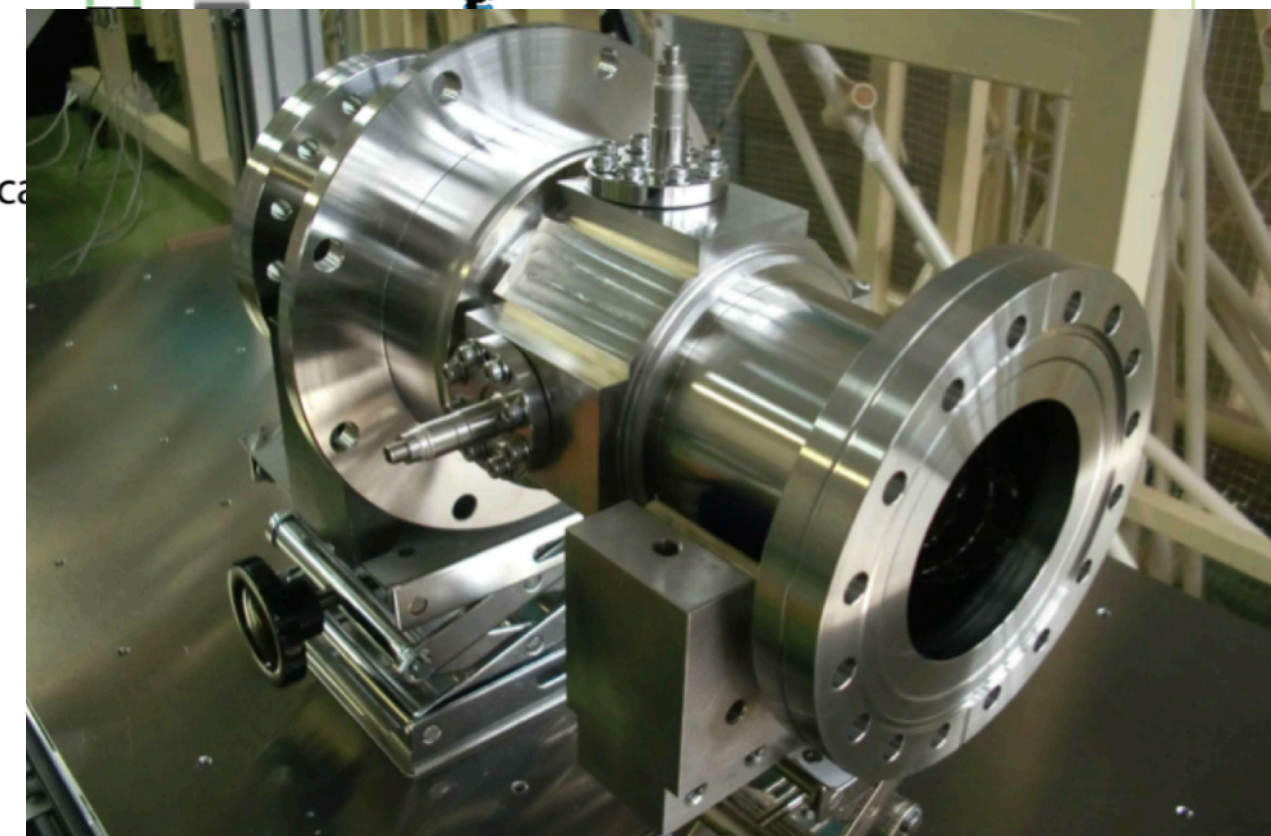
L-band Cavity BPM for ILC

- Two types of cryomodule in the main LINAC of ILC
 - Type A (~1,100 in total): 1.3 GHz 9-cell cavities * 9
 - Type B (~600 in total, at every 3 modules): 1.3 GHz 9-cell cavities * 8 + a SC quadrupole package (quadrupole/corrector/[BPM](#))
- BPM resolution requirement: $5\ \mu\text{m}$ (TDR), $\mathcal{O}(100)\ \text{nm}$ (goal)



1.3 GHz 9-cell cavity (Nb)

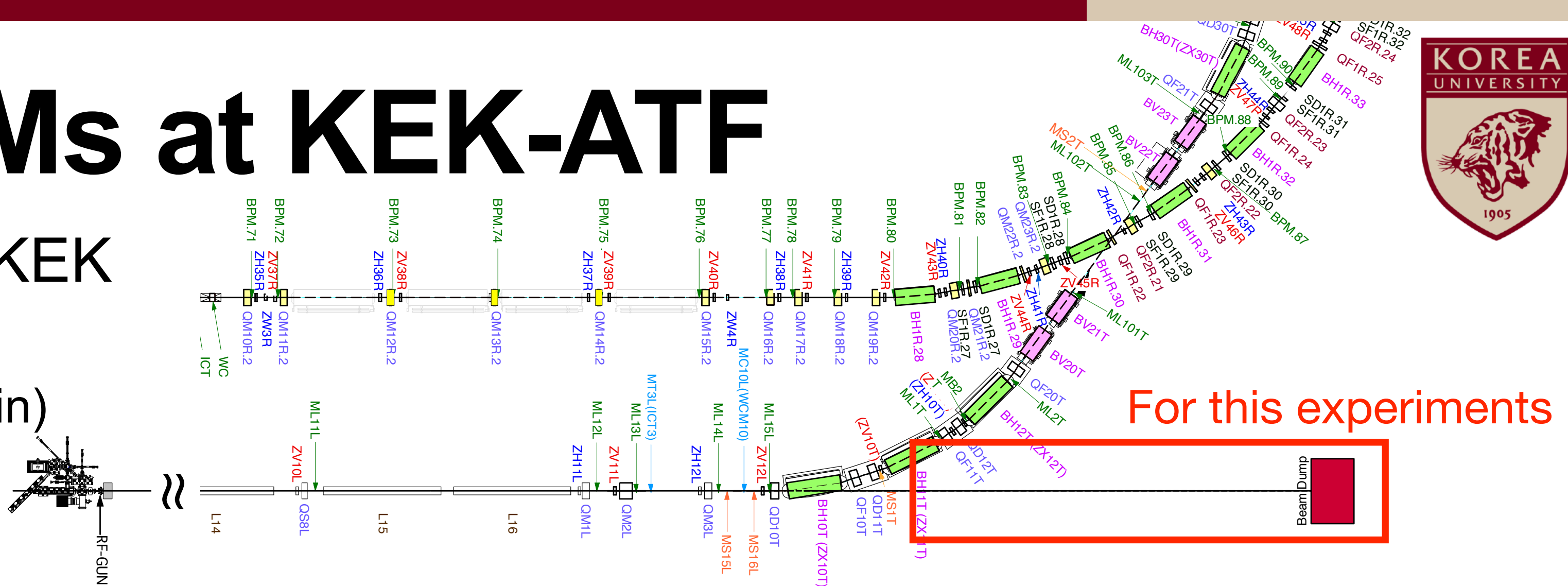
L-band re-entrant cavity BPM



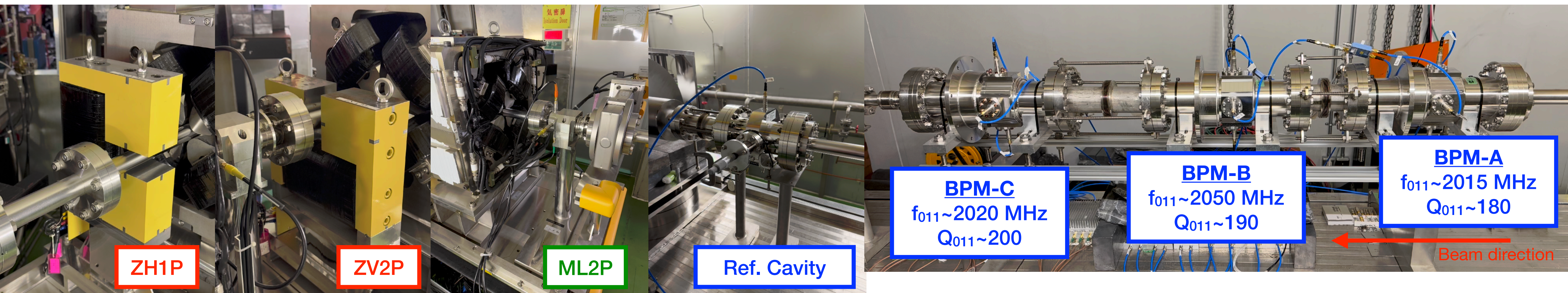
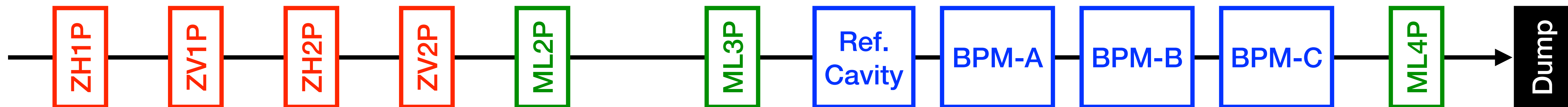
L-band Cavity BPMs at KEK-ATF



- Accelerator Test Facility (ATF) at KEK
 - 1.3 GeV electron LINAC of 110 m long
 - $\sim 10^{10}$ electrons/bunch (1~20 bunches/train)
 - Repetition: 3.125 Hz



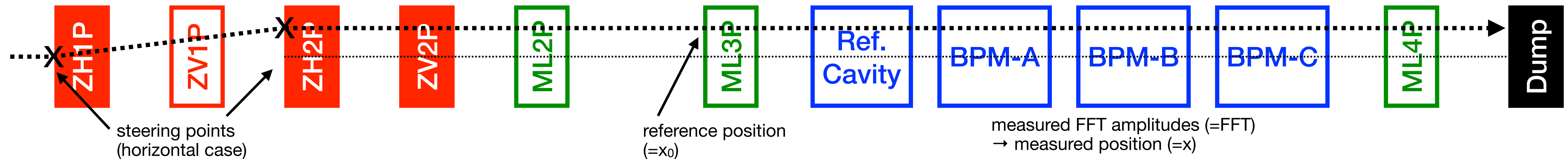
- At the end of the LINAC, 4 steering magnets, 4 stripline BPMs, and 4 cavity BPMs are located



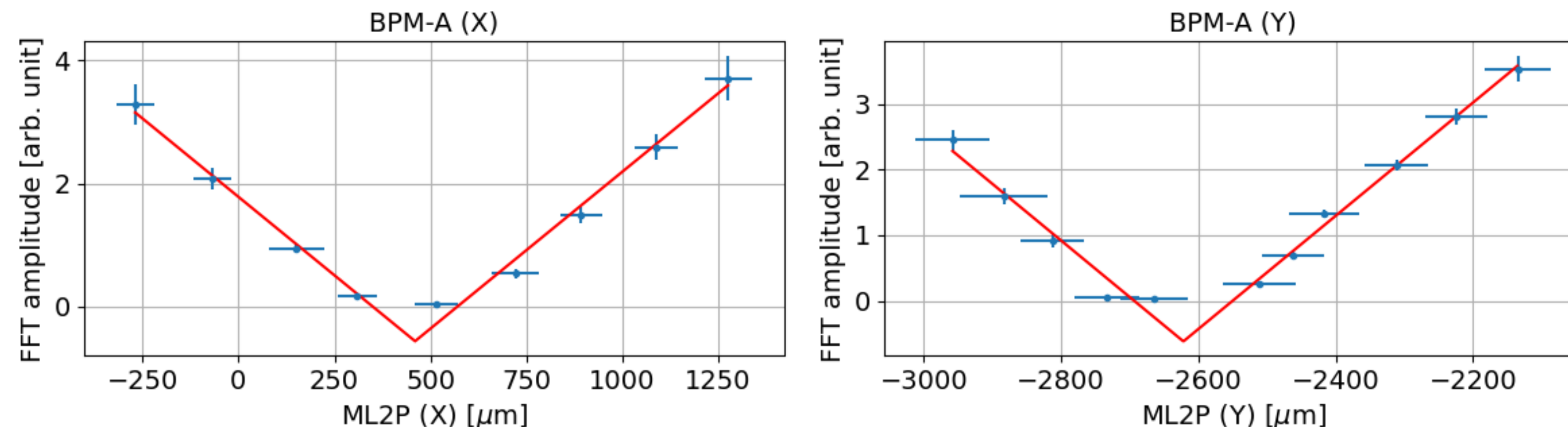
Resolution Measurements of Cavity BPMs

- Calibrations

- Changing the beam orbit by steering magnets
- Referring stripline BPMs for the calibration



- Mapping FFT to x_0 : obtaining $\Delta FFT / \Delta x_0$
 - V-shape appears since the cavity BPM does not know the absolute position of the beam



Resolution Measurements of Cavity BPMs

- Resolution measurements

- Finding a correlation between all channels and the one of interest (k -th channel):

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

$\mathbf{d}_k$: measured positions of the k -th channel

$\mathbf{D}_k$: measured positions not of the k -th channel but of the others

$\mathbf{v}$: correlation coefficients

- Once we get $\mathbf{v}$, predictions of measurements can be made by:

$$\mathbf{d}_k^{\text{pred.}} = \mathbf{D}_k \cdot \mathbf{v}$$

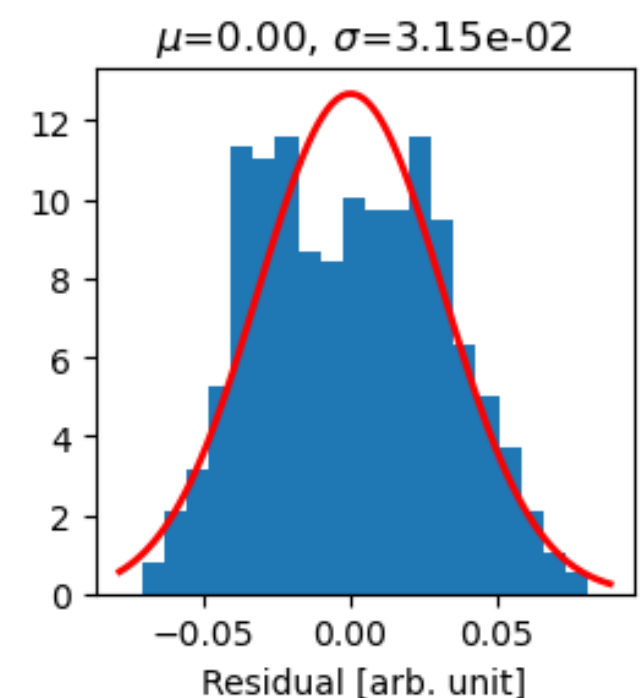
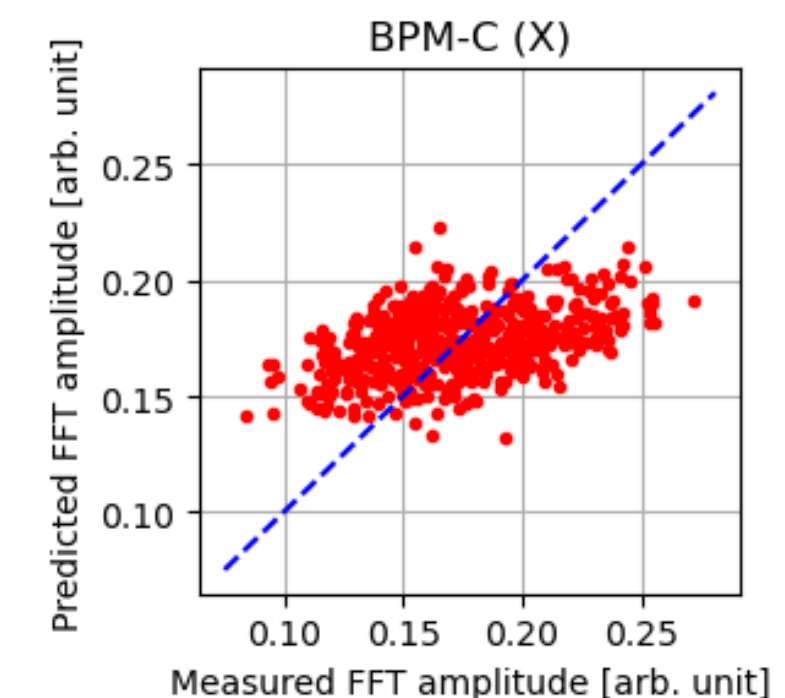
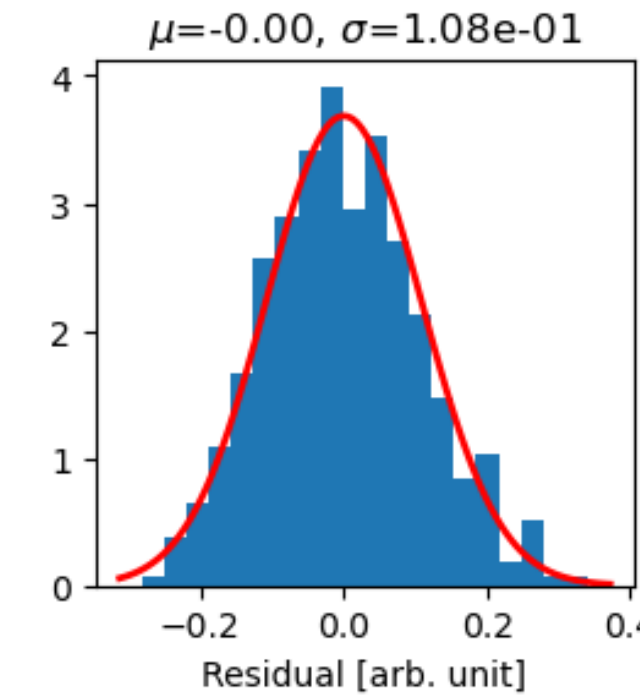
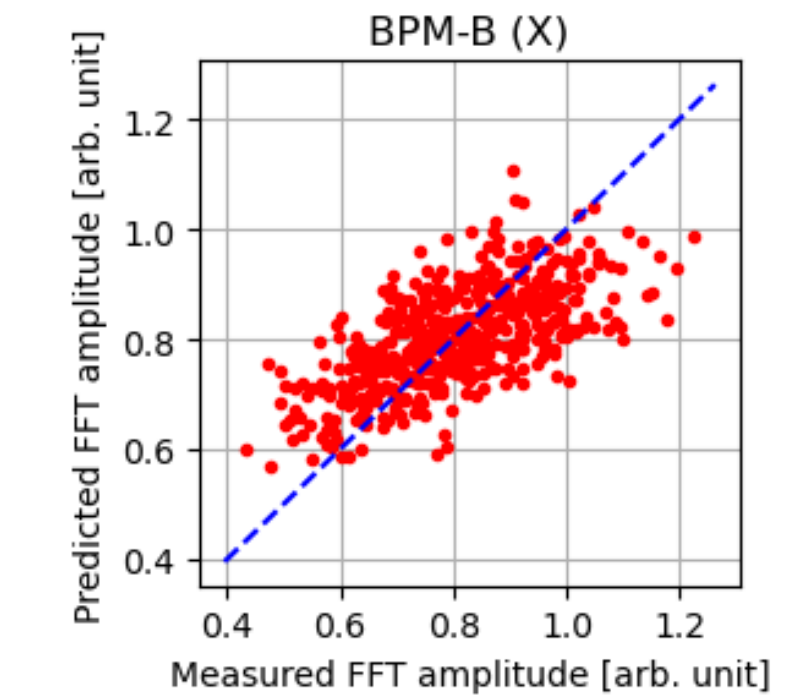
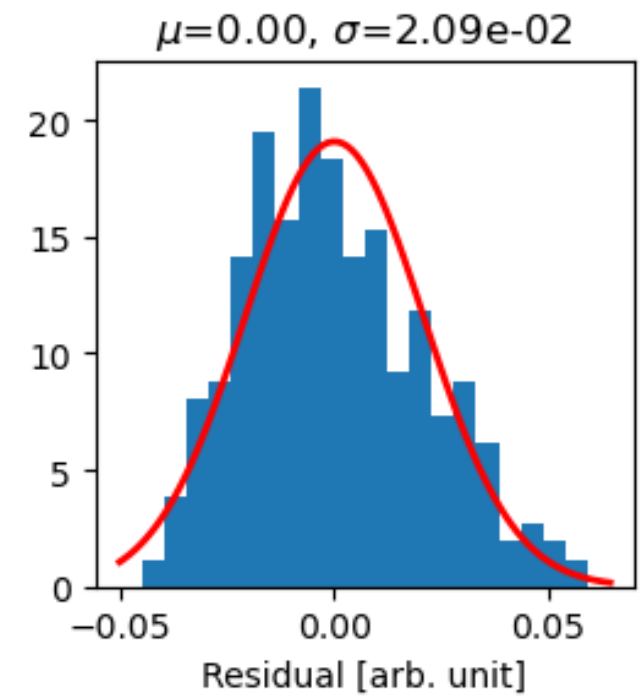
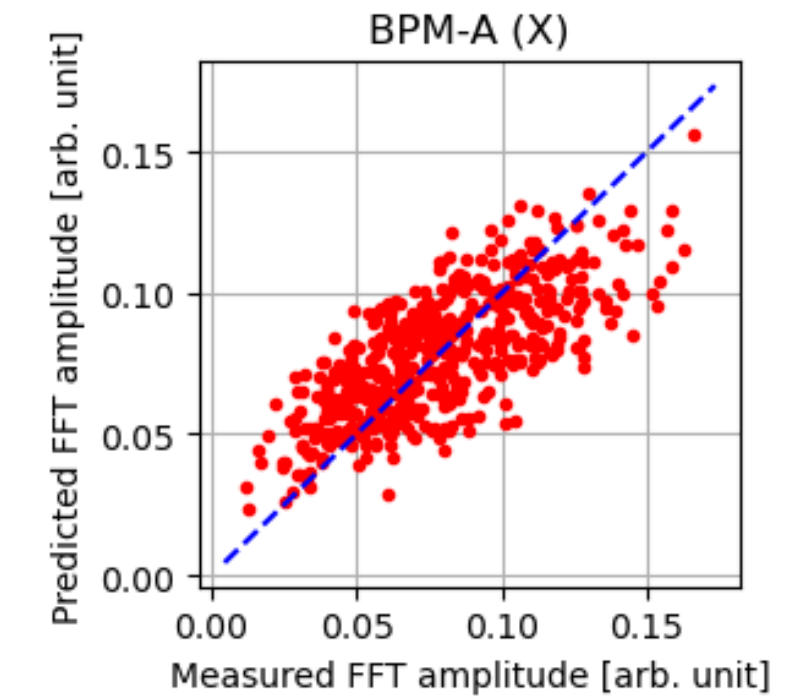
- Singular value decomposition (SVD)

$$\mathbf{D}_k = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T \rightarrow \mathbf{v} = (\mathbf{V}\mathbf{\Sigma}^{-1}\mathbf{U}^T) \cdot \mathbf{d}_k$$

- $\mathbf{d}_k$ is still in FFT amplitude, so it needs to be translated by the calibration factors

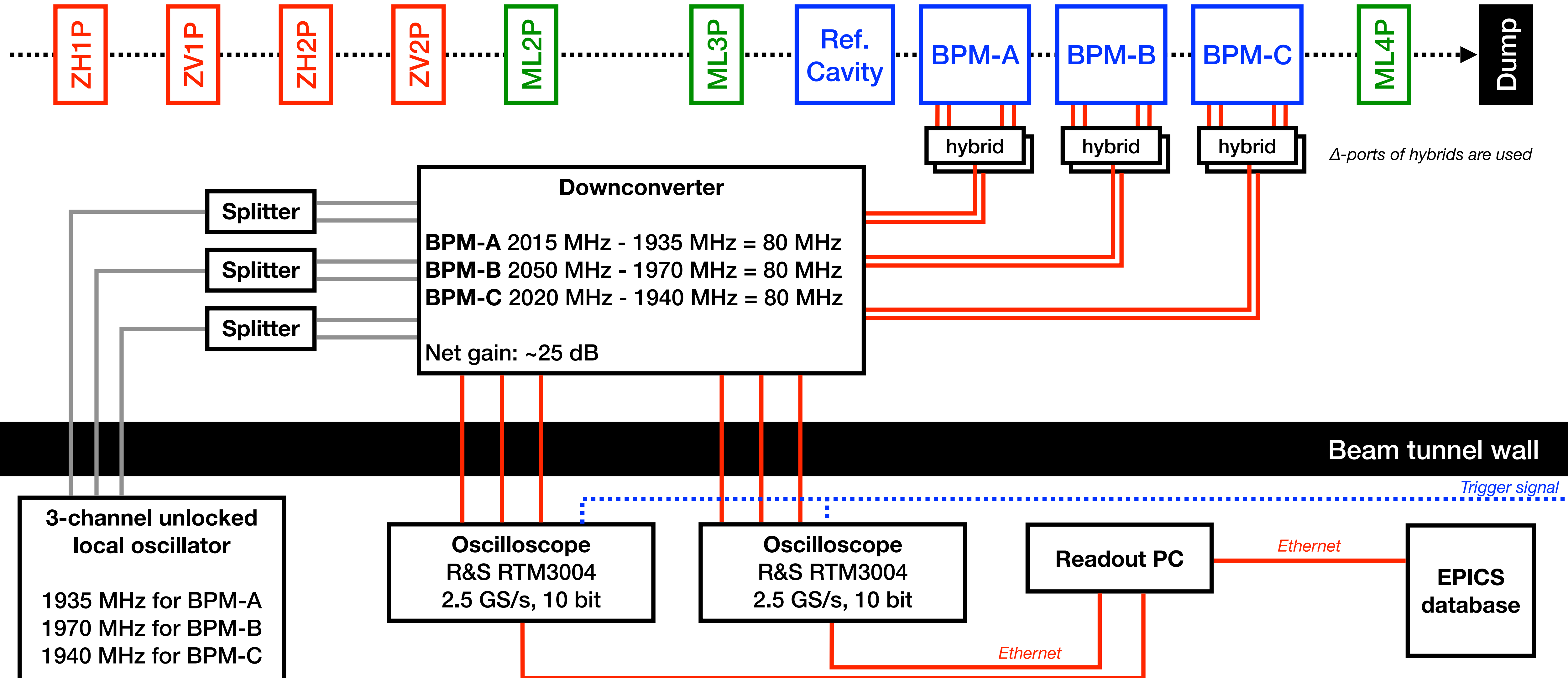
$$\mathbf{d}^{\mu\text{m}} = \mathbf{d}^{\text{FFT}} \cdot \frac{\Delta x_0}{\Delta \text{FFT}}$$

- From the residual ($\mathbf{R} \equiv \mathbf{d}_k^{\text{pred.}} - \mathbf{d}_k^{\text{meas.}}$), the resolutions (σ) are obtained

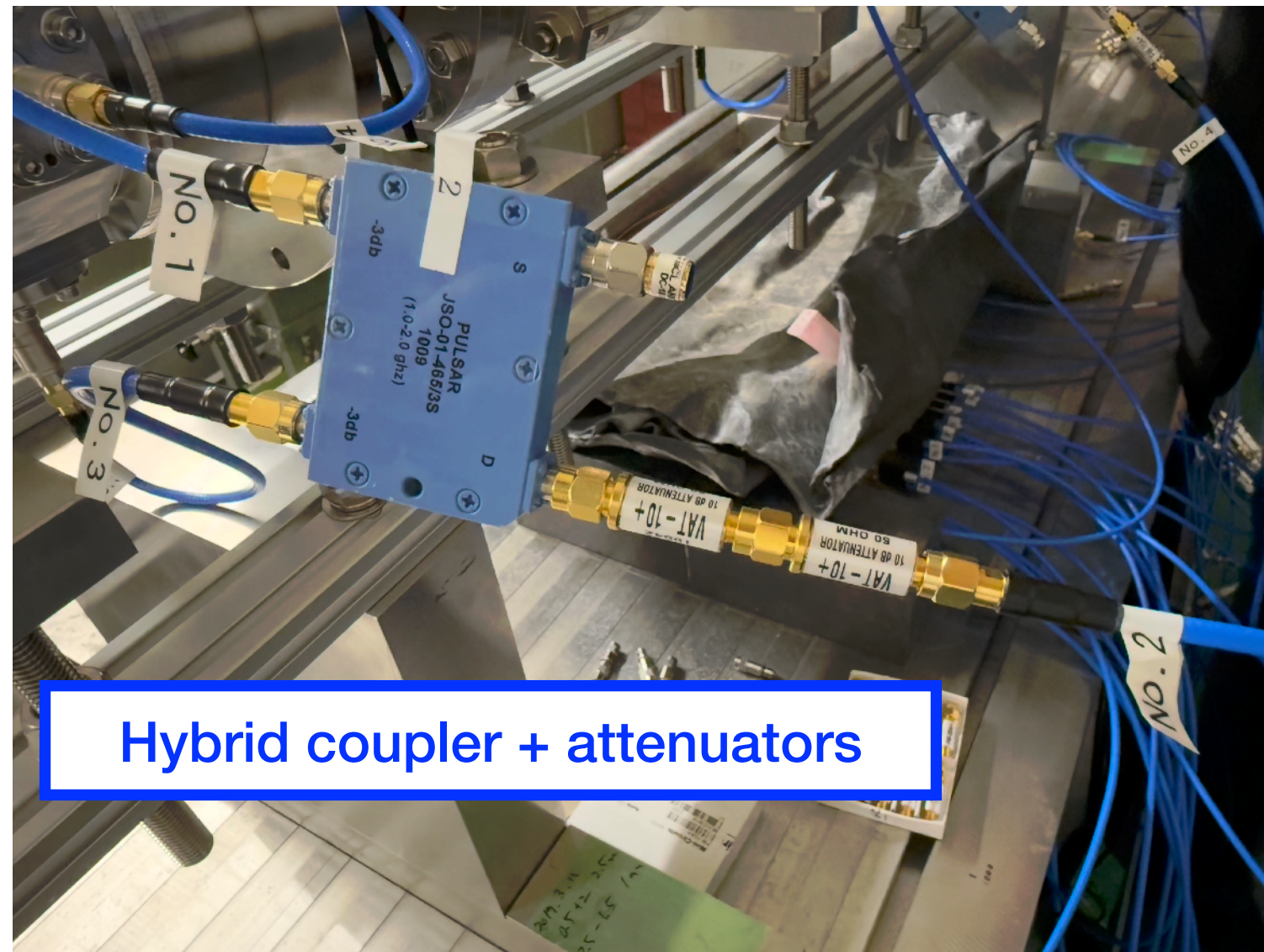


L-band Cavity BPM Readouts

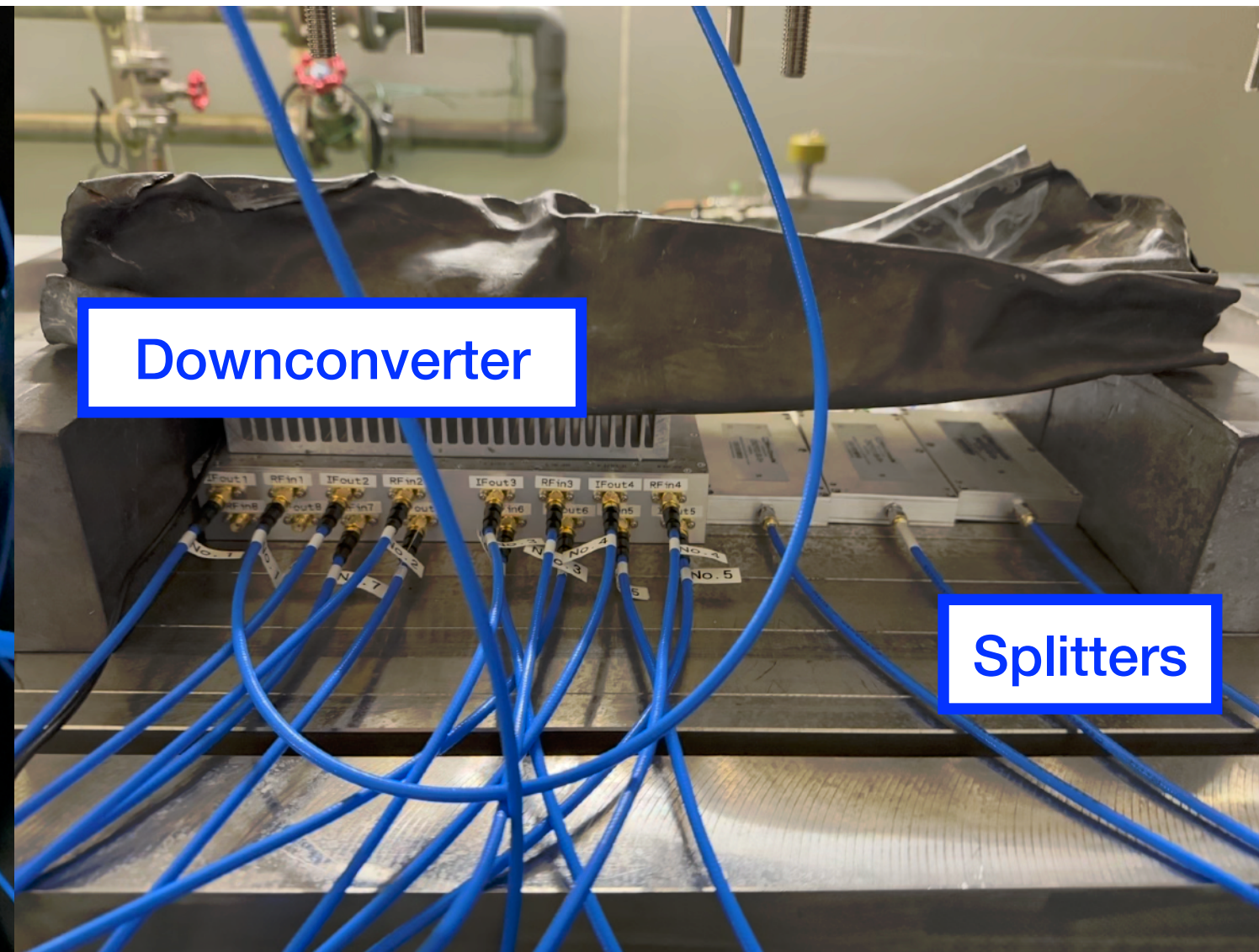
- Signals are merged by hybrid couplers and pass through a downconverter



L-band Cavity BPM Readouts (inside the tunnel)

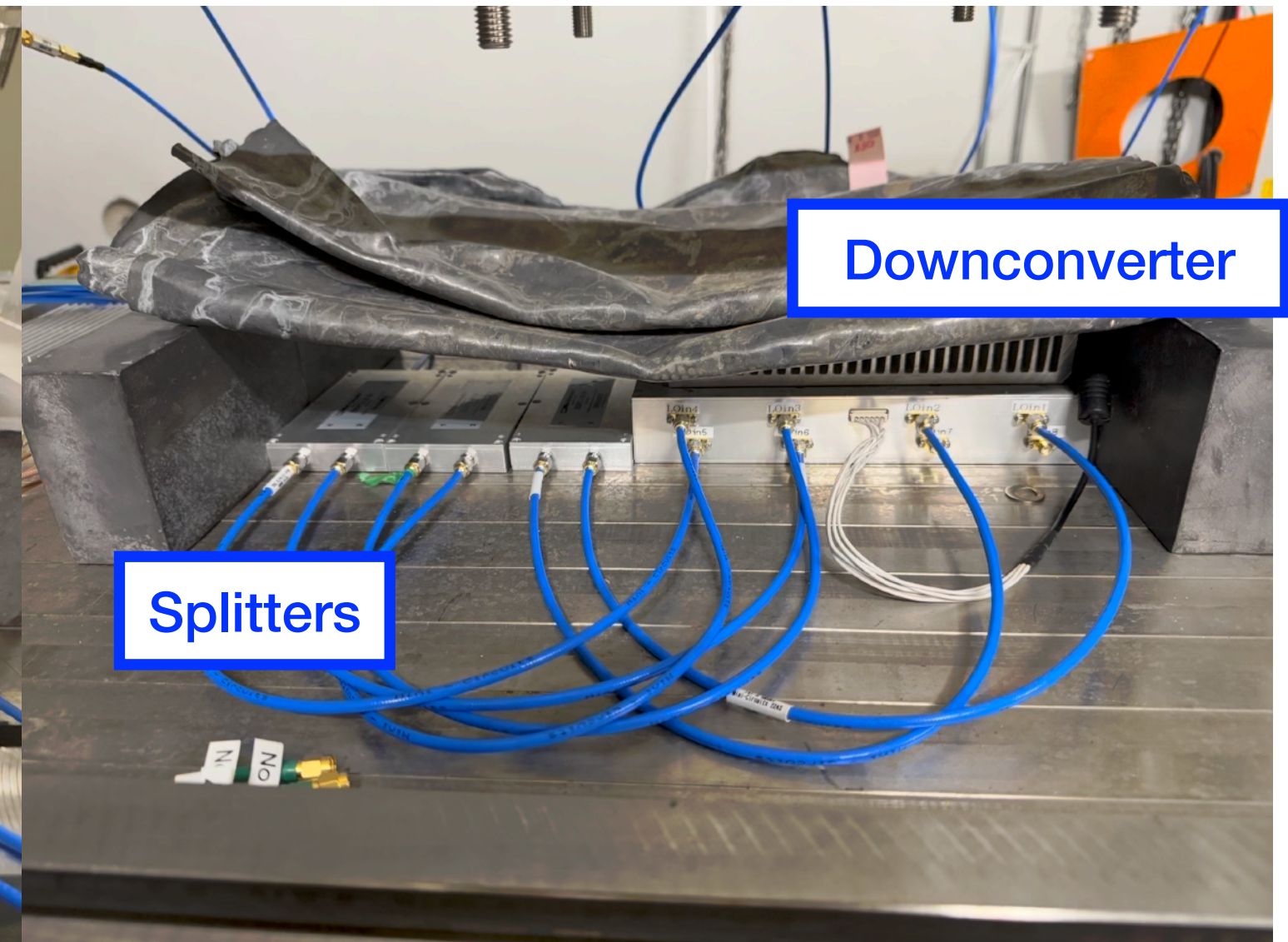


Hybrid coupler + attenuators



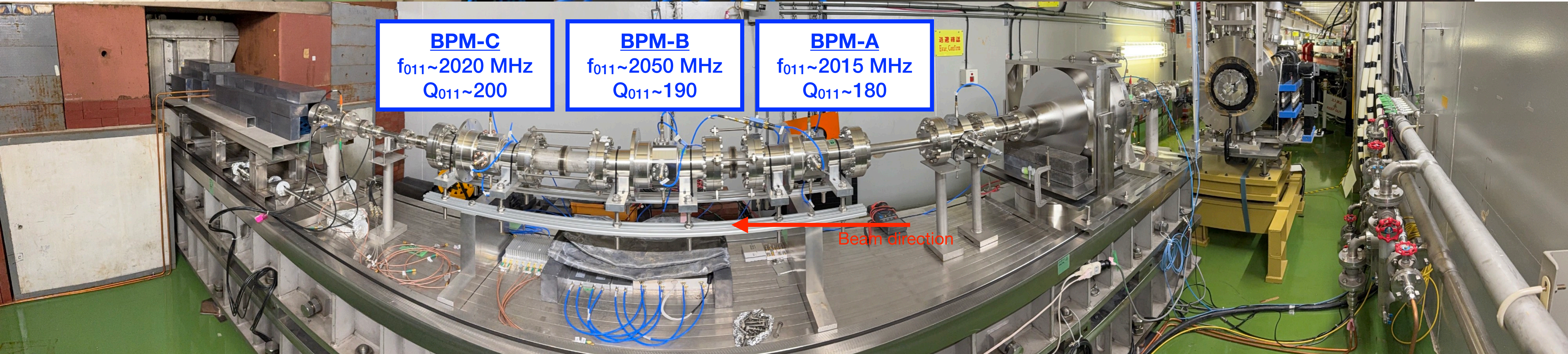
Downconverter

Splitters



Downconverter

Splitters



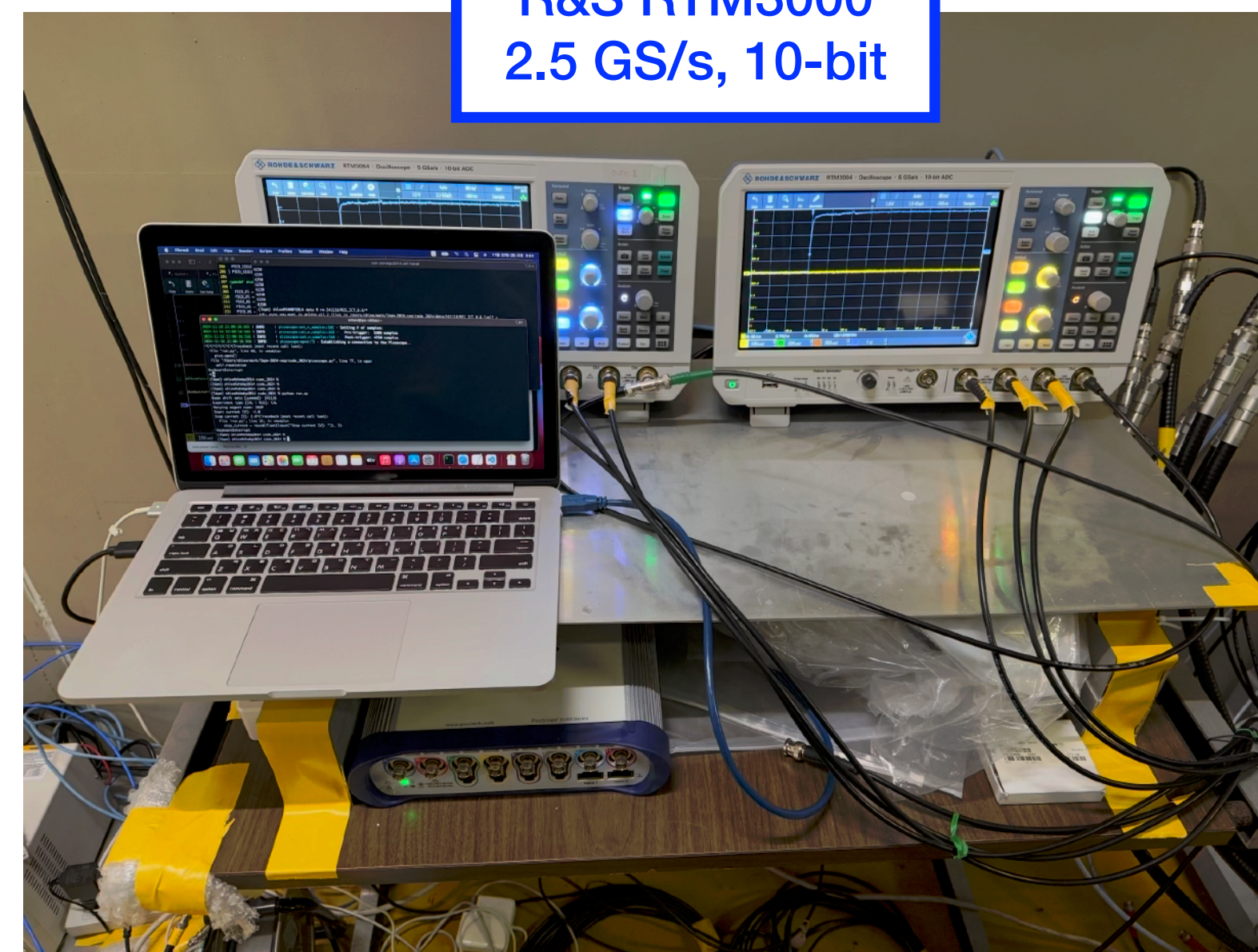
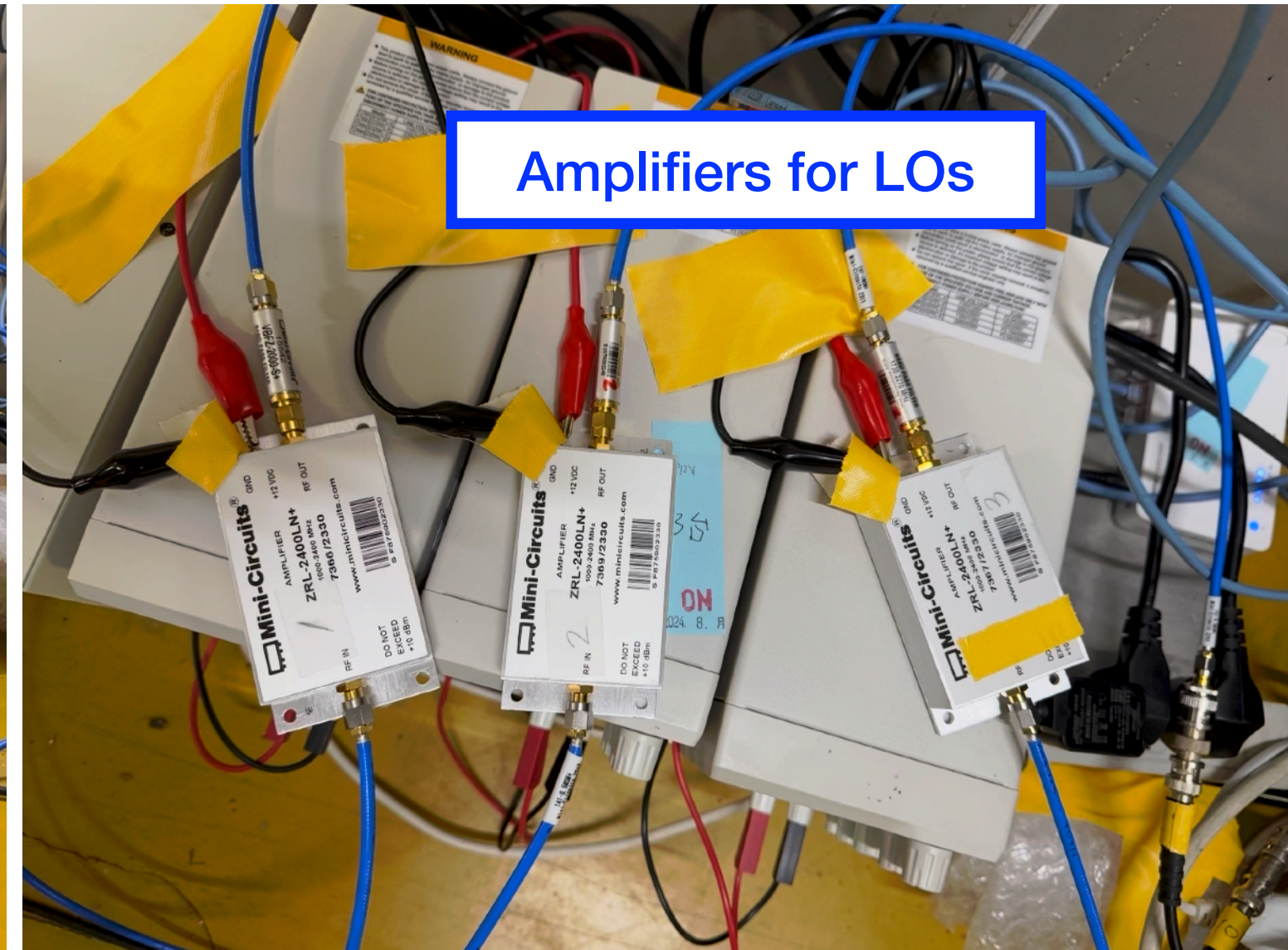
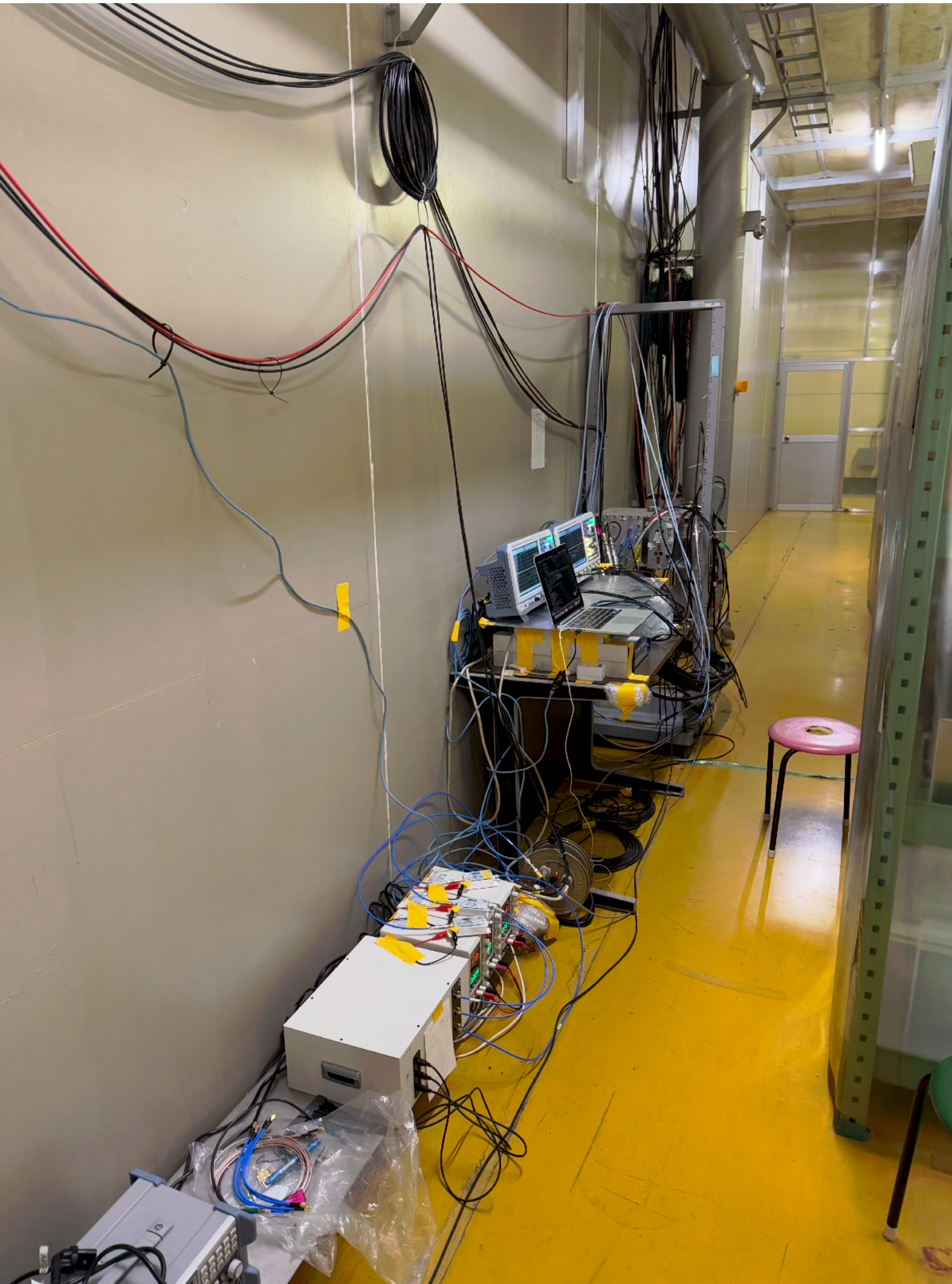
BPM-C
 $f_{011} \sim 2020$ MHz
 $Q_{011} \sim 200$

BPM-B
 $f_{011} \sim 2050$ MHz
 $Q_{011} \sim 190$

BPM-A
 $f_{011} \sim 2015$ MHz
 $Q_{011} \sim 180$

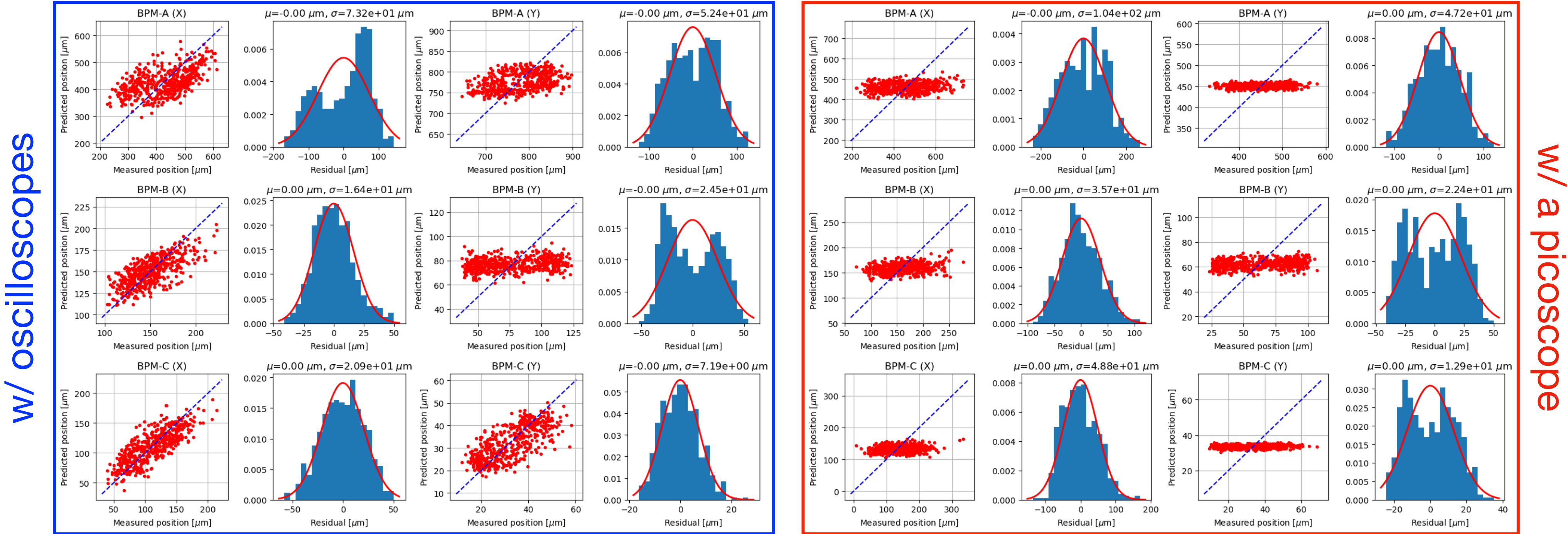
Beam direction

L-band Cavity BPM Readouts (outside the tunnel)



Resolution Measurements in the Past

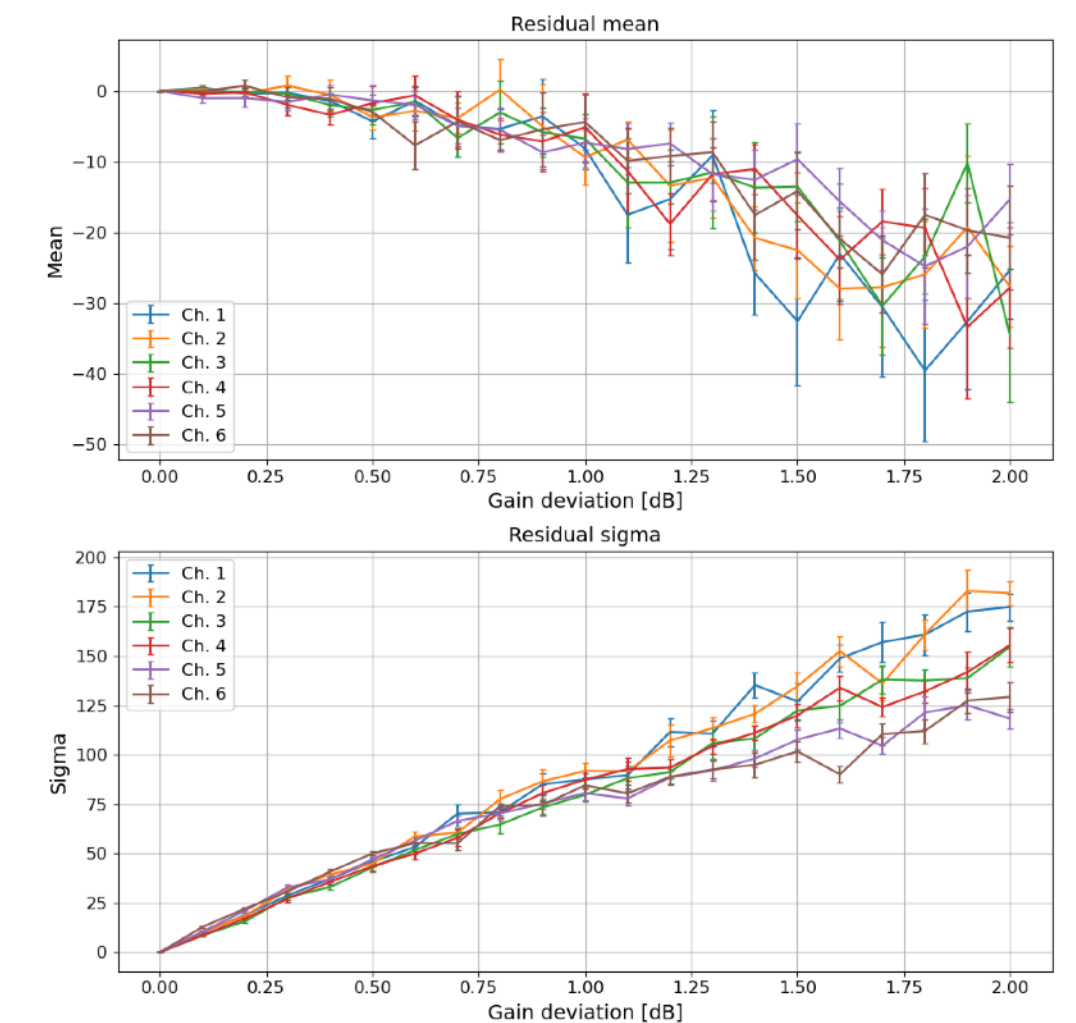
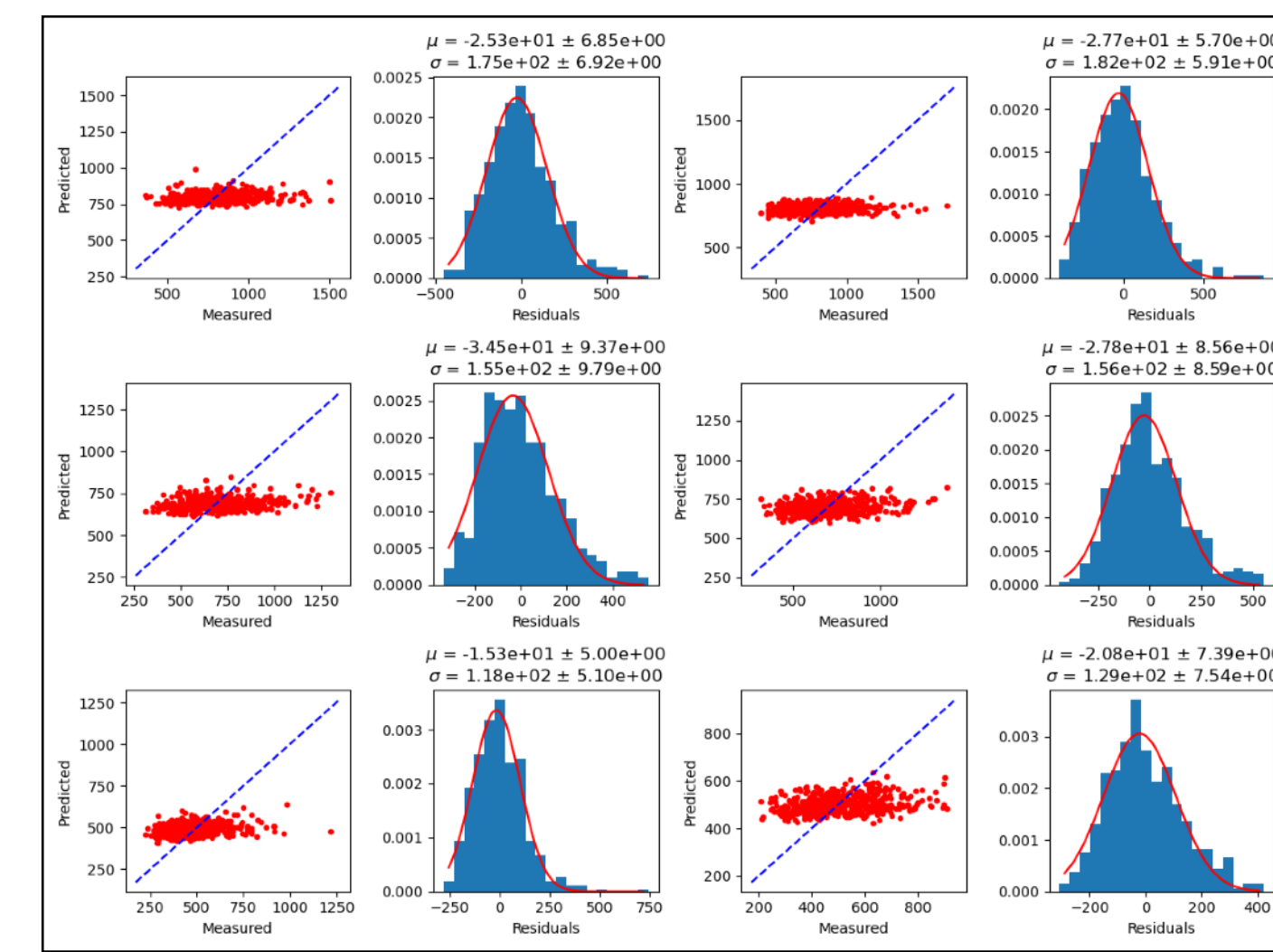
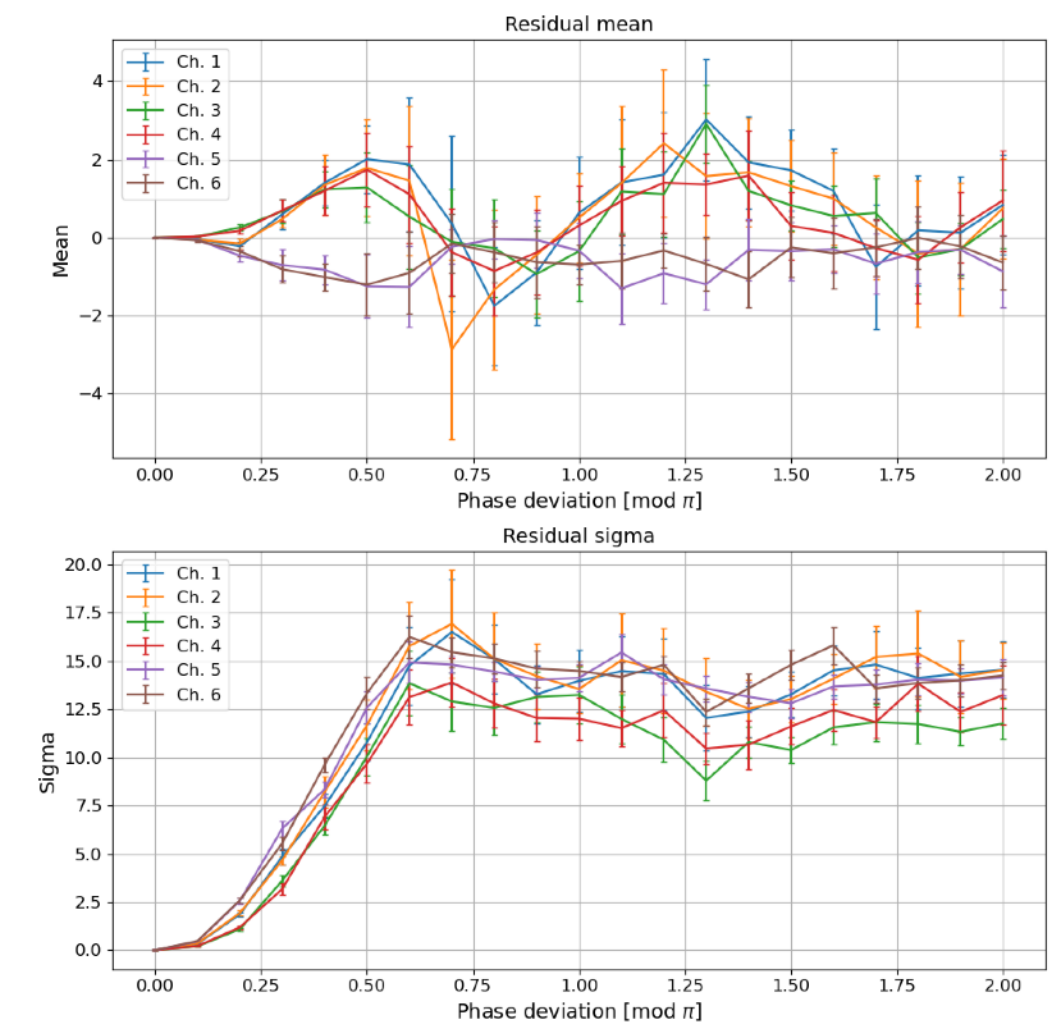
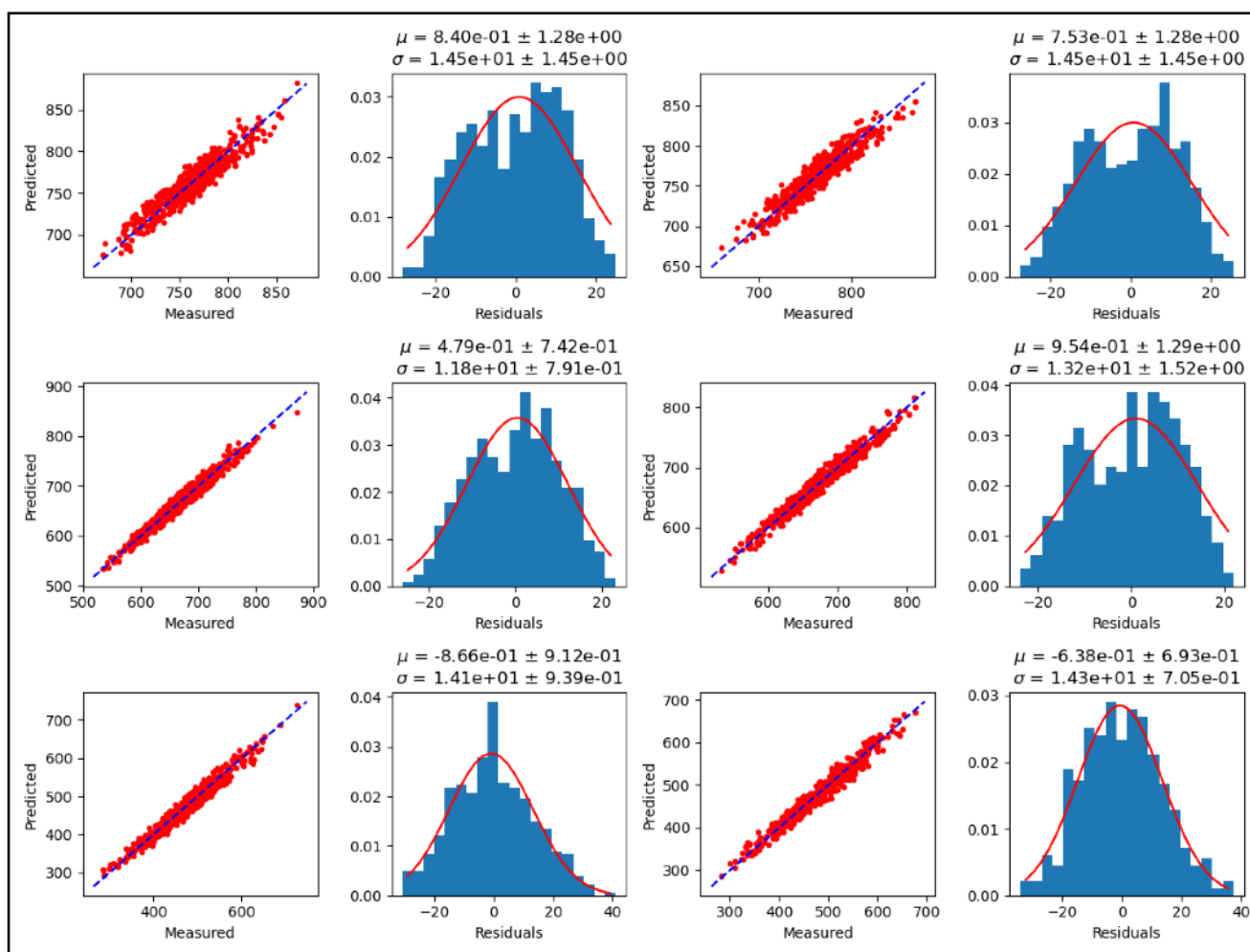
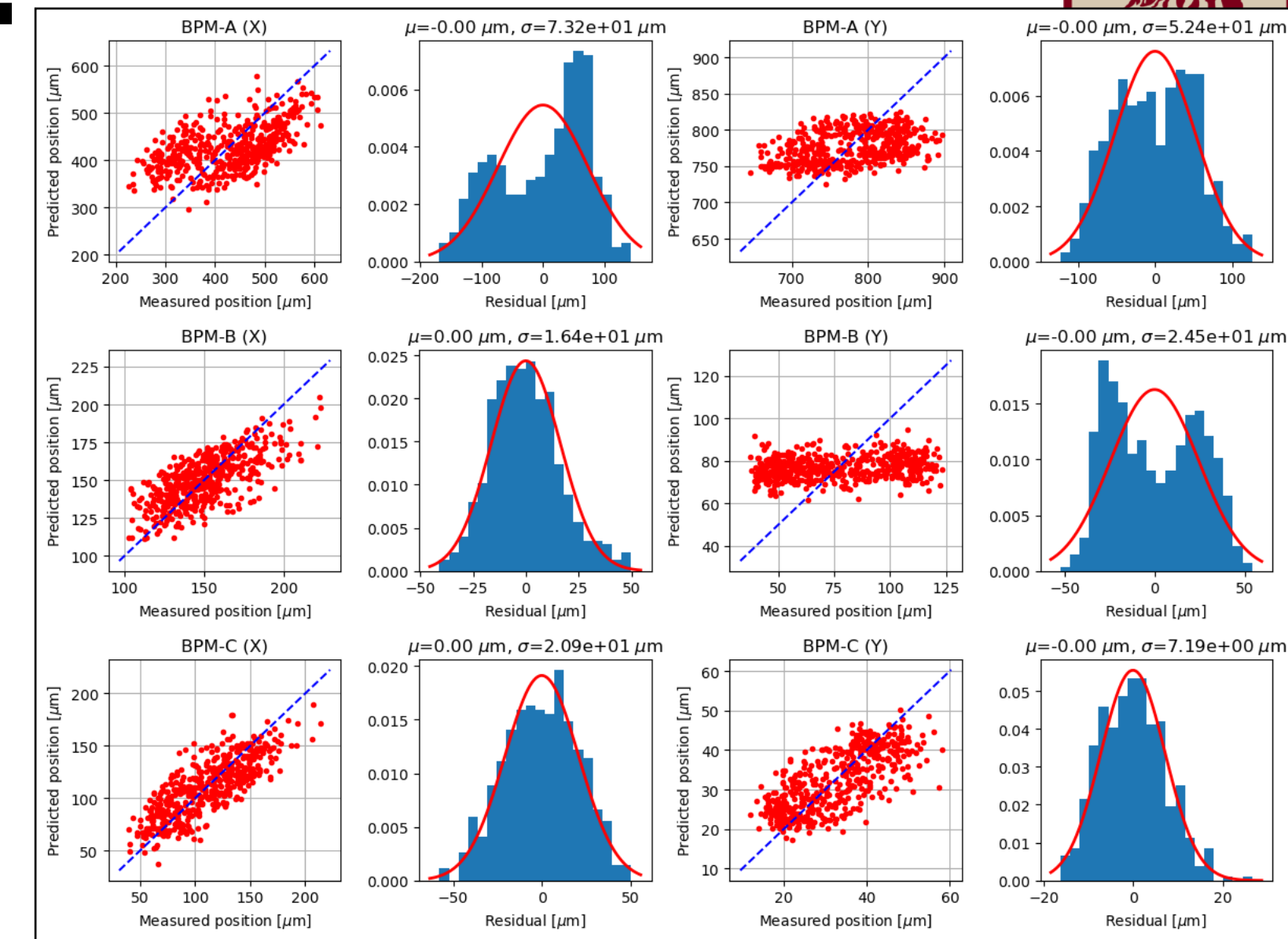
- Very problematic correlations, poorer resolutions compared to the measurement in 2023



[nm]	2019	2023	2024 (w/ osc.'s)	2024 (w/ pico.)
BPM-A (X)	3750	2062	2033	3068
BPM-B (X)	2680	1984	824	1904
BPM-C (X)	985	1831	470	1167
BPM-A (Y)	698	3450	1457	1392
BPM-B (Y)	2260	1948	1234	1198
BPM-C (Y)	324	712	162	309

Problems and Solutions in 2024

- Apparent Problems:
 - Broken linearity in SVD analysis → Unstable gain of channel(s)
 - Two peaks in the residual distributions → Unlocked LO
 - Those effects are confirmed with simulations
- (ad-hoc) solutions:
 - Combining signals and processing through a common path
 - Same gain fluctuation, same unlocked LO

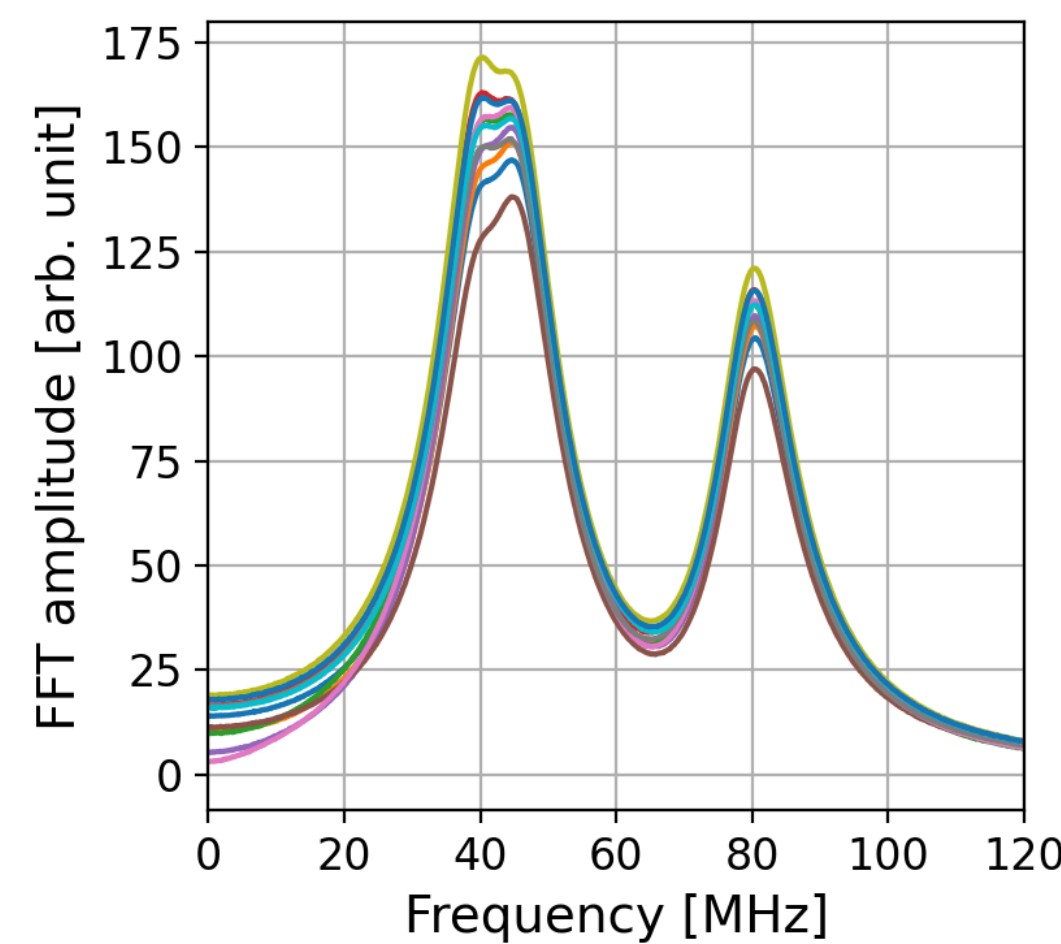
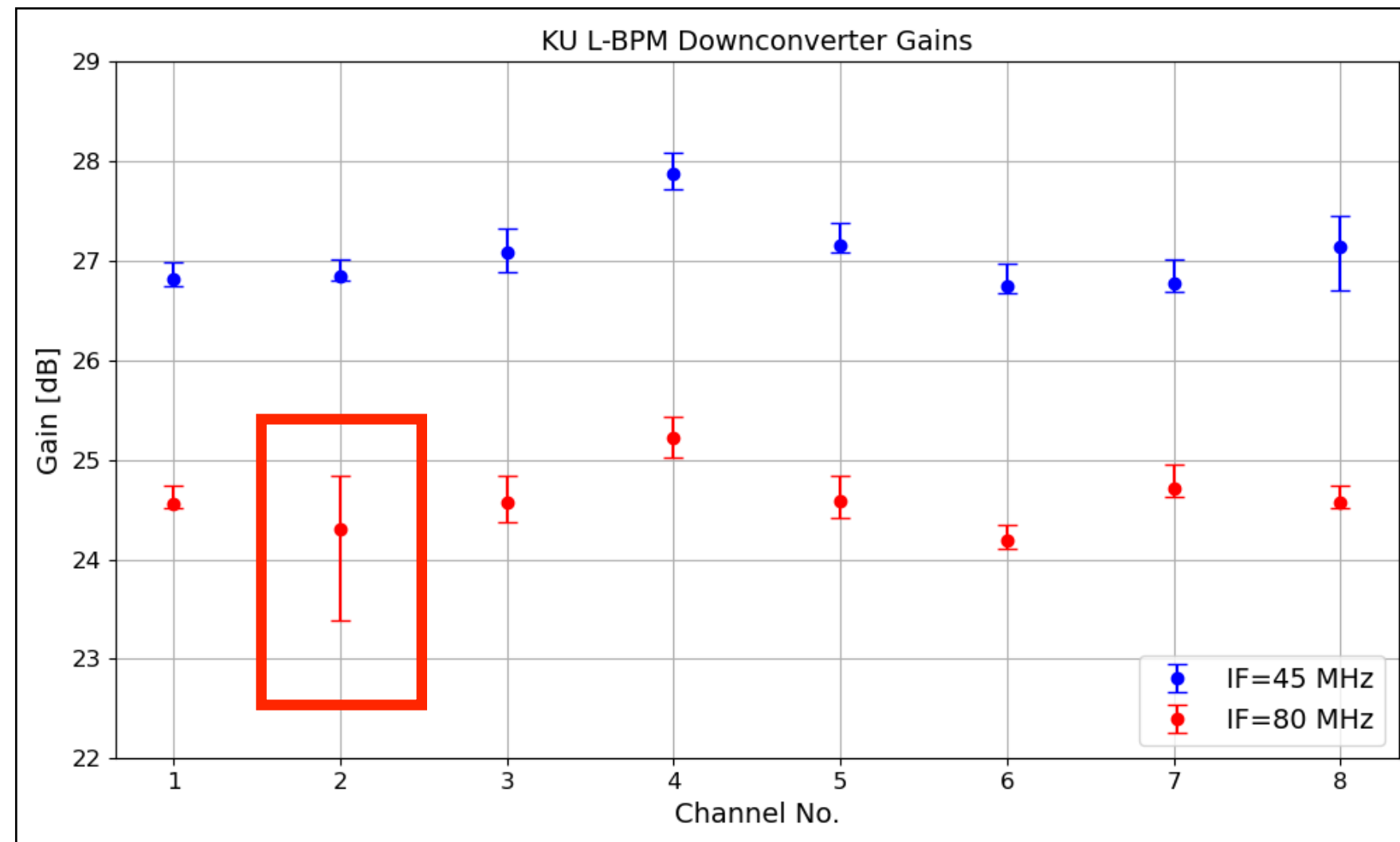
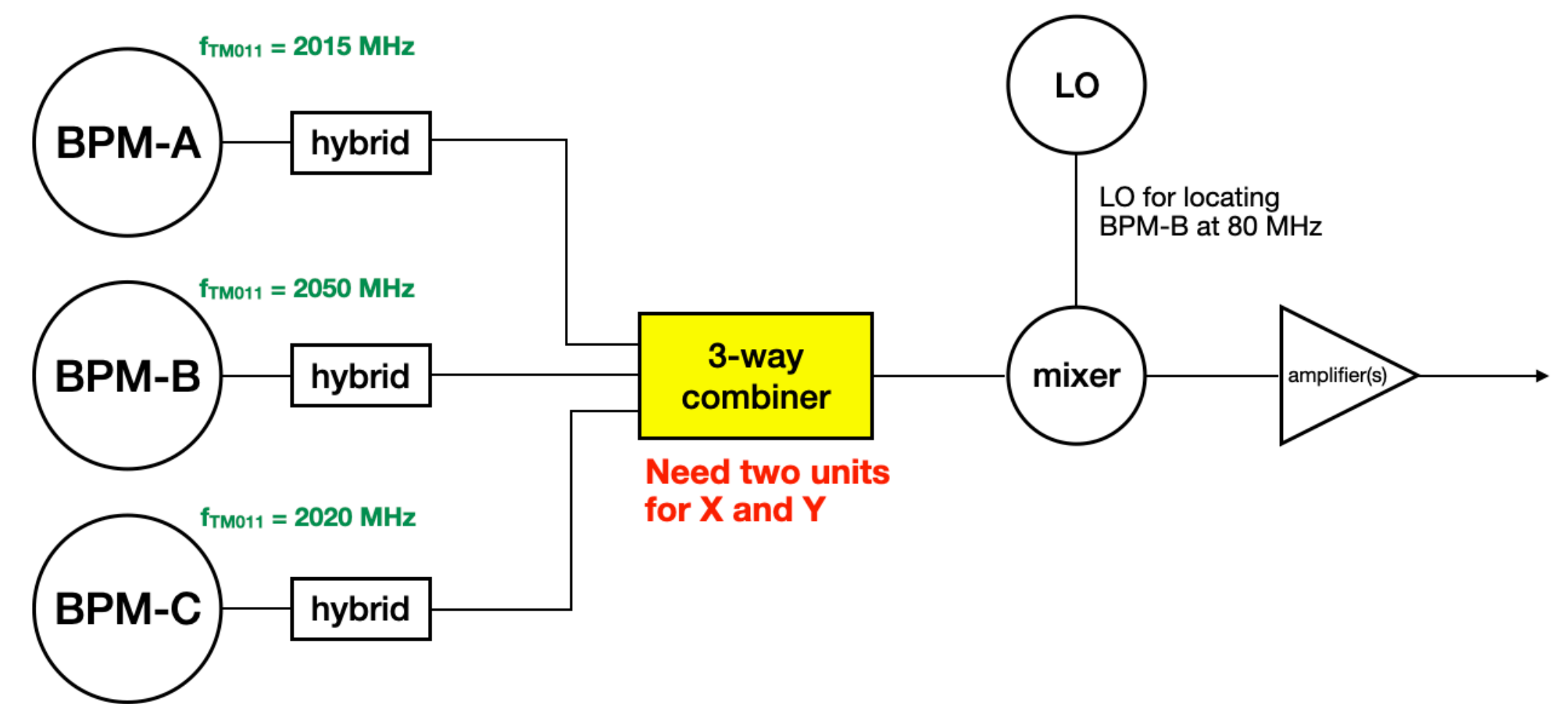


(Simulation) Phase randomly fluctuating up to 2π for all channels

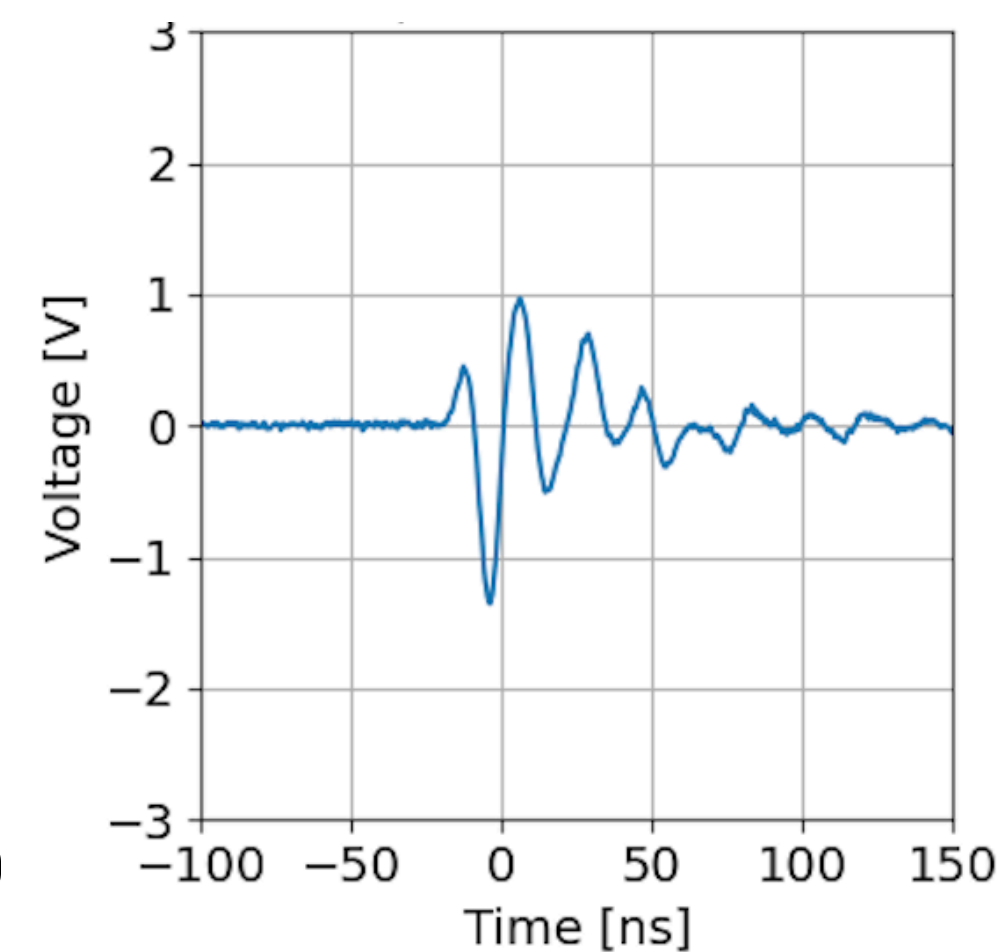
(Simulation) Gain randomly fluctuating up to 2 dB for all channels

Resolution Measurements in 2025

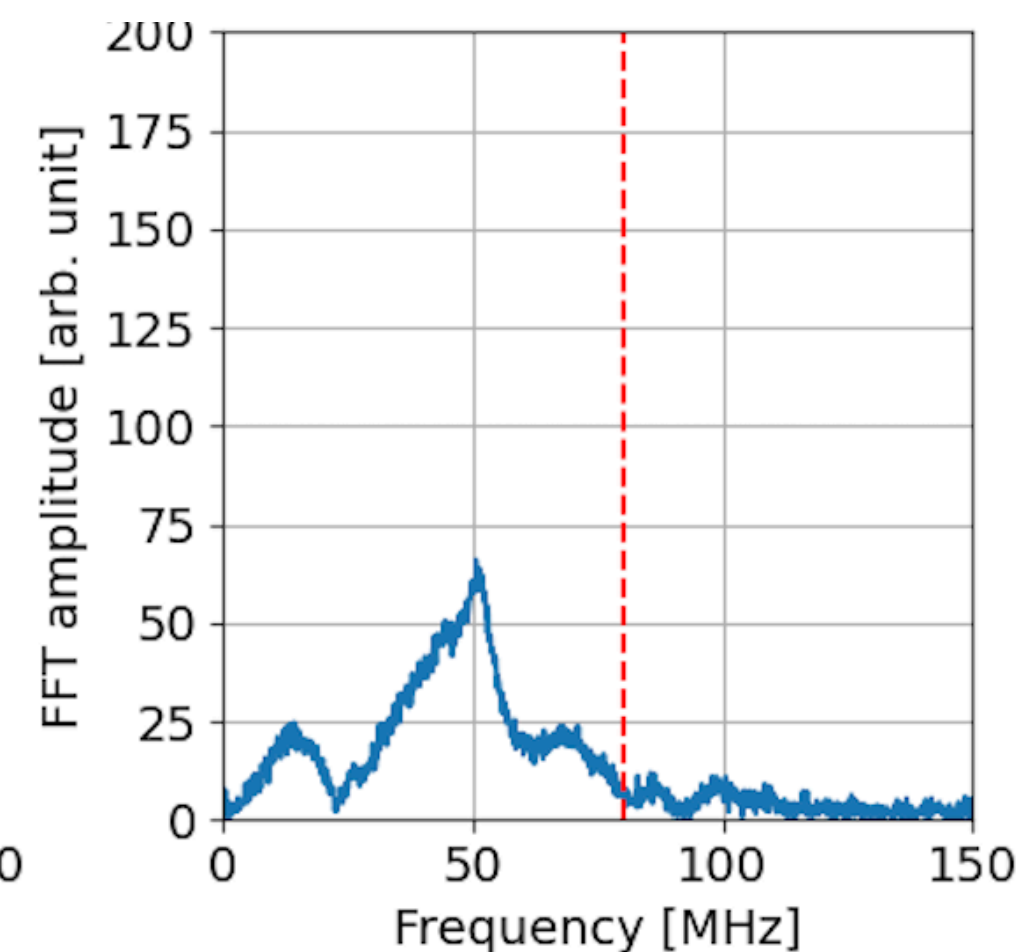
- Confirmed an instability of an RF channel
 - Better RF characteristics found at IF=45 MHz
- Combining signals didn't work very well
- Alternatives:
 - Using IF=45 MHz instead of 80 MHz
 - Common LO so different IF's



Expected (simulation)

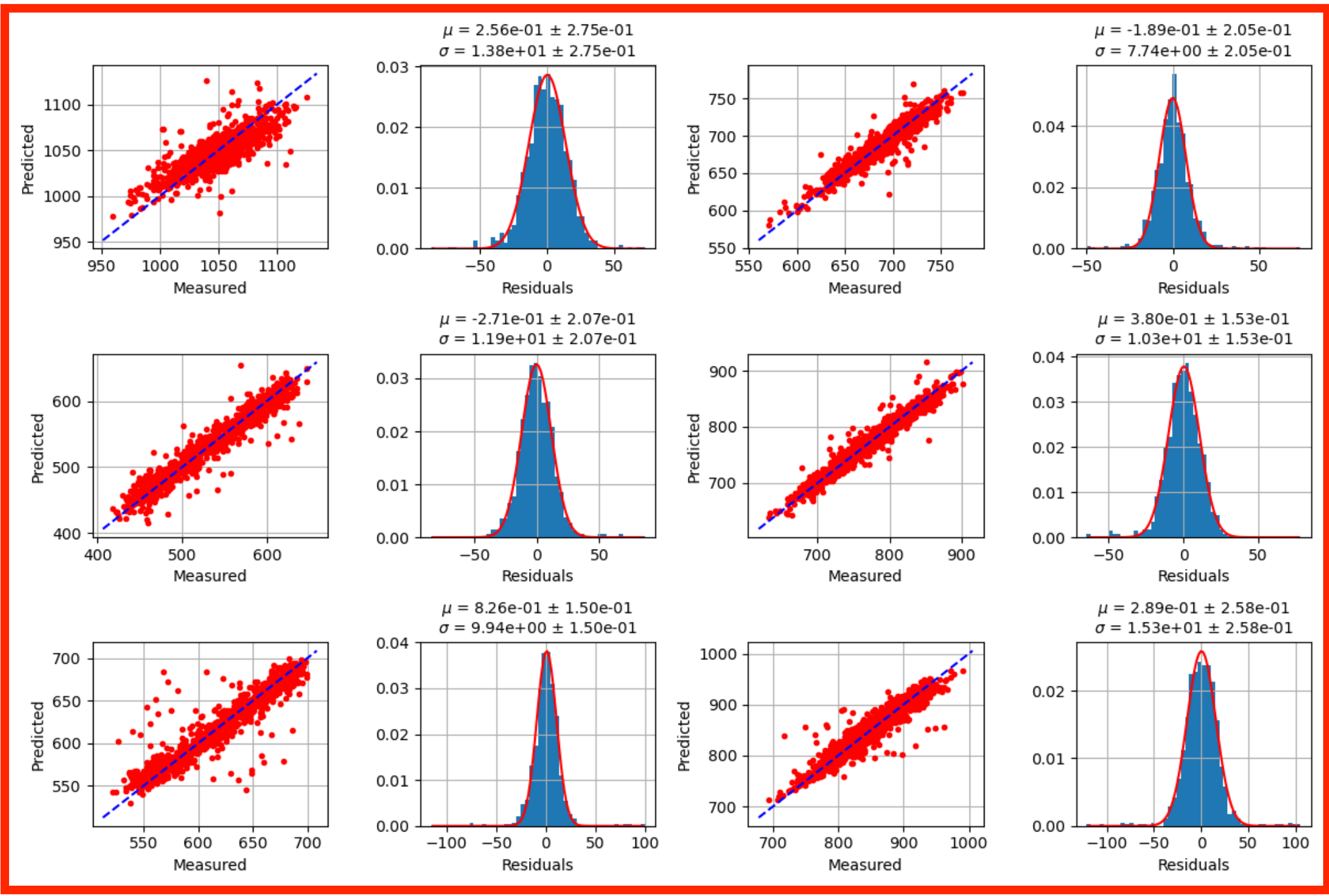
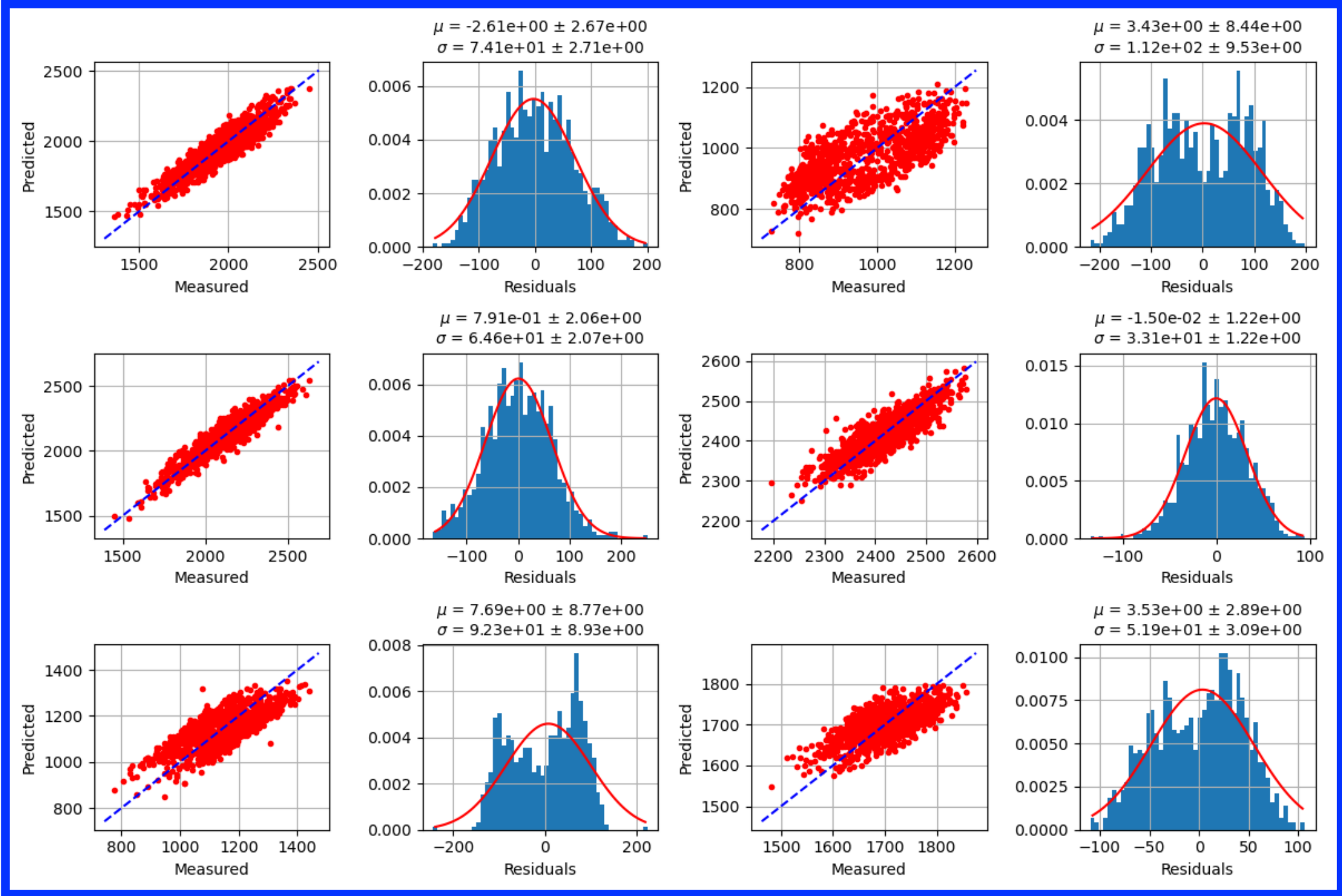


Measurement in 2025



Resolution Measurements in 2025

- IF=45 MHz with 3 different LO's | Different IF's with a common LO

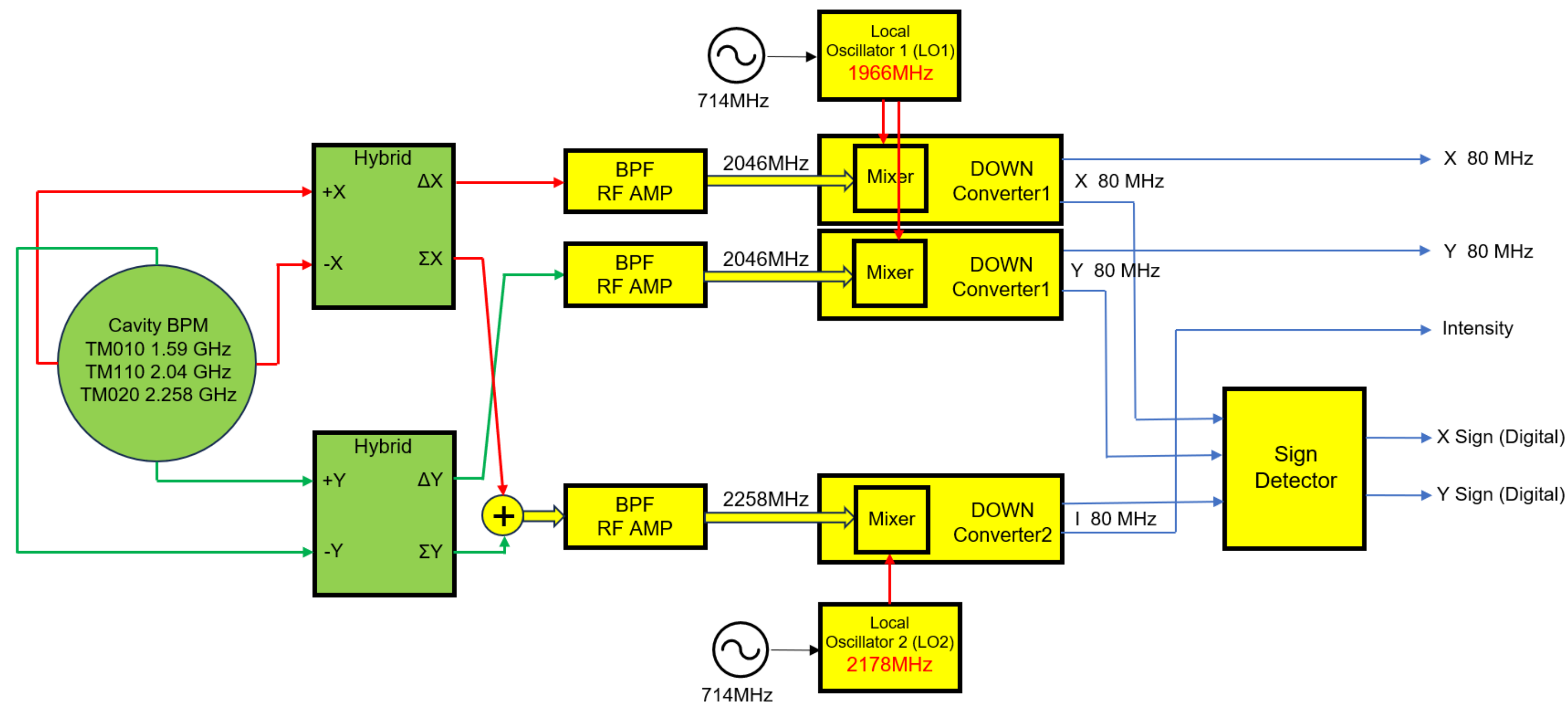


[nm]	2019	2023	2024 (w/ osc.'s)	2024 (w/ pico.)	2025 (IF=45 MHz)	2025 (Common LO)
BPM-A (X)	3750	2062	2033	3068	1372	731
BPM-B (X)	2680	1984	824	1904	1933	1123
BPM-C (X)	985	1831	470	1167	1927	383
BPM-A (Y)	698	3450	1457	1392	1716	317
BPM-B (Y)	2260	1948	1234	1198	695	902
BPM-C (Y)	324	712	162	309	767	485

Further Developments

- Implementation of a new electronics including:
 - Stable gain, phase-locked LO
 - Better horizontal (> 2.5 GSPS) and vertical (> 12 bit) resolutions
 - Sign detector for absolute position measurements

L-Band BPM Block Diagram



Applications for the CEPC



- We may offer an alternative for IP-BPM of CEPC

- ▶ Beam size at IP: $\sigma_x \sim 10 \mu\text{m}$, $\sigma_y \sim 40 \text{ nm}$
- ▶ Due to the space, it would be a C-band ($\sim 6 \text{ GHz}$) cavity BPM
- ▶ nanometer-scale resolution would be achievable

- Adding features of virtual diagnostics would be also considered

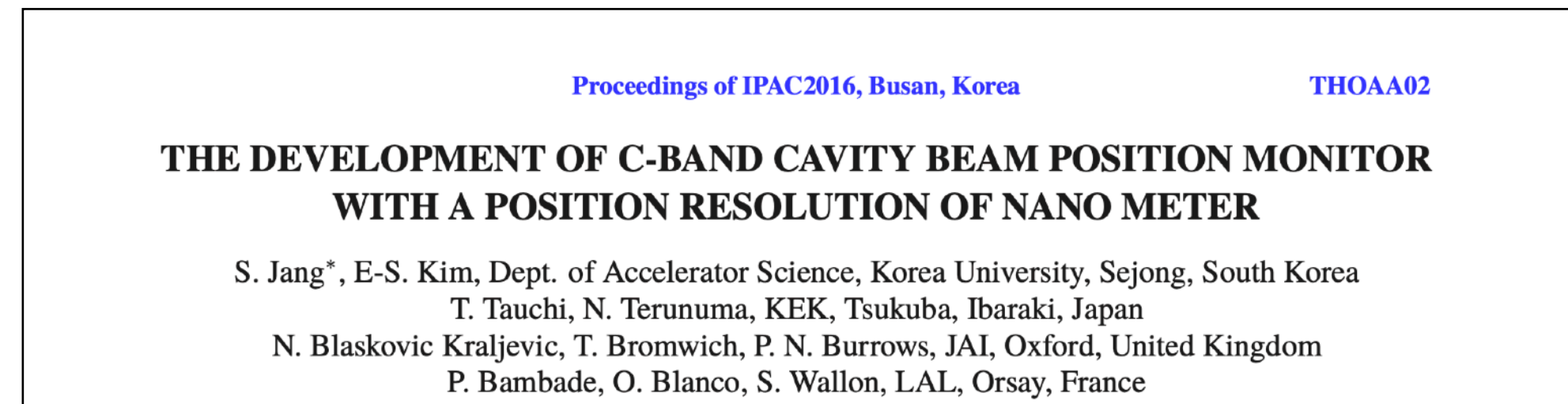
- ▶ Bunch length, arrival time, and so on

- Your consideration would be greatly appreciated!

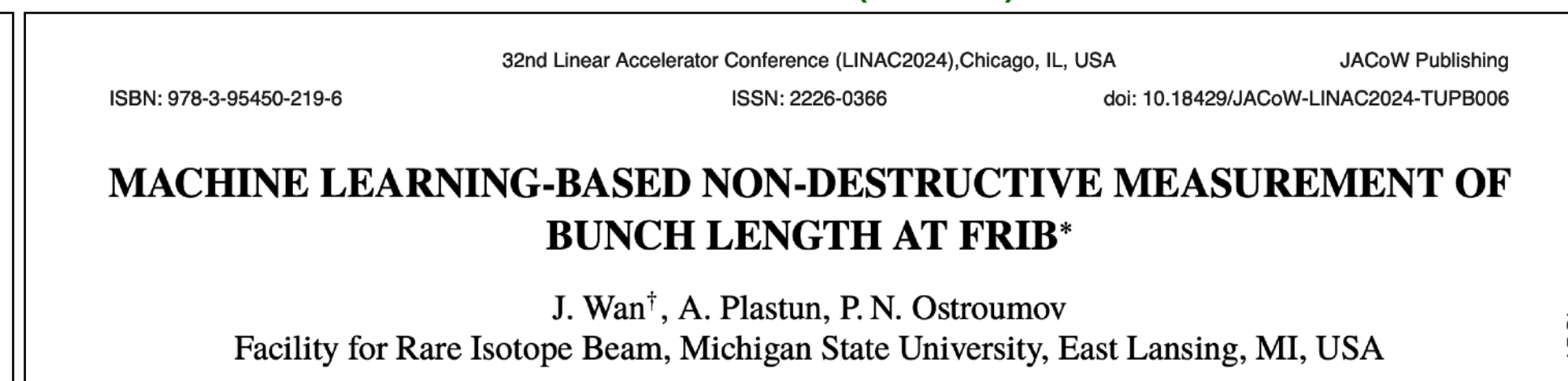
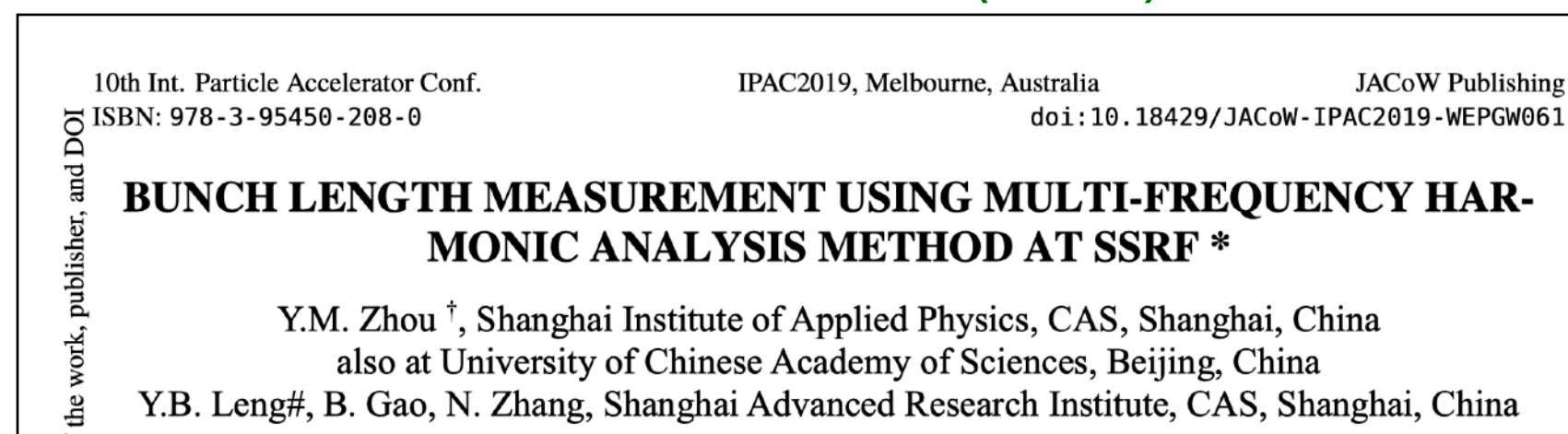
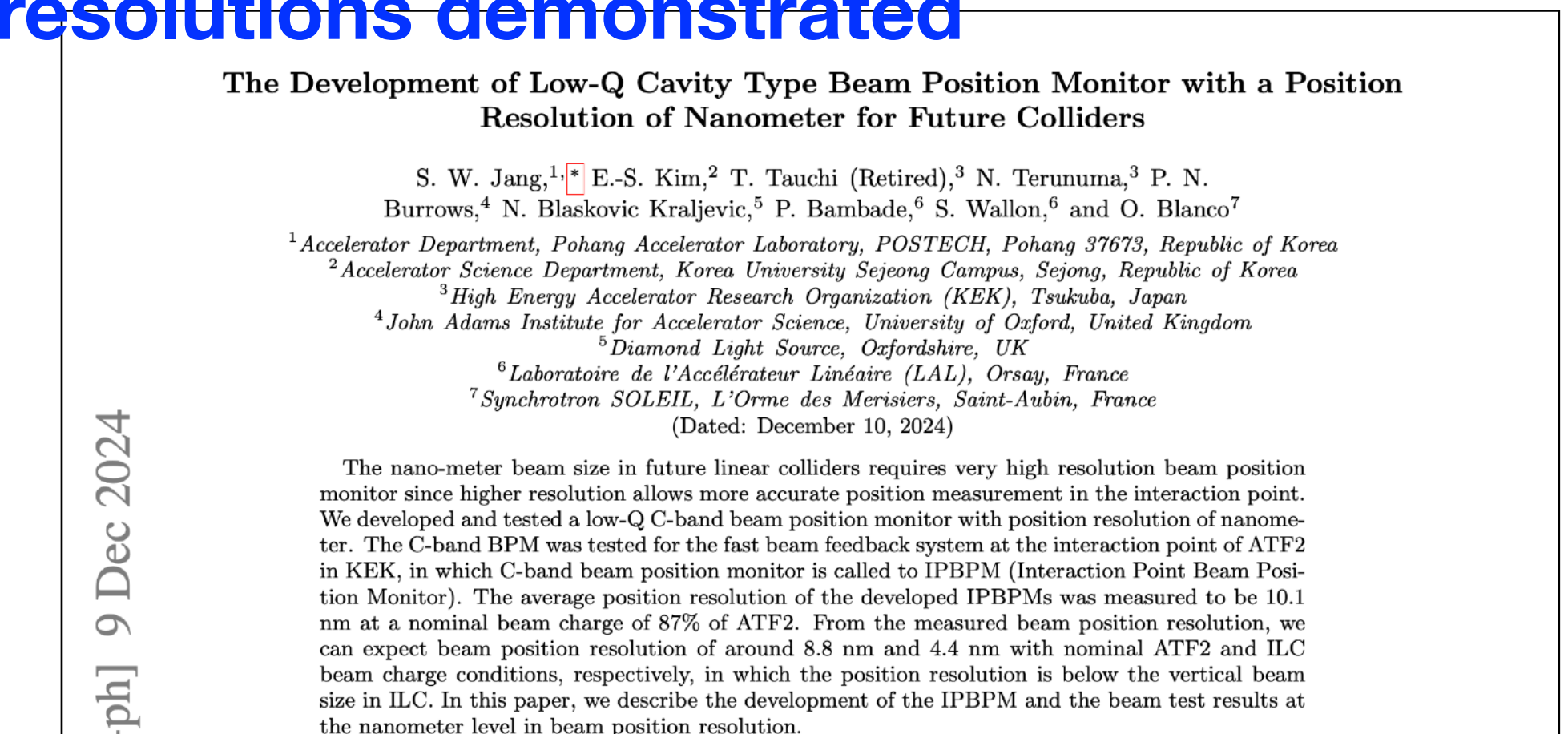
Y. M. Zhou et al. (2019)

J. Wan et al. (2024)

S. Jang et al., (2024)



~9 nm position resolutions demonstrated



Summary

- KU is working on L-band cavity BPM for ILC main LINAC
 - Sub- μm position resolution is targeted
 - Three L-band cavity BPMs are located at KEK-ATF for tests
- Resolution measurements are in progress
 - Better and better resolutions with small improvements in measurements
 - Achieving ~ 300 nm resolution at best
 - Further improvements would reach much better resolutions
 - Also trying to add more features (sign detection, virtual diagnostics, ...)
- We'd like to offer an alternative for IP-BPM of CEPC
 - C-band (~ 6 GHz) cavity BPM would offer nm-scale resolution

Backup

ILC Main LINAC Parameters

<i>Cavity (nine-cell TESLA elliptical shape)</i>		
Average accelerating gradient	31.5	MV/m
Quality factor Q_0	10^{10}	
Effective length	1.038	m
R/Q	1036	Ω
Accepted operational gradient spread	$\pm 20\%$	
<i>Cryomodule</i>		
Total slot length	12.652	m
Type A	9 cavities	
Type B	8 cavities	1 SC quad package
<i>ML unit (half FODO cell)</i>	282 (285)	units
<i>(Type A - Type B - Type A)</i>		
<i>Total component counts</i>		
Cryomodule Type A	564 (570)	
Cryomodule Type B	282 (285)	
Nine-cell cavities	7332 (7410)	
SC quadrupole package	282 (285)	
Total linac length – flat top.	11027 (11141)	m
Total linac length – mountain top.	11072 (11188)	m
Effective average accelerating gradient	21.3	MV/m
<i>RF requirements (for average gradient)</i>		
Beam current	5.8	mA
beam (peak) power per cavity	190	kW
Matched loaded Q (Q_L)	5.4×10^6	
Cavity fill time	924	μs
Beam pulse length	727	μs
Total RF pulse length	1650	μs
RF–beam power efficiency	44%	

Parameter	Value	Unit
Initial beam energy	15	GeV
Final (max.) beam energy	250	GeV
Particles per bunch	2.0×10^{10}	
Beam current	5.8	mA
Bunch spacing	554	ns
Bunch train length	727	μs
Number of bunches	1312	
Pulse repetition rate	5	Hz
Initial $\gamma\epsilon_x$	8.4	μm
Final $\gamma\epsilon_x^\dagger$	9.4	μm
Initial $\gamma\epsilon_y$	24	nm
Final $\gamma\epsilon_y^\dagger$	30	nm
σ_z	0.3	mm
Final $\sigma_E/E^\dagger$	0.07	%
Bunch phase relative to RF crest	5	degrees ahead

[†] at exit of linac

ILC TDR

L-band cavity BPM for ILC

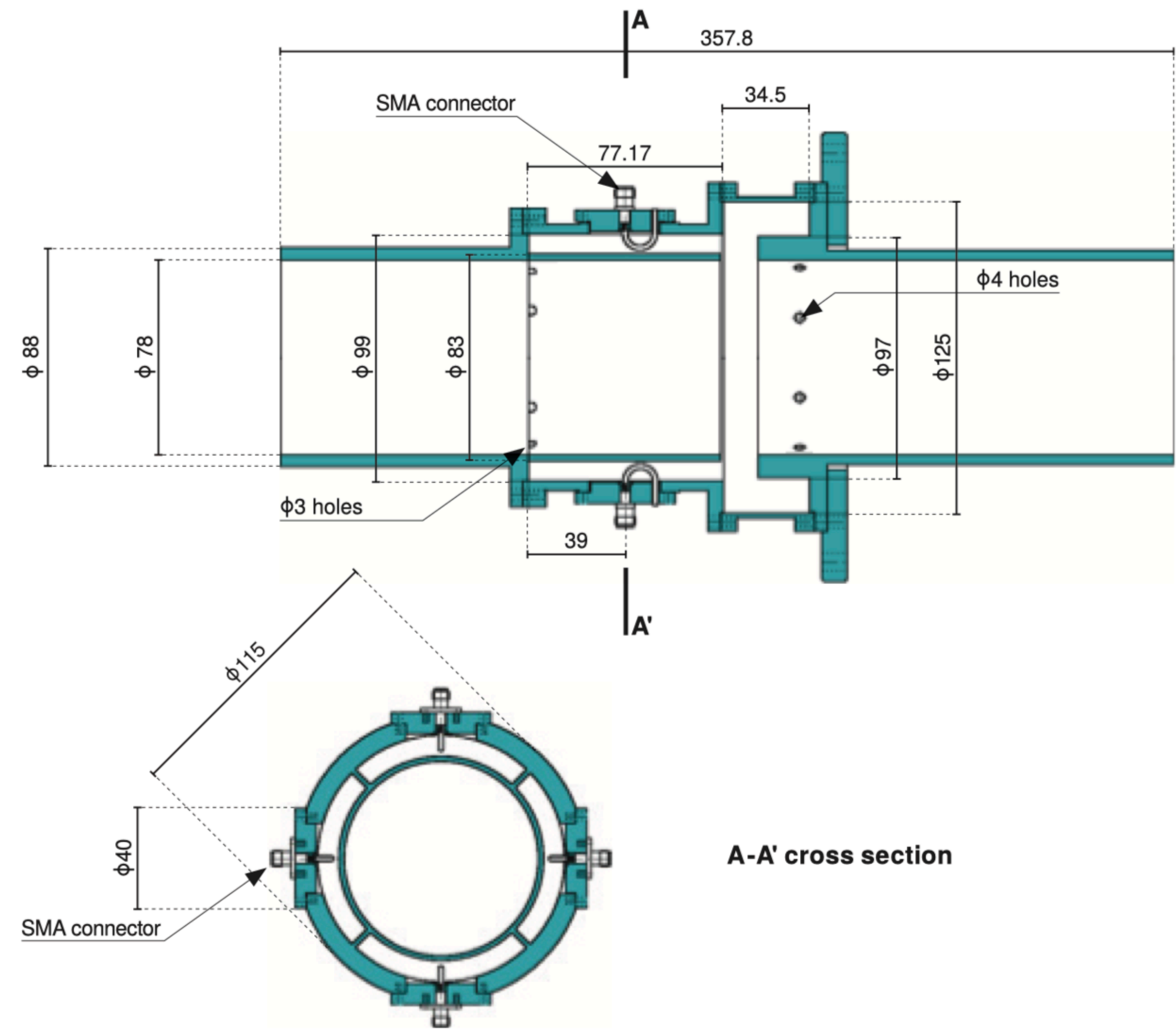
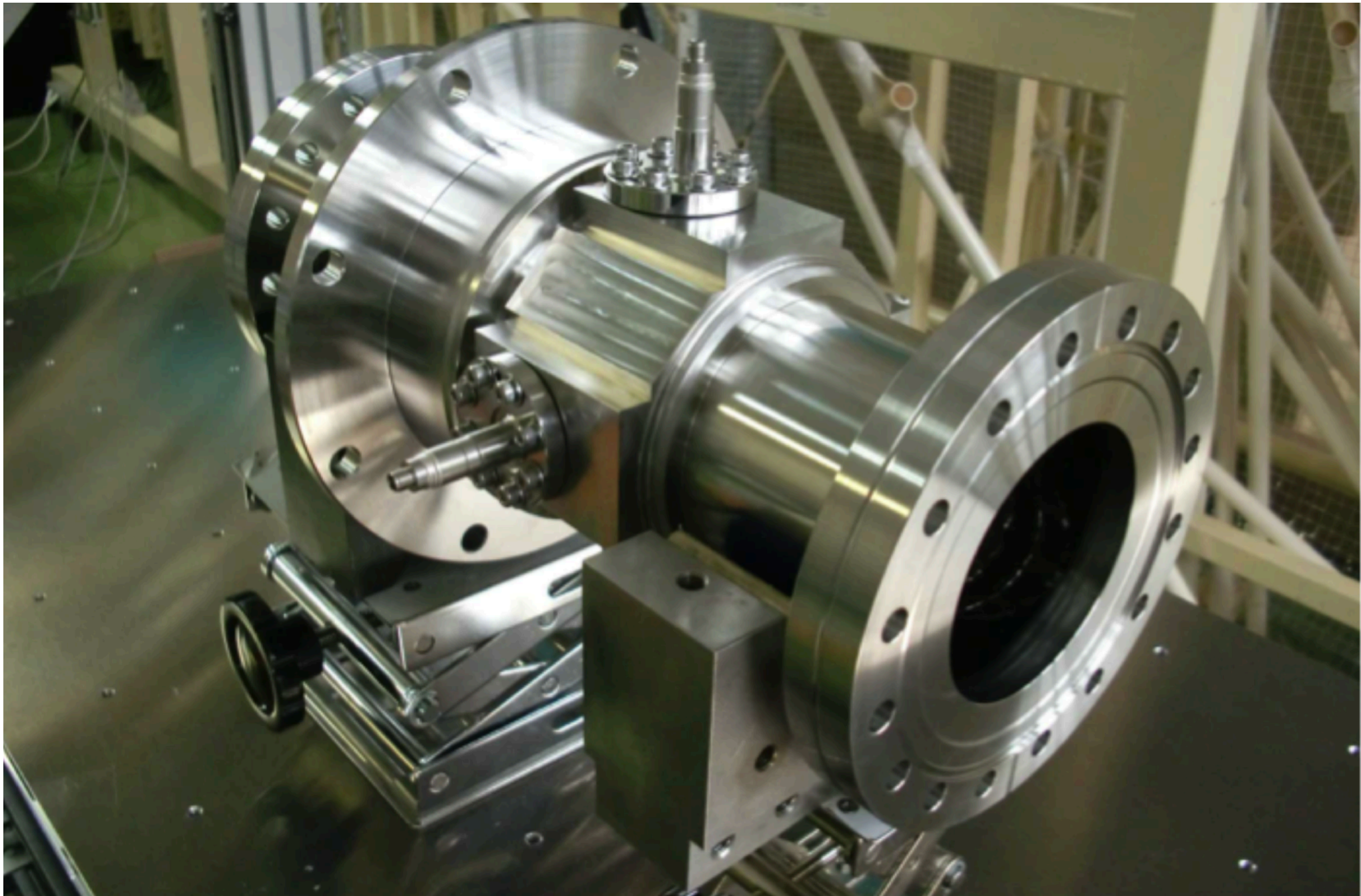
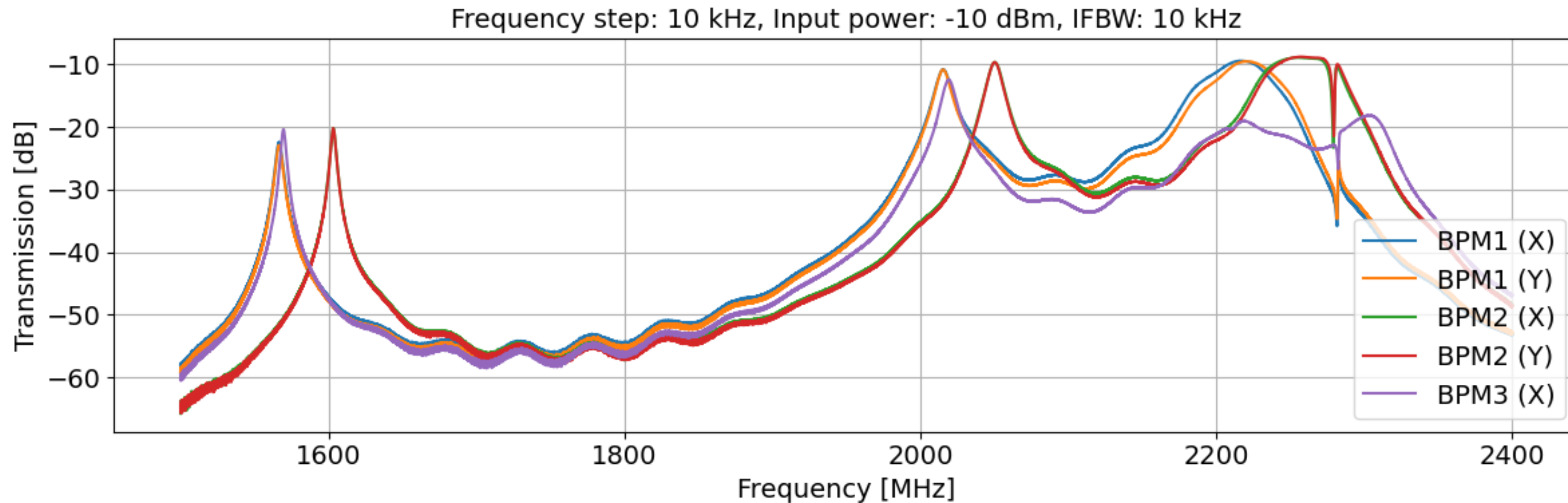


Table 3.4
Installation alignment errors (rms) of the linac beam-line elements. BPM specifications are also included.

Error	with respect to	value	
Cavity offset	module	300	μm
Cavity tilt	module	300	μrad
BPM offset	module	300	μm
BPM resolution		5	μm
BPM calibration		≤ 10	%
Quadrupole offset	module	300	μm
Quadrupole roll	module	300	μrad
Module offset	beamline reference	200	μm
Module tilt	beamline reference	20	μrad



Properties of Cavity BPMs at KEK-ATF



	TM ₀₁₀		TM ₀₁₁		TM ₀₂₀	
	f _x [MHz] f _y [MHz]	Q _x Q _y	f _x [MHz] f _y [MHz]	Q _x Q _y	f _x [MHz] f _y [MHz]	Q _x Q _y
BPM-A	1566.59 1566.60	320 320	2015.53 2015.48	170 187	2213.57 2220.69	45 48
BPM-B	1603.20 1603.18	444 607	2050.34 2050.26	186 195	2253.35 2255.03	48 50
BPM-C	1569.54 1569.54	441 445	2019.32 2021.60	197 219		