SAPIENZA
UNIVERSITÀ DI ROMA

Department of Physics

Accelerator Physics PhD School – XXXII cycle

Studies and Measurements on Cavity Beam Position Monitors for Novel Electron Linacs

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Agenda

1. ELI-NP GBS overview
2. Cavity Beam Position Monitor and readout electronics
3. Test bench design and measurements at LNF-INFN
4. Beam Measurements at DESY
5. Conclusion and future work

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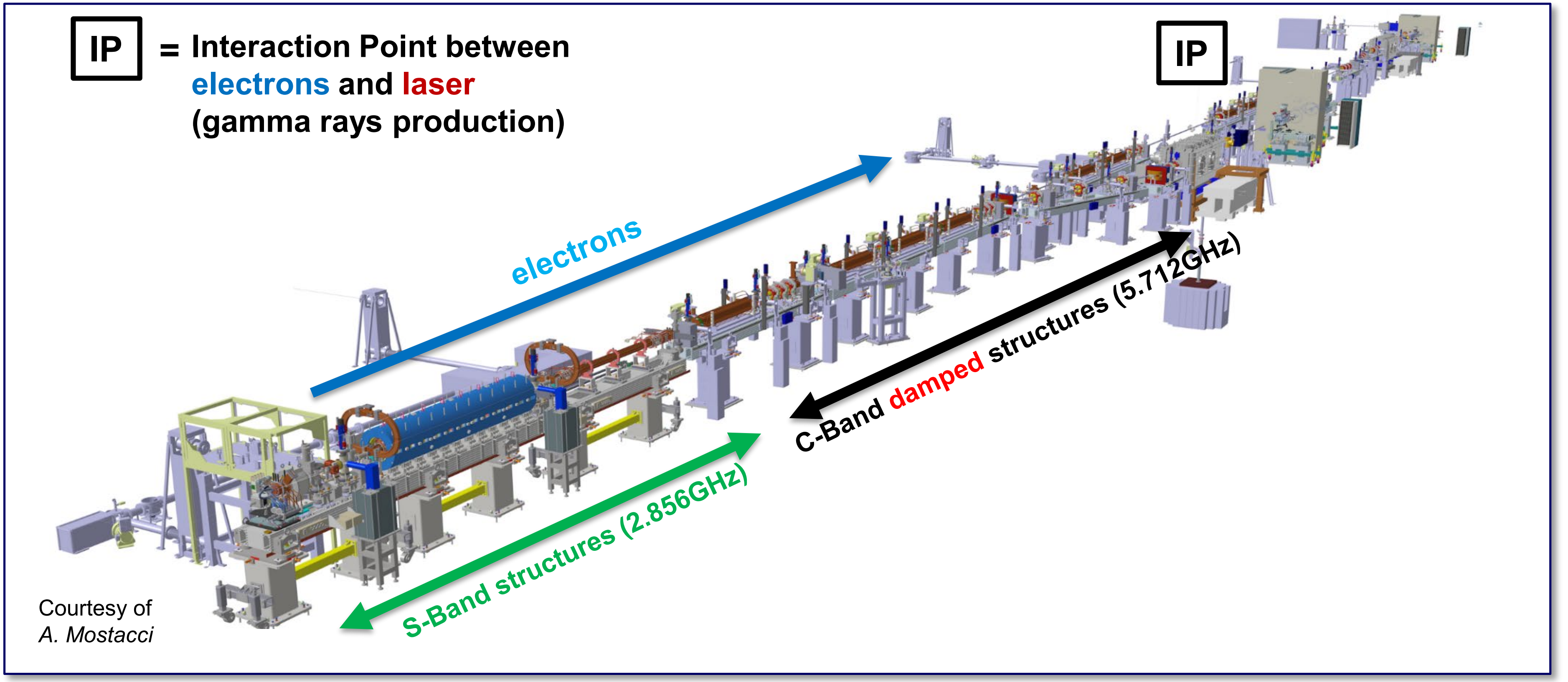
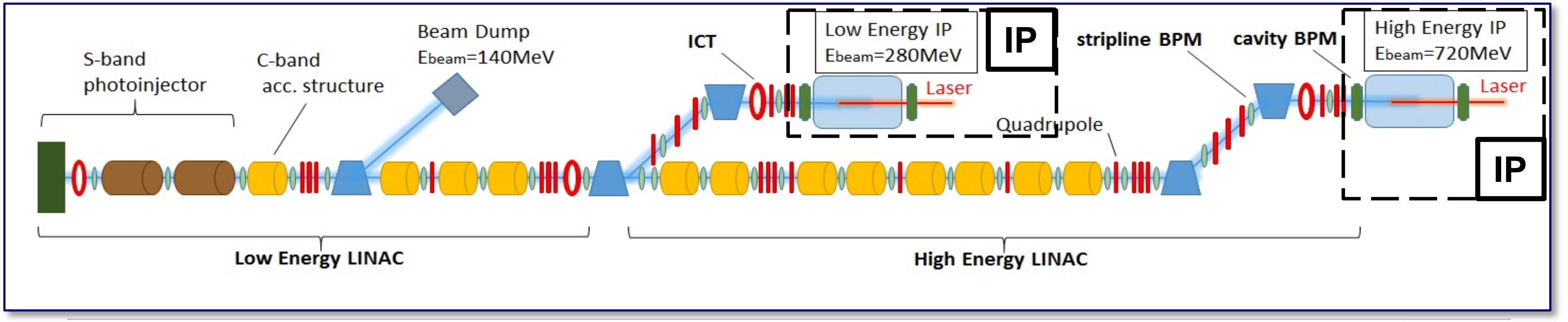
ELI-NP Gamma Beam System

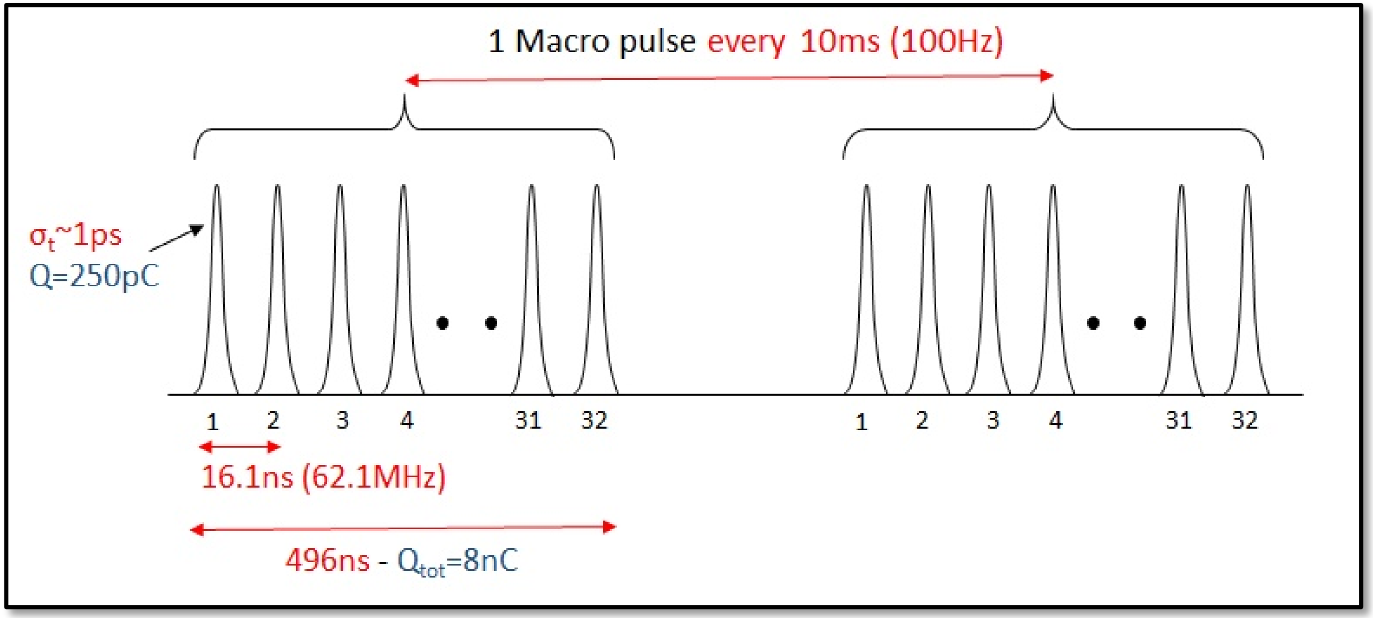
- **ELI-NP GBS** (Extreme Light infrastructure – Nuclear Physics, Gamma Beam System) is an **Advanced Gamma Source** for studies in new nuclear spectroscopy and new photonuclear physics.
- It will generate photons (up to 19.5 MeV) by **Compton back-scattering** in the collision between a multi-bunch electron beam and a high intensity recirculated laser pulse.
- The EuroGammaS consortium, led by INFN, is responsible for its development and delivery. **The machine installation is halted due to a contract dispute.**

ELI-NP Linac Layout





Beam Parameters and structure

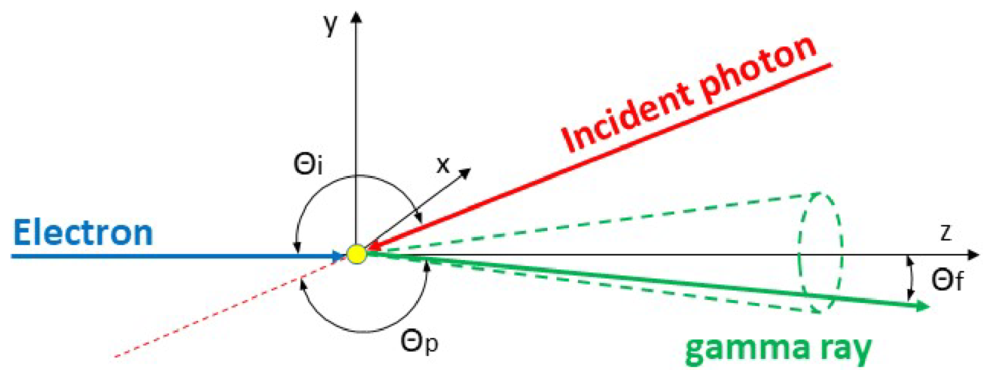


Electron Beam Specifications

Parameter	Value
Max. Energy at IP [MeV]	280 – 720
Macro Pulse rep. Rate [Hz]	100
Number of bunches	up to 32
Bunch spacing [ns]	16.1
Bunch length [ps]	0.91
Bunch charge [pC]	25-250
Bunch Energy Spread	< 0.1%

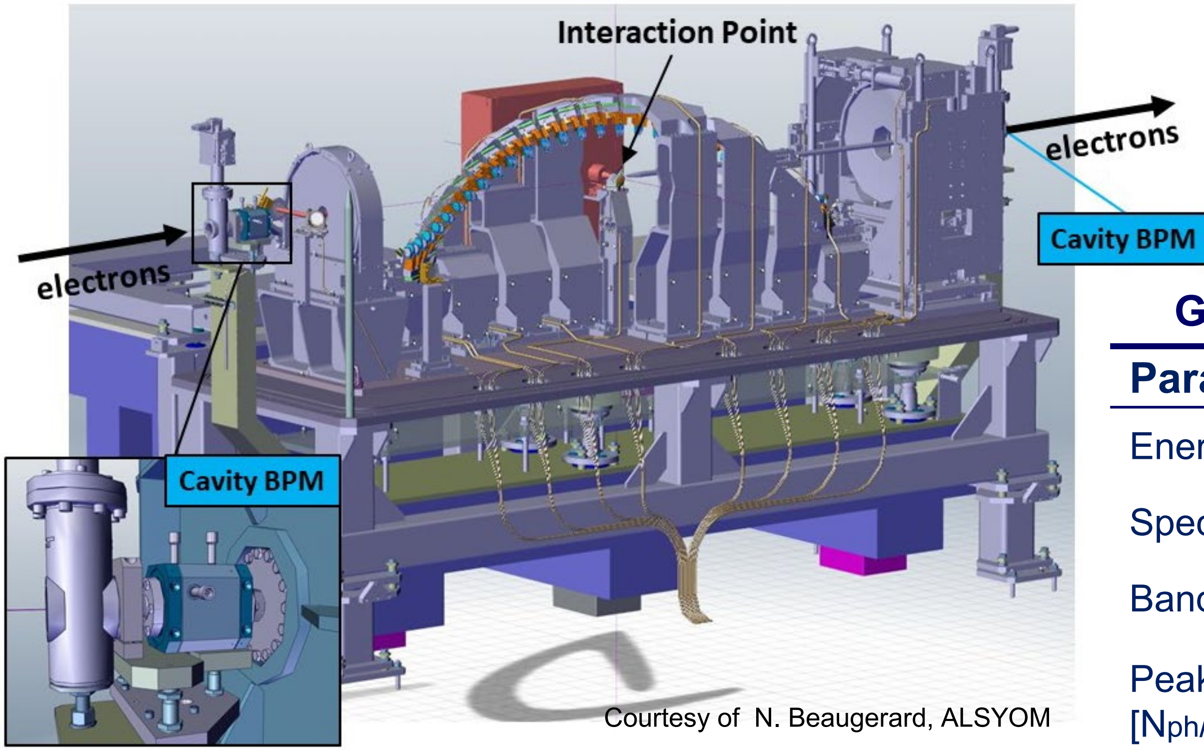
Gamma Rays production

- Gamma rays are scattered inside a cone with the axis that approximately coincides with the incoming electron beam.
- Their **intensity** and **energy depends** on the the **scattering angle** (θf).



- By using a gamma ray collimation system, a photon beam with small energy spread can be obtained.
- **Measurement of the electron beam trajectory** at the IP **is critical** to optimize the gamma ray production.
- **Four Cavity Beam Position Monitor** will be used to measure the **transverse position** of each electron bunch, immediately before and after the Interaction Point Modules.
- **The requirement for bunch position resolution is 1 μm over ±1 mm.**

Interaction Point Module



Gamma Beam Specifications

Parameter	Value
Energy [MeV]	0.2 – 19.5
Spectral Density [ph/(s·eV)]	$0.8 – 4 \cdot 10^4$
Bandwidth rms [%]	≤ 0.5
Peak brilliance [N_{ph}/(s·mm^2·mrad^2·0.1%)]	$10^{20} – 10^{23}$

- By using an **optical re-circulator**, a single **laser pulse** will collide with a multi-bunch (up to 32) **electron beam** at the interaction point, generating **the gamma beam by Compton back-scattering.**
- **Two Interaction Point modules are foreseen.** One at low energy ($E_{el.}$ ≤ 280 MeV), the other at high energy ($E_{el.}$ ≤ 720 MeV).

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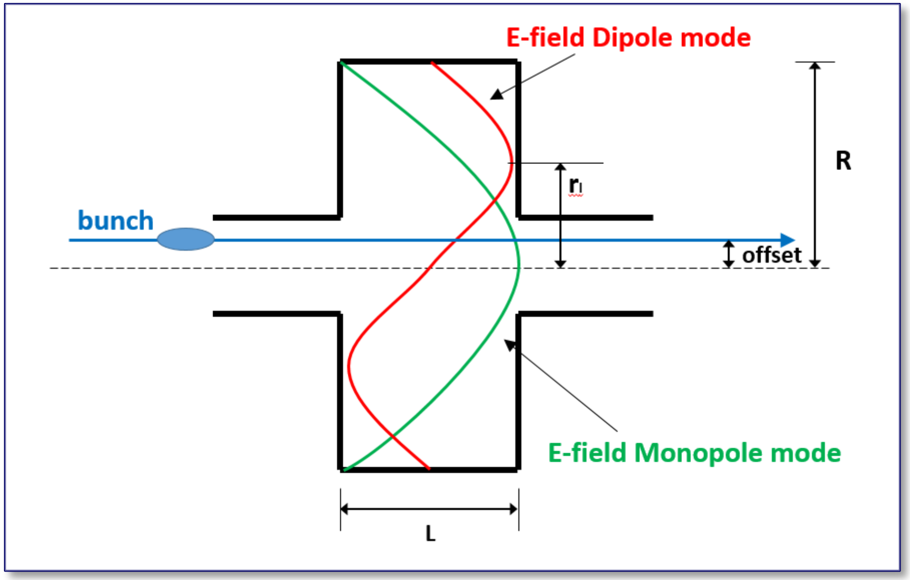
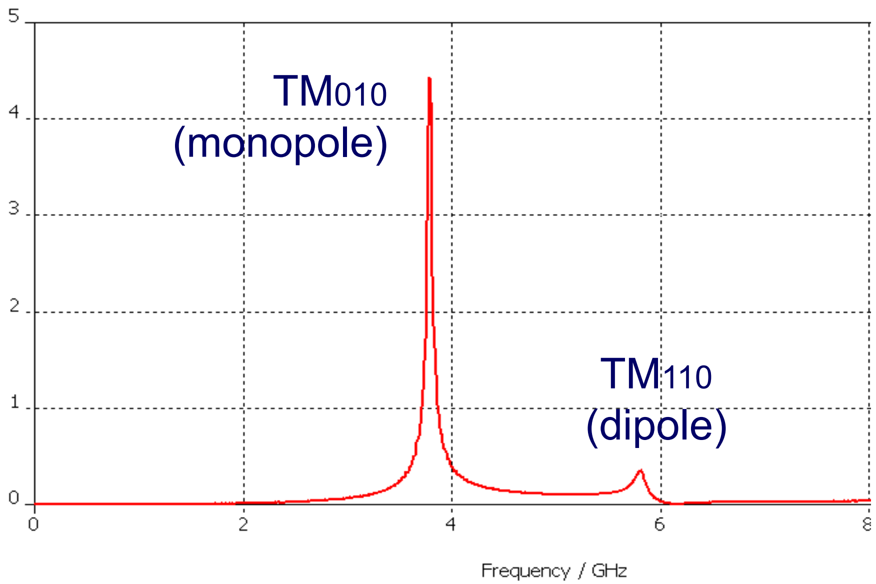
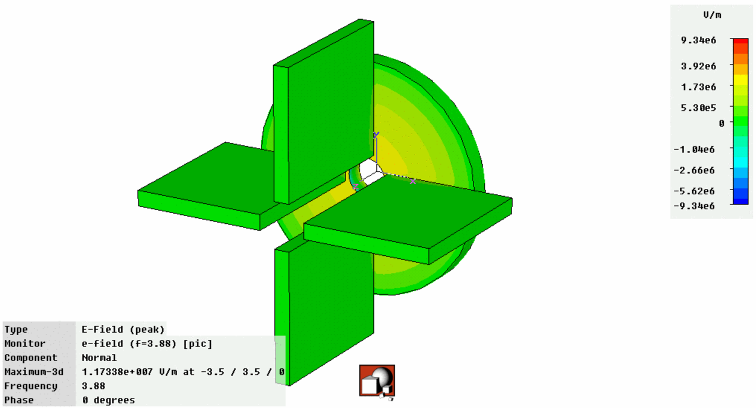
Cavity BPM (pillbox resonator)

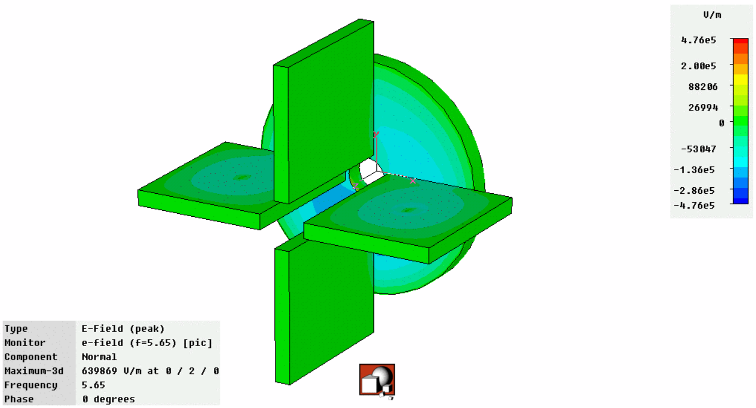




monopole mode

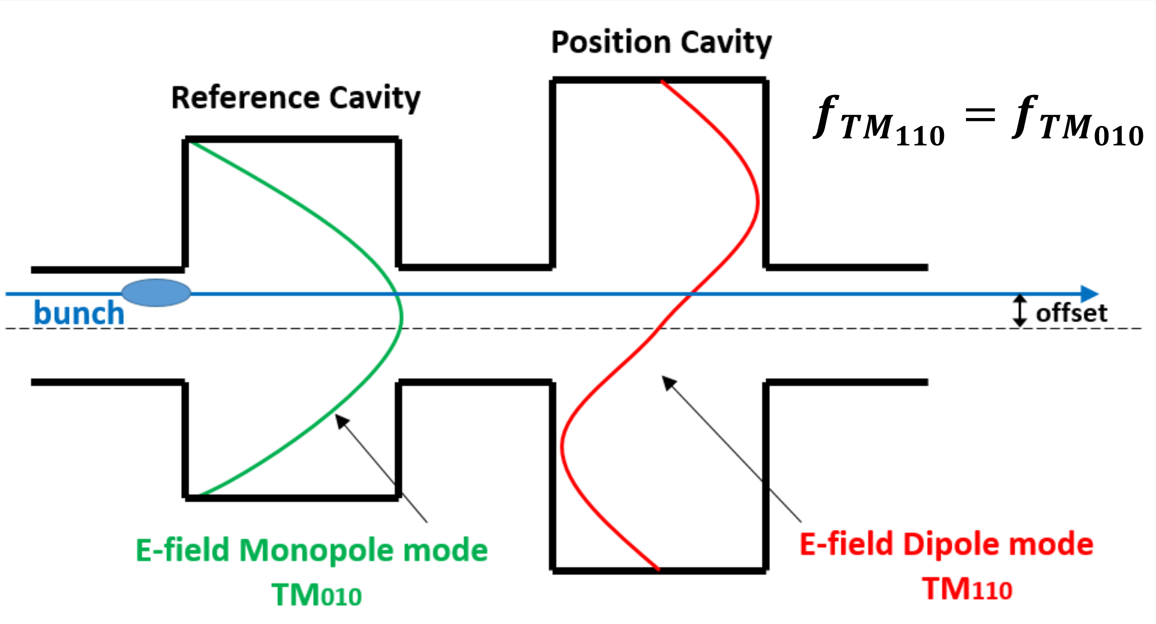


dipole mode



Courtesy of
D. Lipka

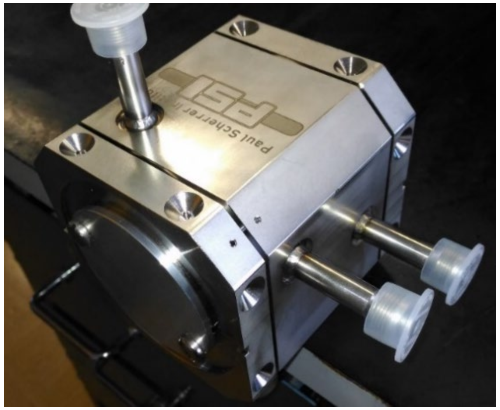
Cavity BPM (two pillbox resonators)

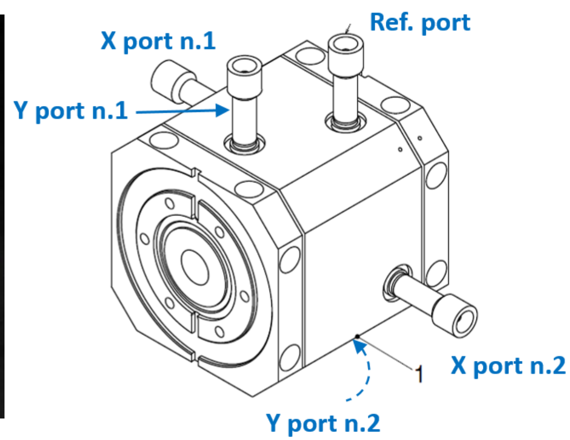


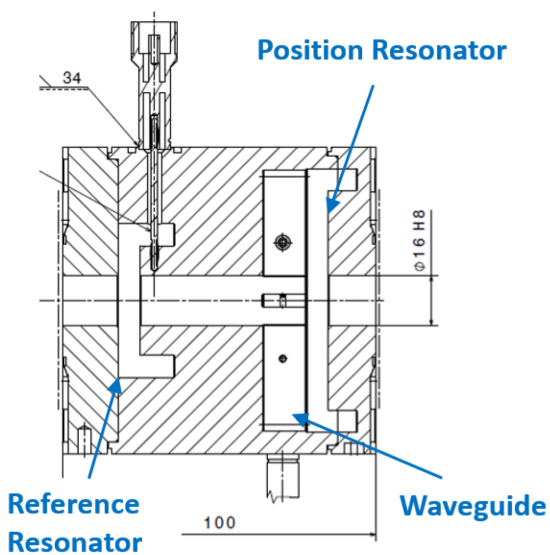
- ***Monopole mode** is proportional to the **bunch charge**.*
- ***Dipole mode** is proportional to the **bunch charge and bunch offset**.*

- By **dividing** the extracted signals associated to **Dipole and Monopole mode** is possible to obtain a quantity that is proportional to the beam offset (and not to beam charge).
- The extracted signals associated to Dipole and Monopole mode are compared to determine the beam offset sign.

Cavity BPM (PSI BPM16 Design)







General Pickup Parameters

Parameter	Value
Material	Stainless Steel 316LN
Length [mm]	100
Inner Aperture [mm]	16
Distance from Pos. To Ref. Resonator [mm]	60

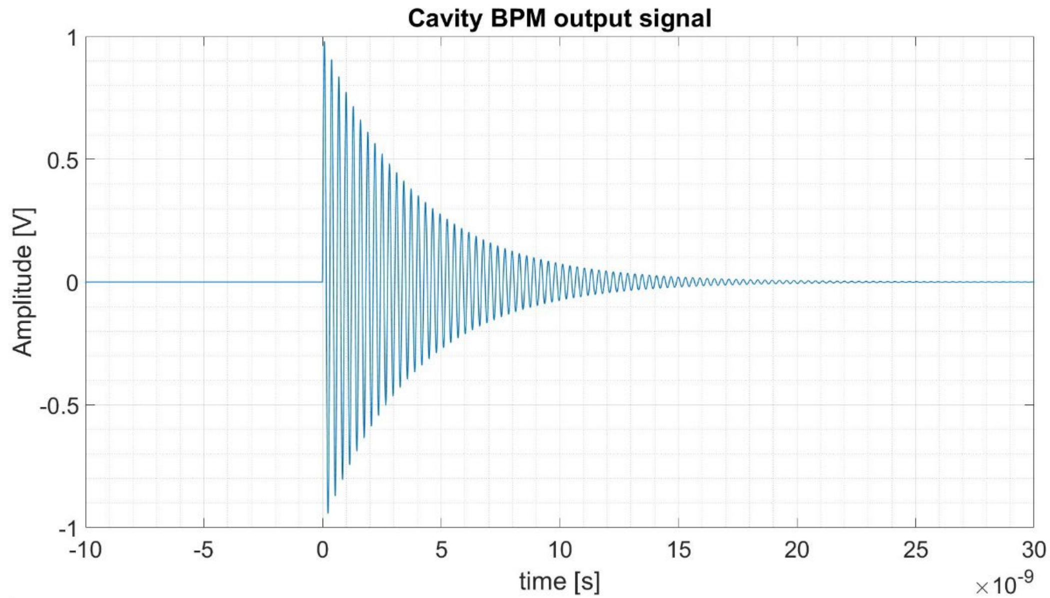
Position Resonator

Parameter	Value
Gap between res. walls [mm]	7
Q_L	**40**
TM_{110} Frequency [GHz]	**3.284**
TM_{010} Frequency [GHz]	2.252
Position Signal [V/mm/nC]	**7.07**
Angle Signal [µm/mrad]	4.3

Reference Resonator

Parameter	Value
Gap between res. walls [mm]	7
Q_L	**40**
TM_{010} Frequency [GHz]	**3.284**
Charge Signal [V/nC]	**135**
Angle Signal [µm/mrad]	4.3

Output Signals



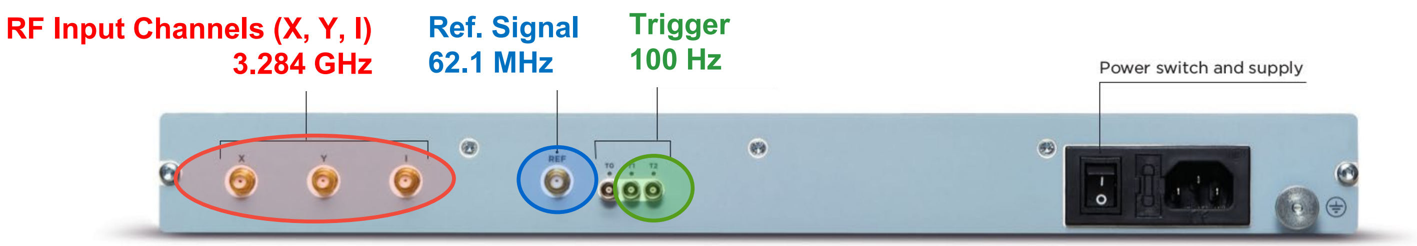
$$V_{out}(t) = A \cdot \sin(2\pi f_{res} t + \theta) \cdot e^{-t/\tau}$$

$$\tau = \frac{Q_L}{\pi f_{res}}$$

A is proportional to beam charge for TM_{010} and proportional to charge and beam offset for TM_{110}.

- The two cavities are designed to produce signals with the **same frequency and decay constant (τ)** respectively for monopole and dipole mode.
- With every beam bunch, **a total of three signals are extracted**. Two for the horizontal and vertical polarization of the dipole mode (**X** and **Y**). One for the monopole mode (**I**).

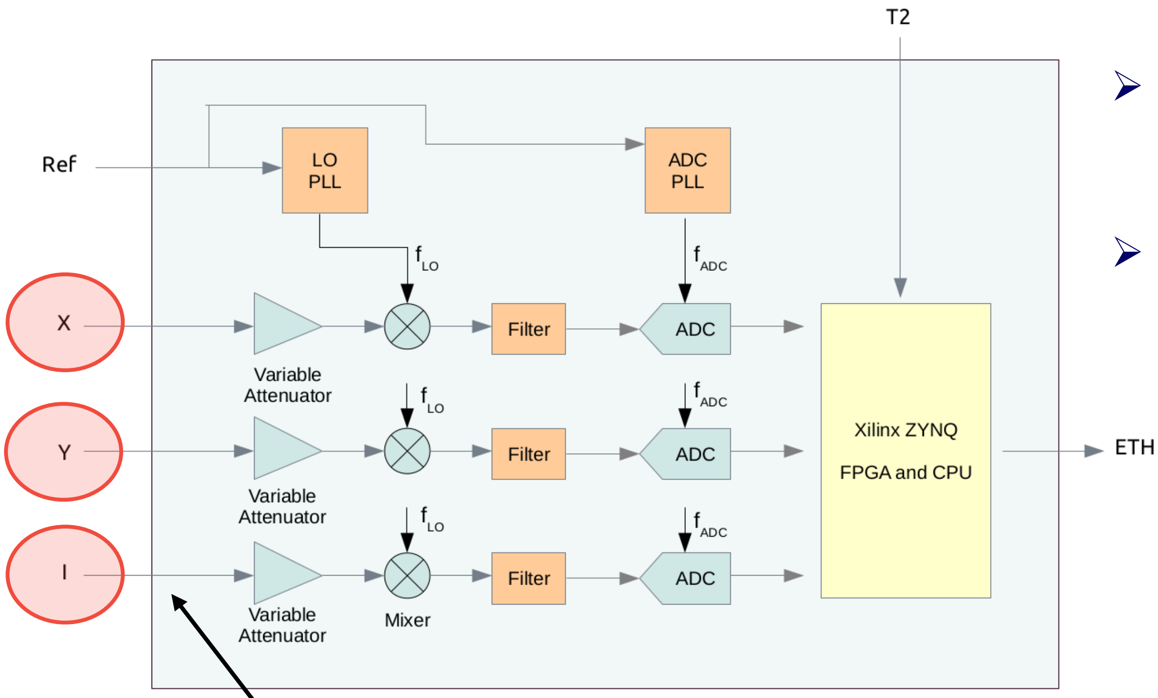
Readout Electronics 'LIBERA CavityBPM'



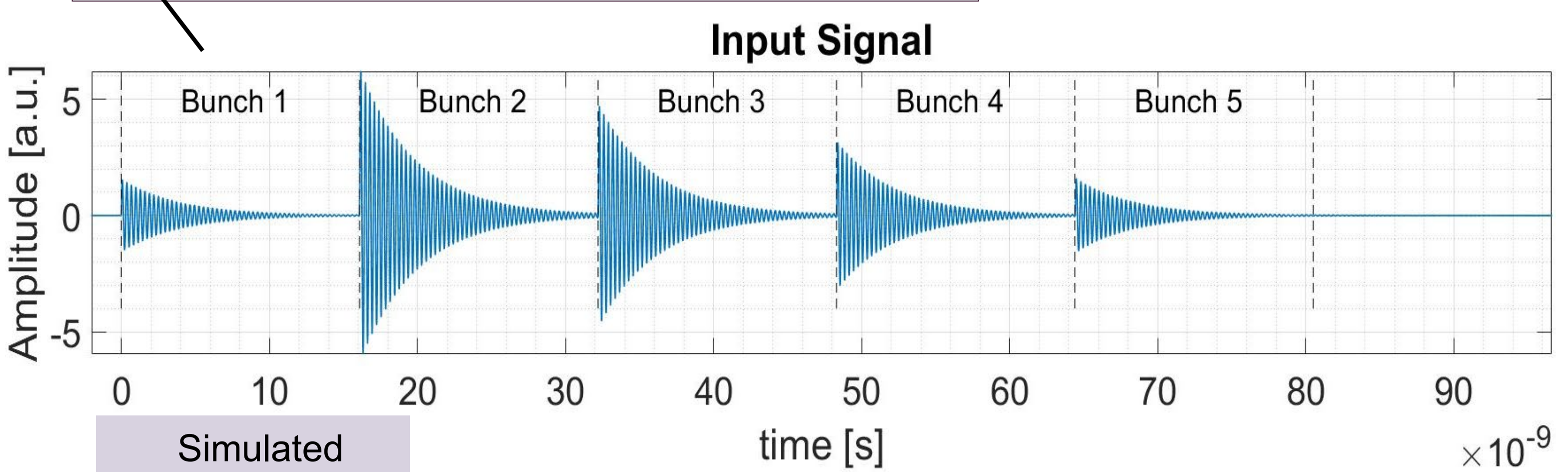
Main Specifications

ADC	4 channels, 500MS/s, 14bit
FPGA / CPU	ZYNQ 7035 / ARM Cortex A9
ADC buffer	4kS/channel (~8us)
Variable attenuation	31dB, channel-independent
Input signal freq.	C-band, S-band
Ref. signal freq.	Up to 250MHz

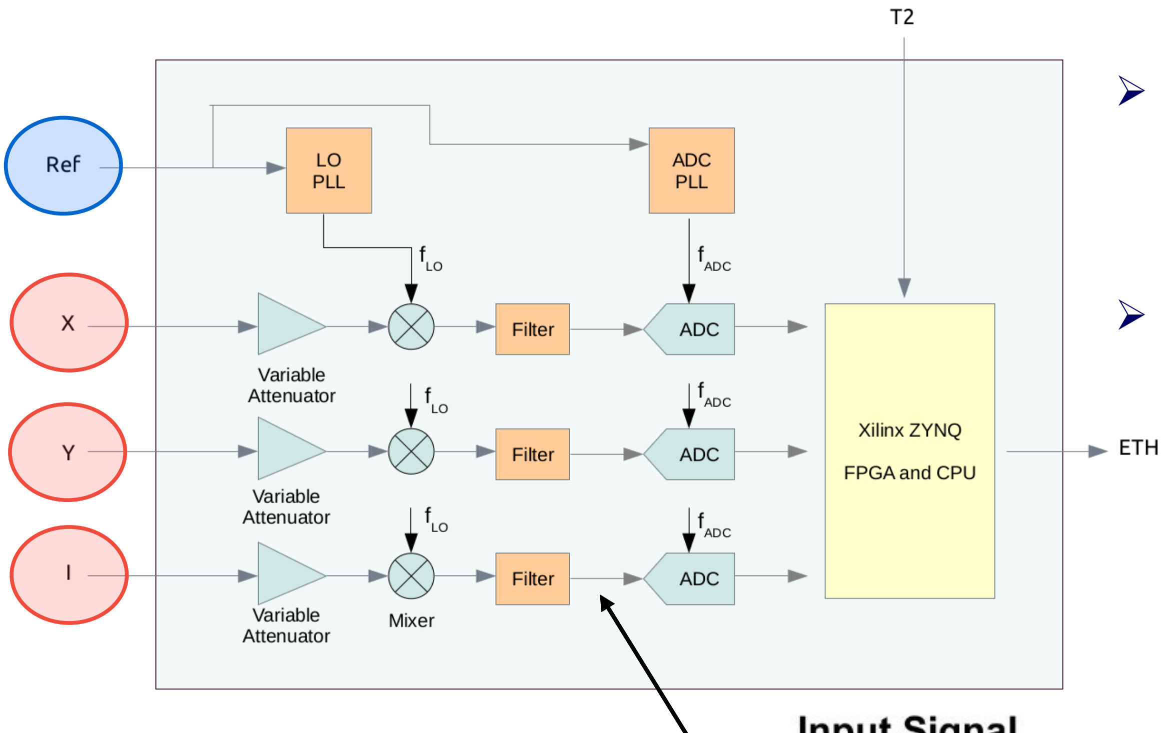
Signal processing (1/3)



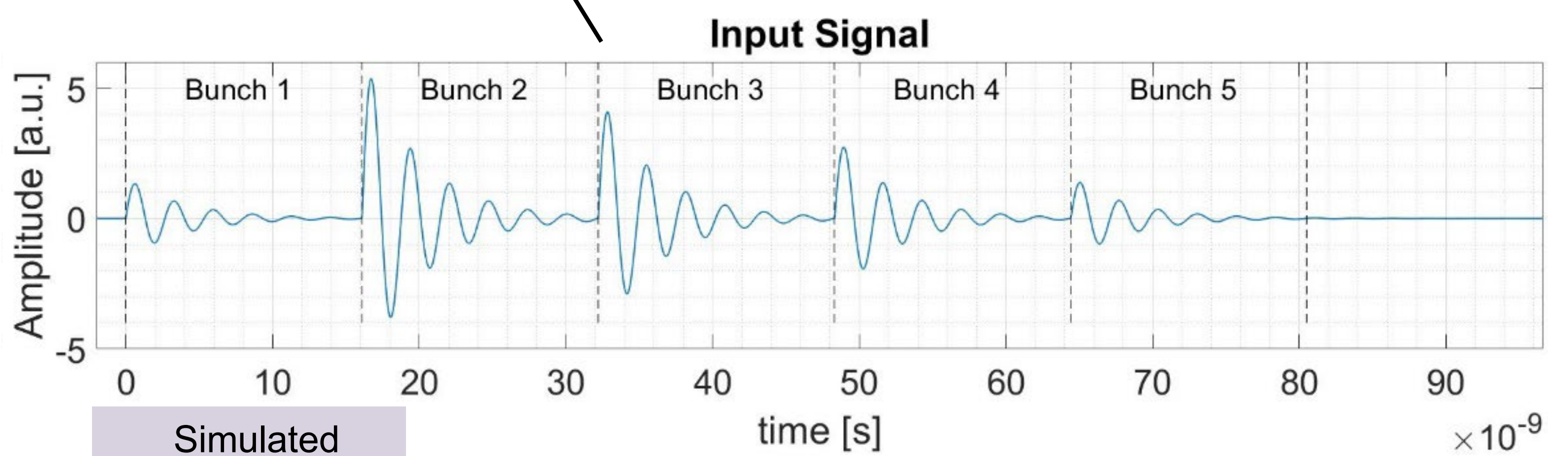
- RF signals (X, Y, I) use three identical and independent channels.
- They are filtered and attenuated by means of three configurable attenuators (0 / 32 dB).



Signal processing (2/3)

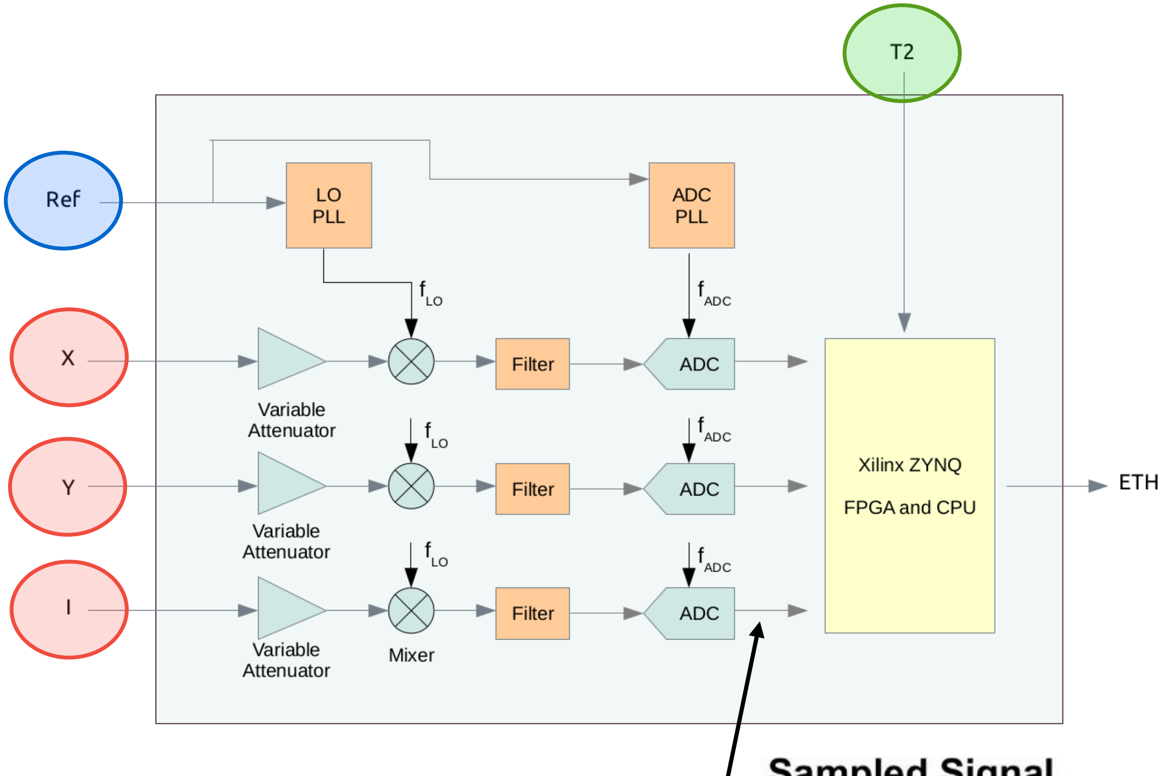


- Reference signal (62.1 MHz) is used to generate f_{LO} (for the mixer) and f_{ADC} for the ADC clock.
- Signals are down-mixed from 3.284 GHz to 375 MHz.



Simulated

Signal processing (3/3)



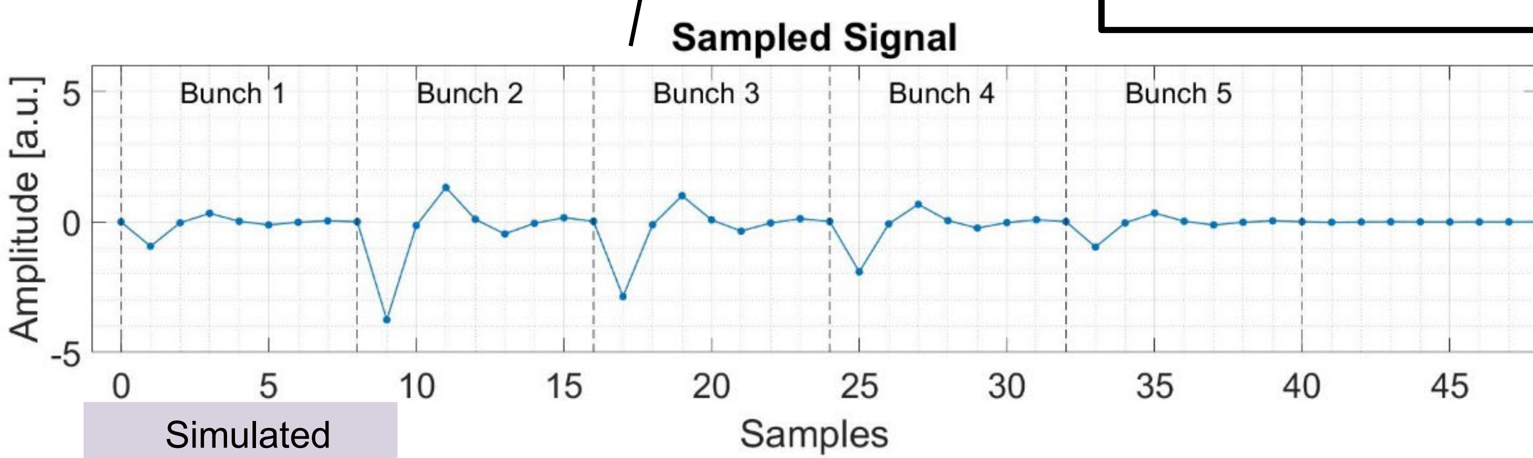
$$V_{X_b} = \sqrt{\sum_{bth\ bunch\ window} {x_n}^2}$$

$$V_{Y_b} = \sqrt{\sum_{bth\ bunch\ window} {y_n}^2}$$

$$V_{I_b} = \sqrt{\sum_{bth\ bunch\ window} {i_n}^2}$$

Calc. beam position

$$X_b = K_x \frac{V_{X_b}}{V_{I_b}} \qquad Y_b = K_y \frac{V_{Y_b}}{V_{I_b}}$$



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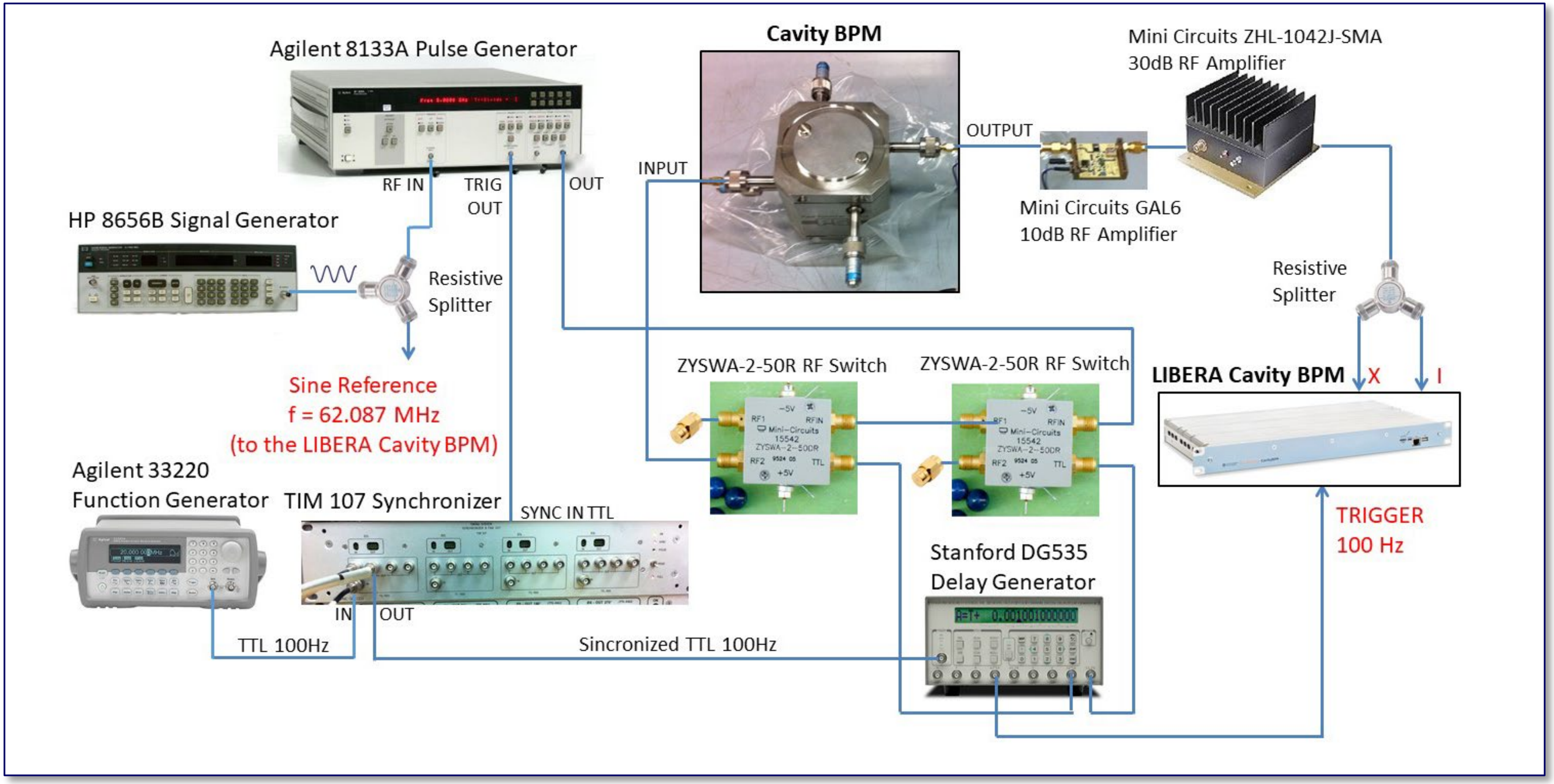
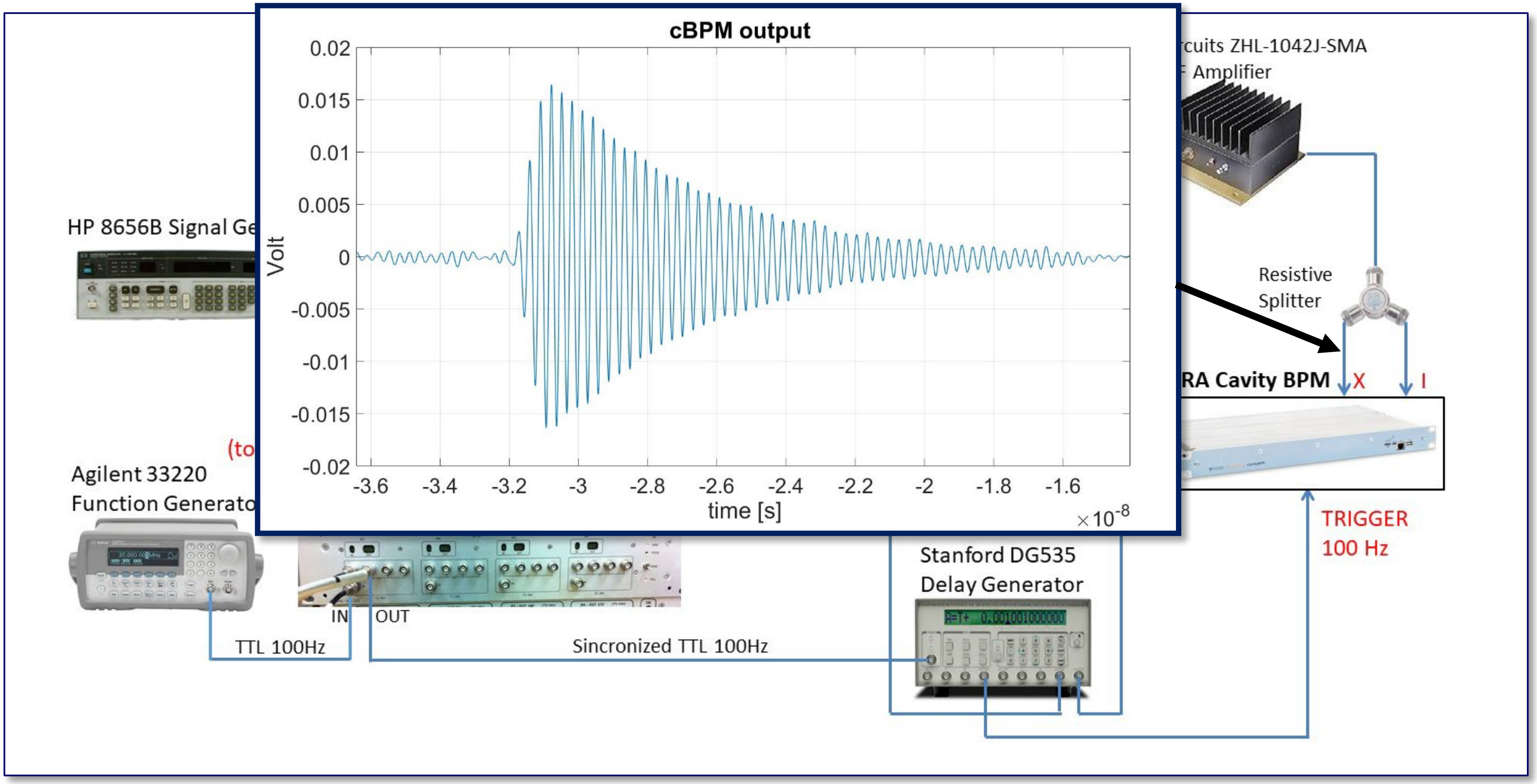
Test Bench at LNF-INFN for Cavity BPM



- A **pulse generator excites the "position resonator"** of the cavity BPM (**mimicking the passage of a beam bunch**). The output signal is then split and provided to the input channels of the readout electronics.
- The test bench offers the possibility to perform **measurements with train of pulses**, which are synchronized with the reference signal and the trigger provided to the readout electronics.

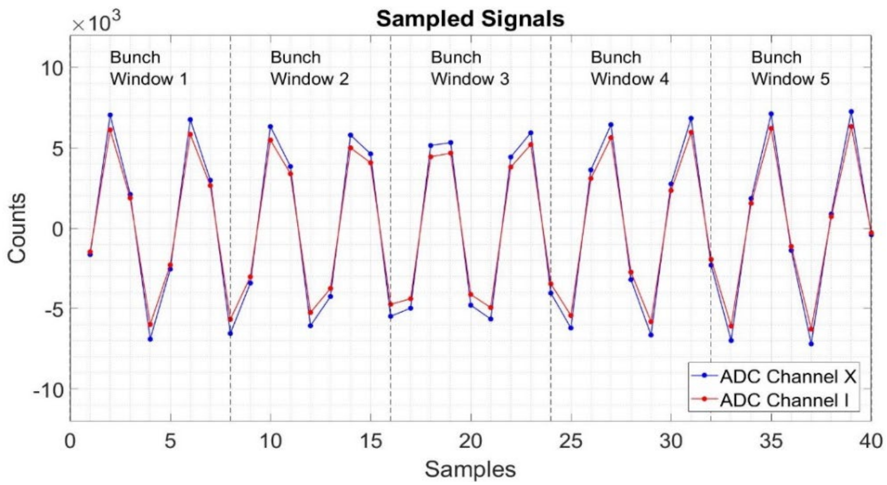
Test Bench at LNF-INFN for Cavity BPM



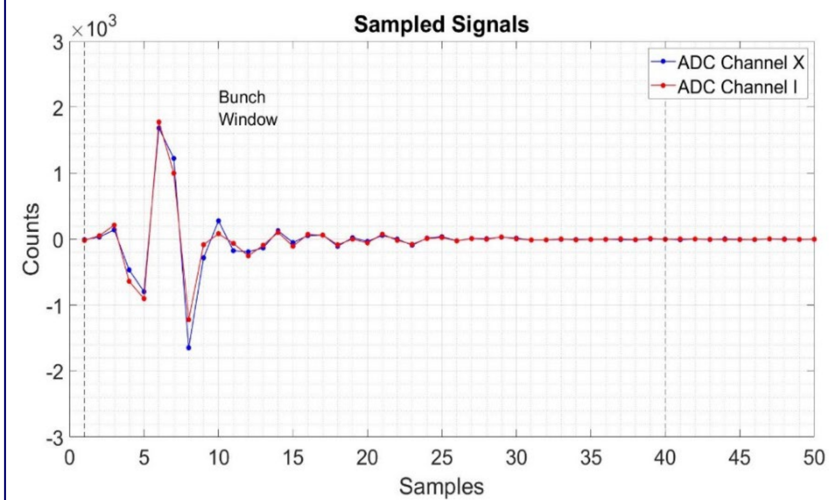
- **Advantages:** no beam required; signal coupling (X-I) greatly reduces noise introduced by the setup.
- **Limits:** not possible to test the reference cavity; signal coupling (X-I) limits the possible measurements which can be performed; difficulty on amplify the signals without introducing distortions.

Resolution measurements

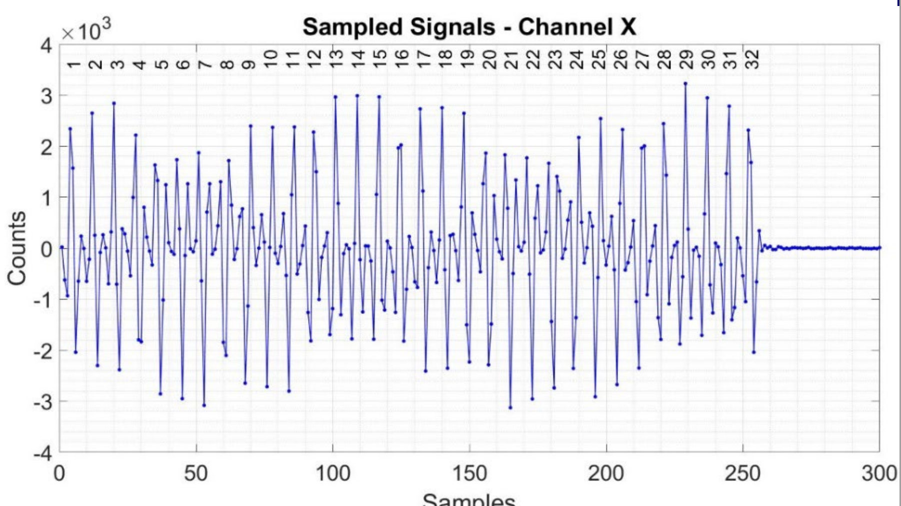
- Sinewave measurements -



- Single pulse measurements -

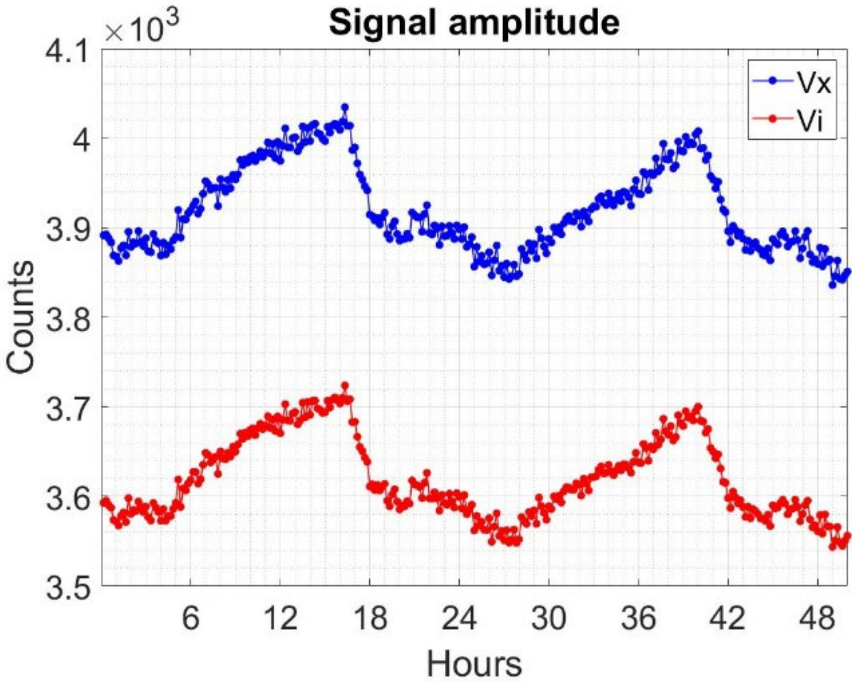


- Train of pulses measurements -

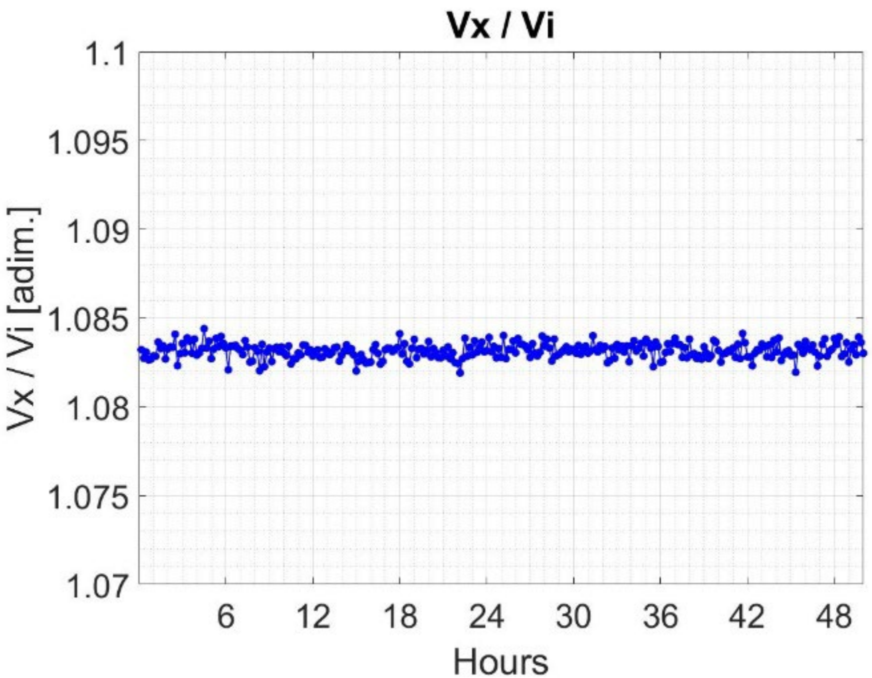


➢ **Resolution measurements:**
best relative standard deviation achieved: $0.4\cdot10^{-3}$ (0.4 µm over ±1 mm). Resolution with pulses is worse than the sinewave case (3 µm over ±1 mm), mainly due to the fact that we were not exploiting all the input available range of the readout electronics (SNR degradation).

Stability over time



Maximum excursion of ~5% on the signal amplitudes, due to temperature variations. Nevertheless…



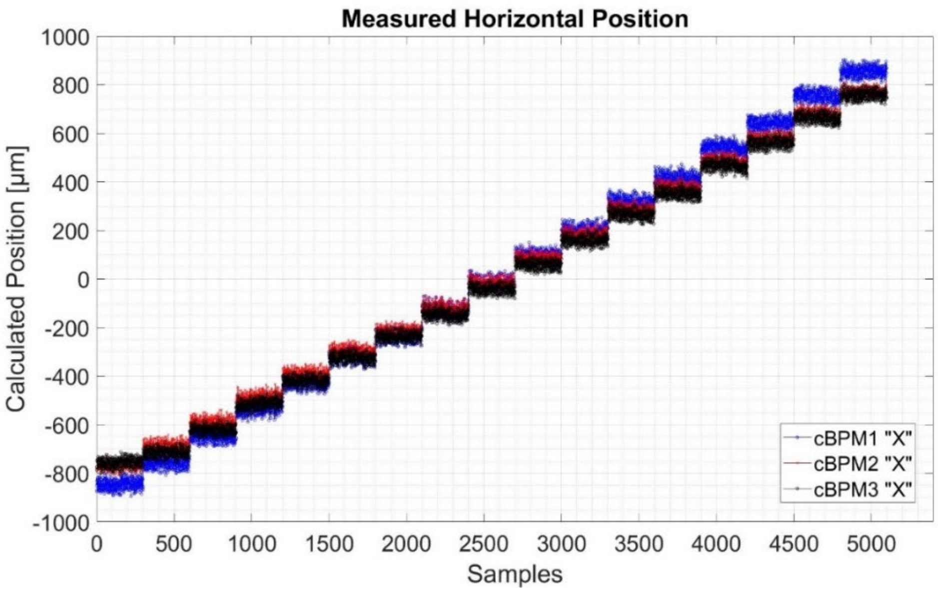
…there are negligible effects on the ratio Vx/Vi (position)

Agenda

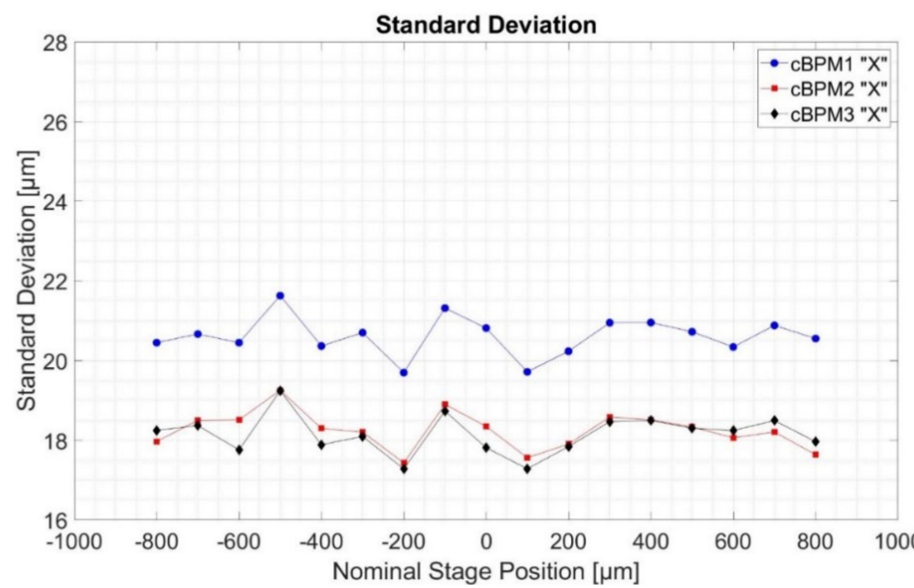
Measurements at FLASH1 (DESY)

Cavity BPM	FLASH	ELI-NP
Parameter	**Value**	**Value**
Q_L	70	40
Dipole Res. frequency [GHz]	3.30	3.28
Reference Res. Frequency [GHz]	3.30	3.28
Dipole Sensitivity [V/mm/nC]	3	7.1
Reference Sensitivity [V/nC]	60	135

Position Measured with 500 pC bunches

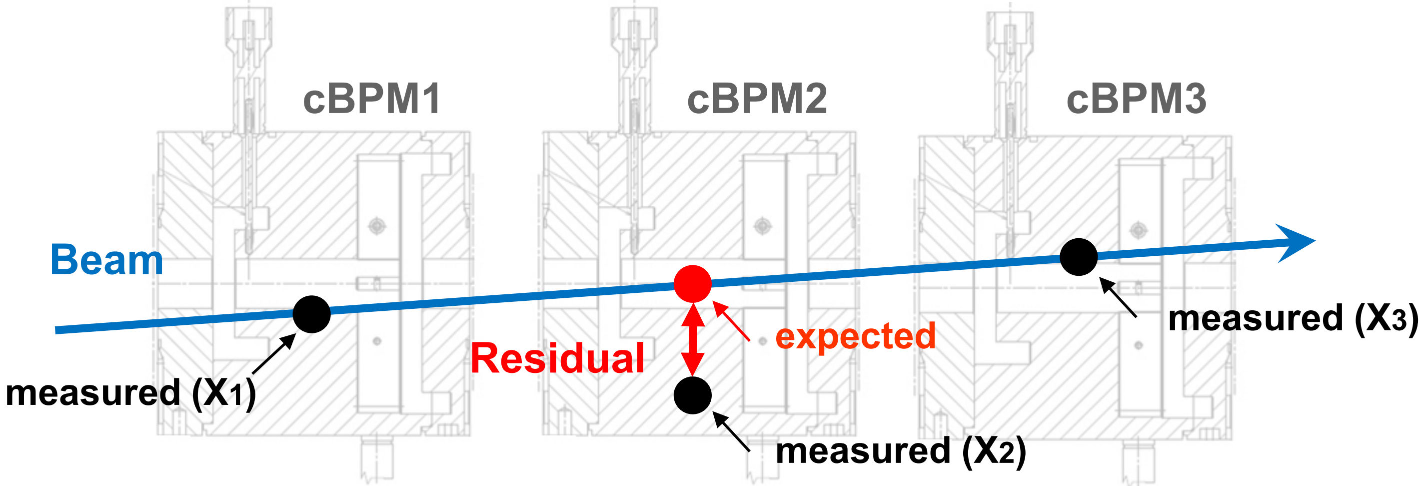


- 300 samples collected for each step (100 µm) of the moveable stages.
- Different values of gain were detected for the three cBPM. They were compensated with calibration factors.



- The Standard deviation measured is mainly due to shot to shot beam fluctuations. (Resolution of cBPMs is much lower)

Resolution Measurements

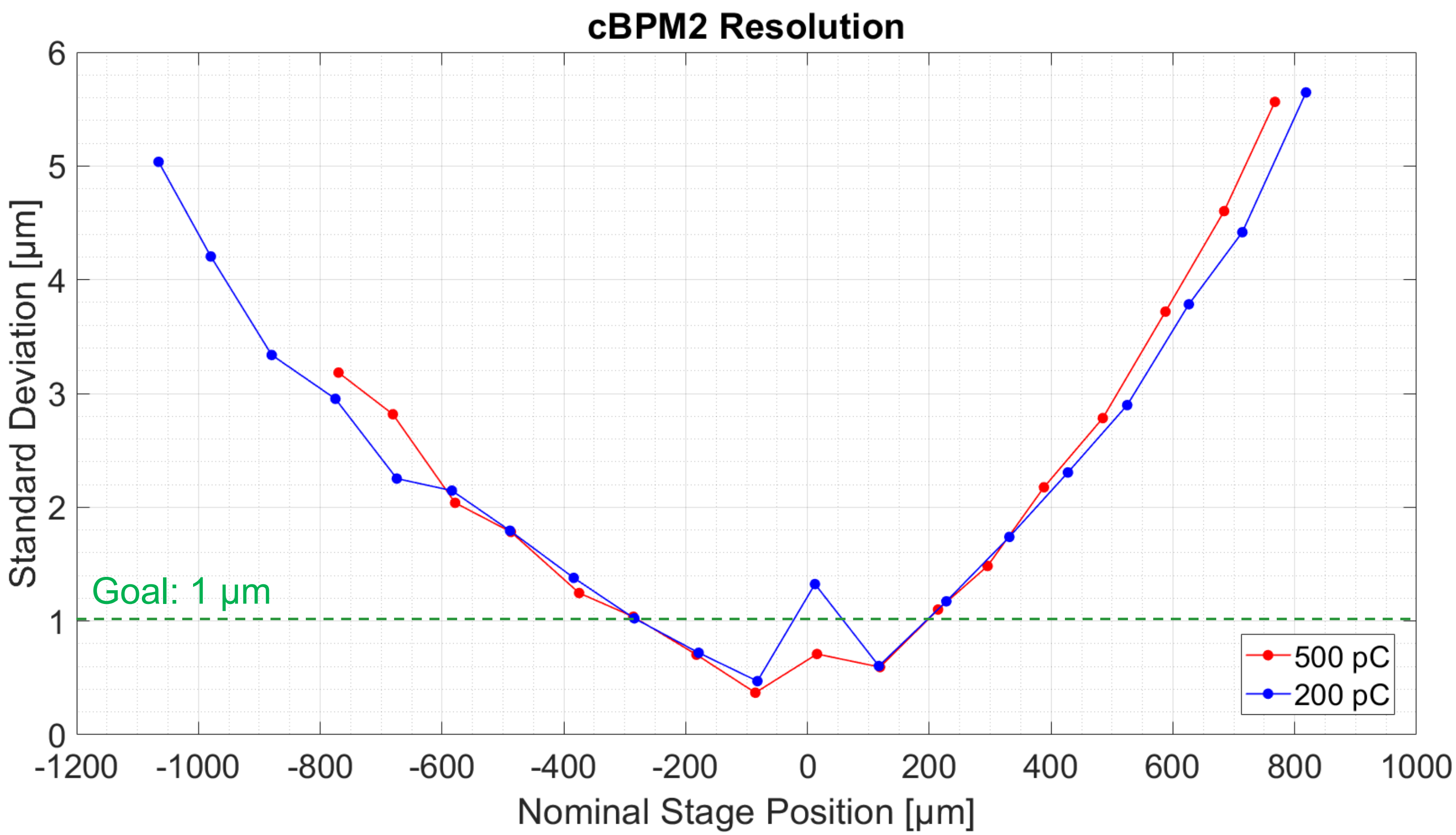


$$ResX_2 = X_2 - \frac{X_1 + X_3}{2}$$

$$\sigma_{ResX_2} = \sqrt{\sigma_{X2}{}^2 + \frac{\sigma_{X1}{}^2 + \sigma_{X3}{}^2}{4}} = \sqrt{\frac{3}{2}} * \sigma_X$$

Position resolution measurements were performed with three cBPMs.
The resolution of the device under test (cBPM2) is calculated by measuring the residual for cBPM2 (the difference between the position measured by the cBPM2 and the expected position calculated with the measurements of cBPM1 and cBPM3).

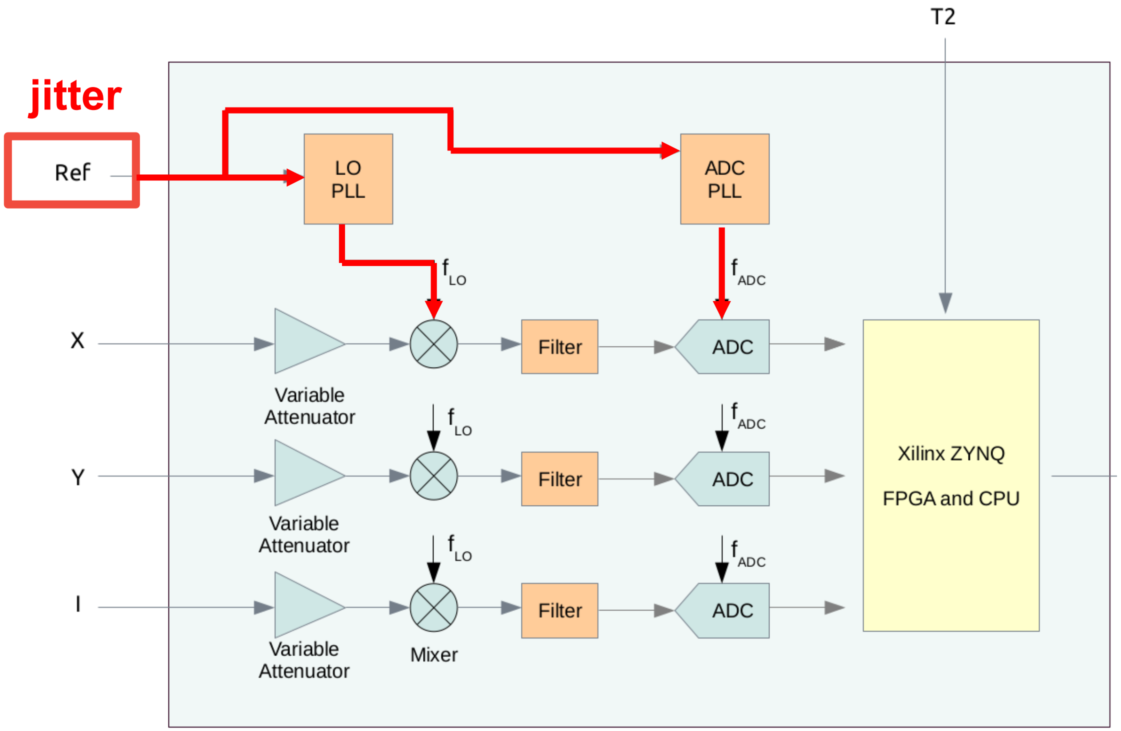
Resolution Measurements

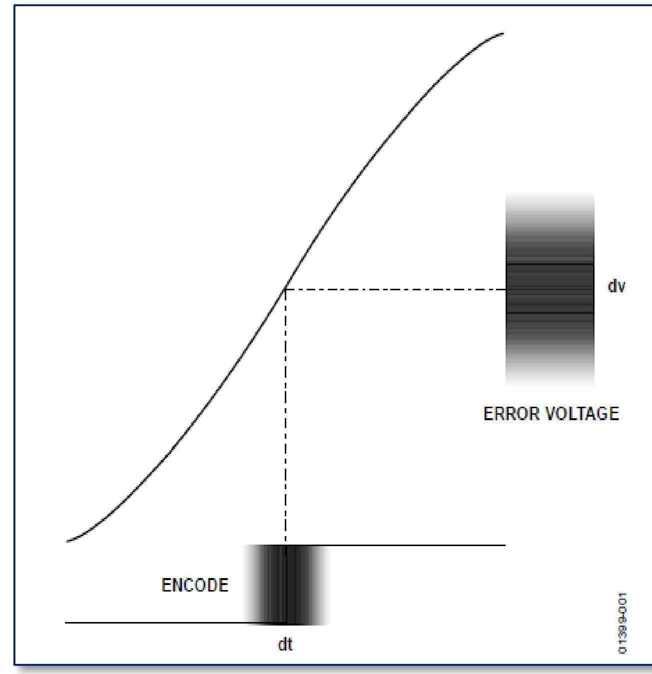


Resolution measurements at FLASH show two main issues:

- **The resolution depends on the position of the beam.** We believe that this depends on a high jitter (3 ps) of the external reference signal at FLASH (i.e. FLASH setup problem).
- **The resolution at the center get worse.** We believe that this is related to the digital signal analysis performed by the instruments (i.e. read-out electronics problem).

Hypothesis: Measurement resolution affected by jitter

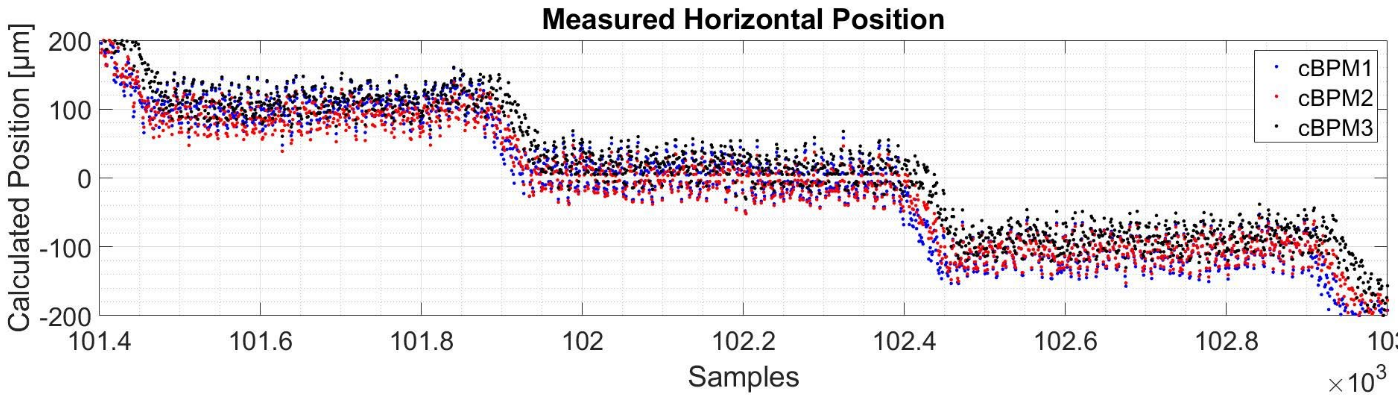


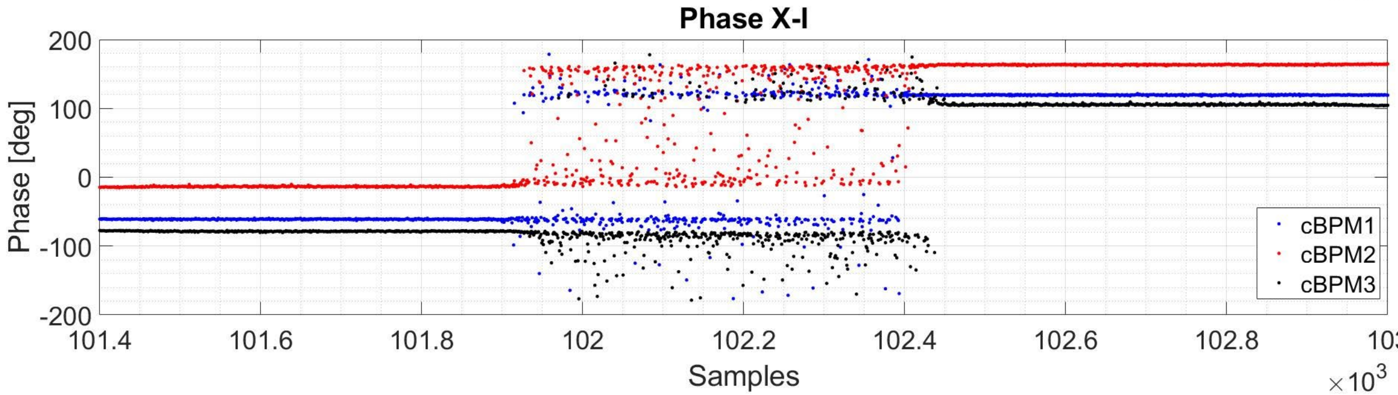


Noise induced by jitter: $V_{err} = 2\pi \cdot A \cdot f \cdot t_{jit}$

- **Noise induced by jitter could explain the resolution dependency on the signal level**
- A jitter on the reference signal is translated to an **amplitude-dependent noise**.
- It is hard to predict/simulate its effects, since a lot of devices are involved and all channels are affected. Nevertheless, on a first analysis the level of jitter measured is compatible with the worsening of the position resolution affecting the measurements.

Measurements at the e.m. center of the cBPM





- **Electronic noise and offset are sampled, adding an always positive contribution to the signal amplitude, making impossible to measure "0 μm" of beam position.**

  Solution: implementation of an algorithm that measure the noise without the signal and compensate its amplitude contribution.

- **Phase difference between "X" and "I" signals is not properly calculated when the signals are too low, leading to erratic measurements of the beam position sign (left/right, up/down).**

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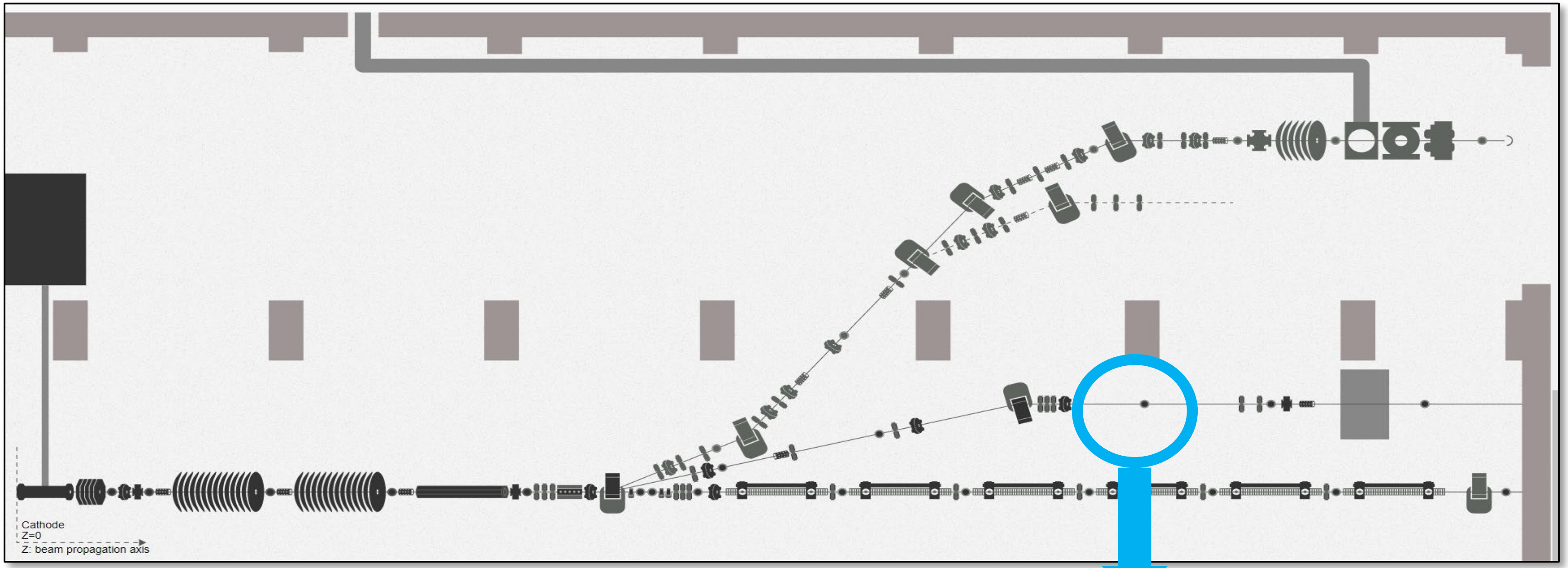
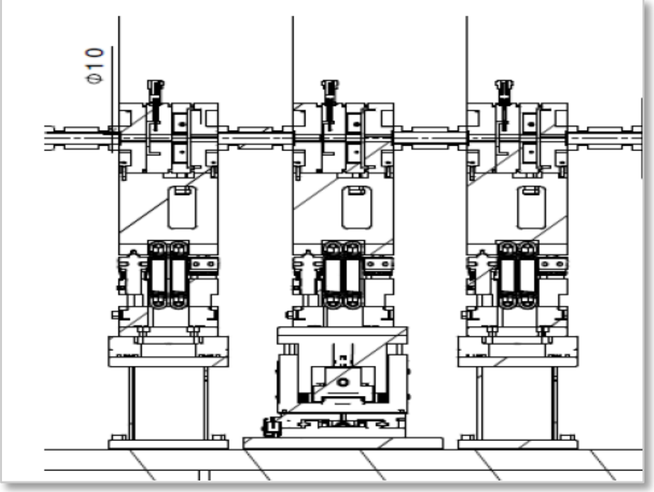
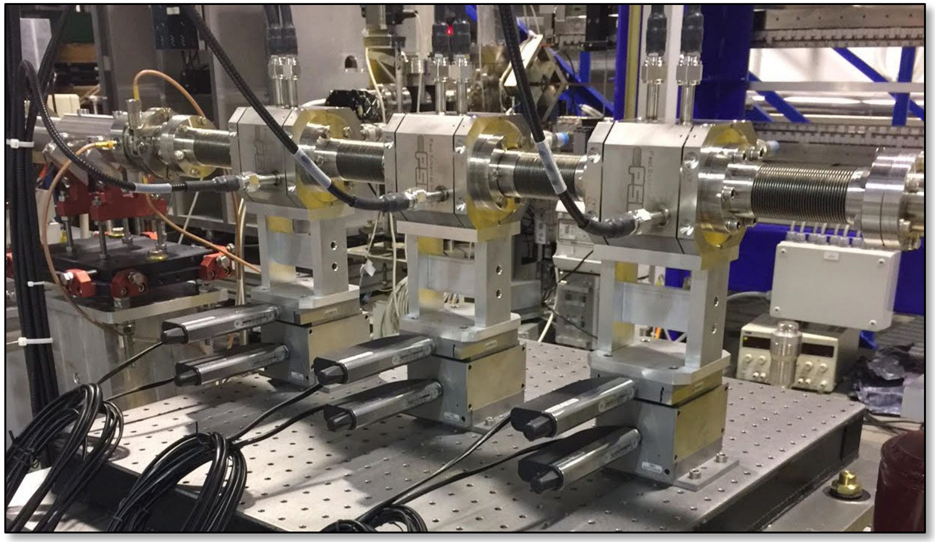
Conclusion

- **A resolution as low as 0.37 μm over a range of ±1.3 mm was obtained** for beam bunch of 200 pC and 500 pC.
- **Resolution depends on the beam position**, which could be justified by taking into accounts **jitter**. The problem is probably related to the reference signal provided to the system and can be addressed with a low jitter reference signal.
- **Measurements for beam at the e.m. center of the cBPM are problematic.** This issue can be partially compensated with the implementation of an algorithm that compensate the noise contribution on the signal amplitude.
- **Other measurements** (linearity, crosstalk between channels, frequency analysis of the signals,…) **were performed both in lab and with beam, showing good results** for ELI-NP GBS applications.
- **Further measurements are ongoing at SPARC-LAB**, to complete the characterization and to provide a starting point for the design of the **diagnostics of the EUPRAXIA linac**.

Test Bench at SPARC-LAB



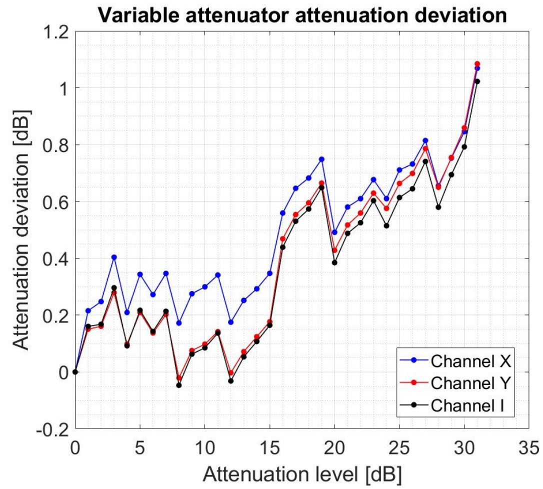


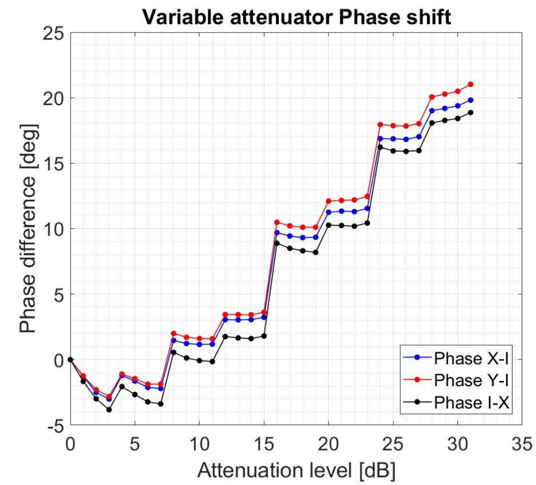


Thank you for your attention!

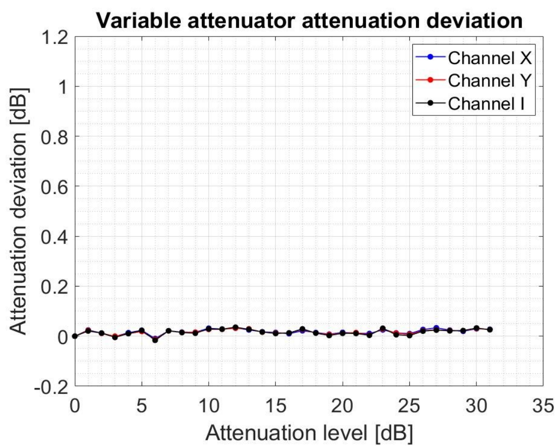
Spares

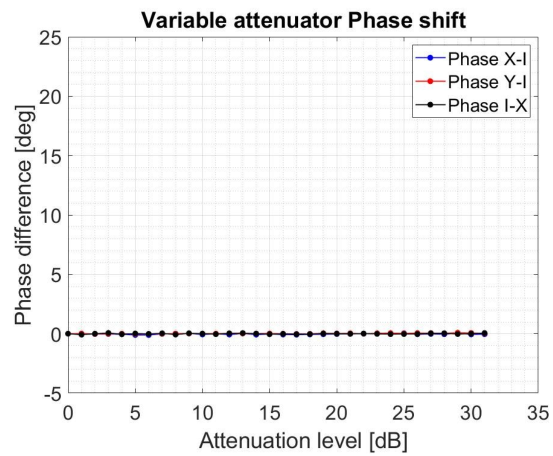
Attenuator Calibration





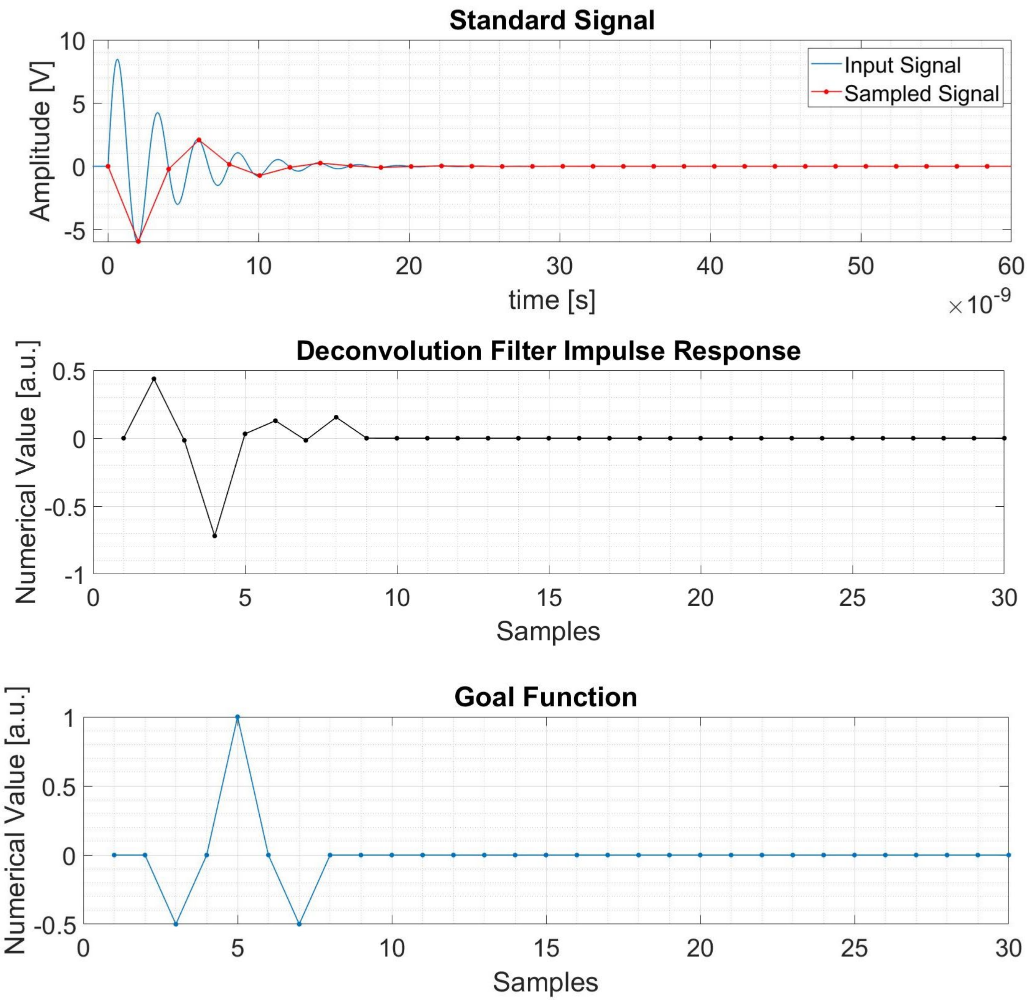
Calibration





- **Calibration of the variable attenuators:** if not performed, the variable attenuators could lead to variation of amplitudes of 1dB (~12%) (Accuracy deterioration).

Deconvolution Filter



$\mathbf{In(t)}$

$\mathbf{DF(t)}$

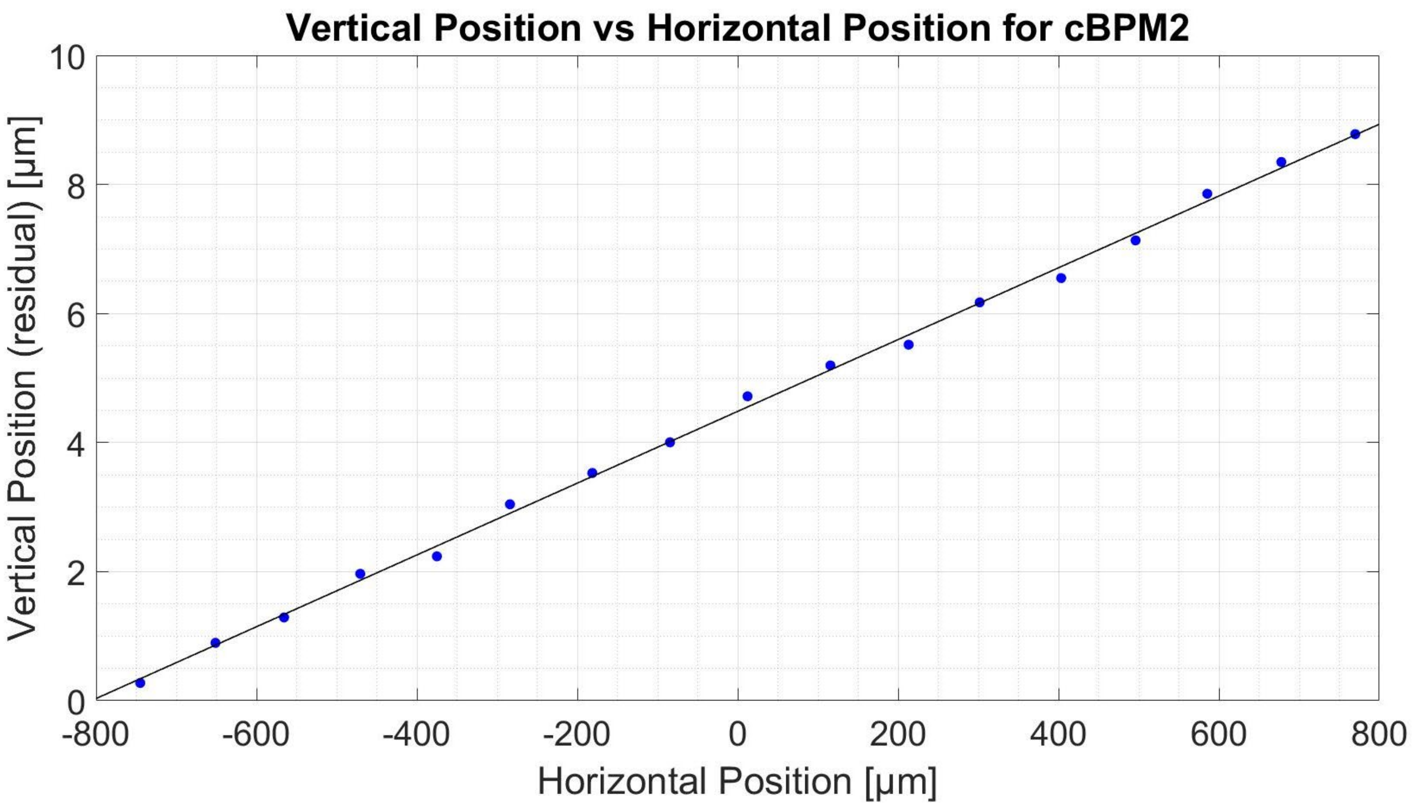
Previously calculated as:

$$DF(f) = \frac{Out(f)}{In(f)} \overset{iFFT}{\Longrightarrow} \mathrm{DF(t)}$$

$$\mathbf{Out(t) = DF(t) * In(t)}$$

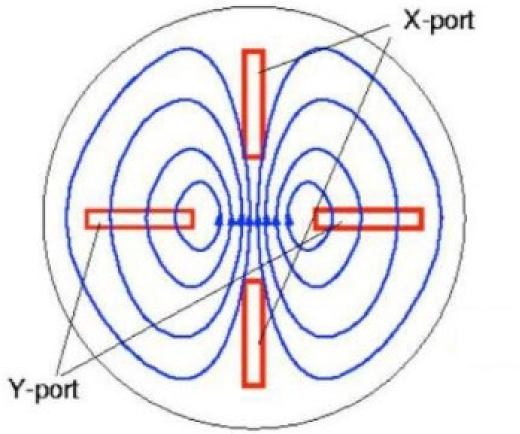
- To set the Deconvolution Filter, one has to provide a single bunch signal In(t) and define a goal function Out(t).
- After that, the DF filter will affect all the input signals (also multibunch).

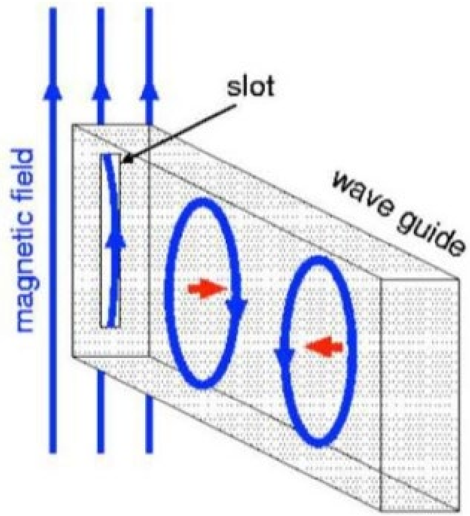
Crosstalk



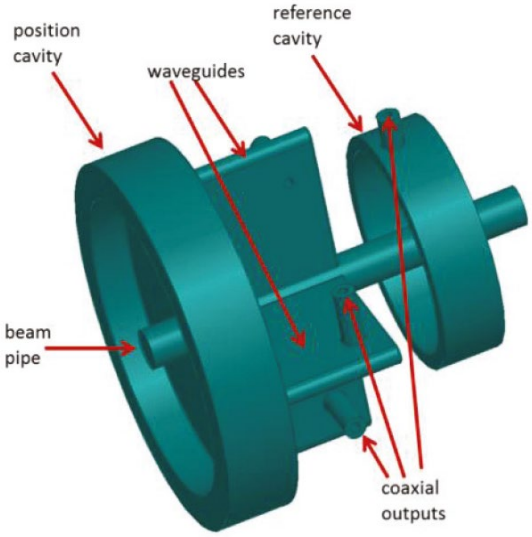
- **Correlation** coefficient between the vertical plane and the horizontal plane is **-45 dB (0.0056).**
- This could be elated to cBPM geometry, electrnics or test-stand misalignment

Waveguides





Courtesy of *T. Okugi (KEK)*



Courtesy of *F. Marcellini (PSI)*

- For the **"Position" cavity**, **waveguides** are used to isolate and extract the **dipole mode**.
- For the **"Reference" cavity**, a **probe** directly inserted into it is used to extract **the monopole mode**.