Libera Workshop 2022

Measurements with Cavity Beam Position Monitors and LIBERA Read-out Electronics at SPARC-LAB

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INSTRUMENTATION TECHNOLOGIES

What is a Cavity Beam Position Monitor?

- Cavity Beam Position Monitors (cBPM) are typically made up of two resonators (e.g. pillbox cavities).
- The passage of the beam excites e.m. fields within the resonators.
- By measuring the amplitude of the e.m. fields is possible to measure the beam position.

Features of Cavity Beam Position Monitors:

- **Pros:**
  - Potentially higher resolution than other types of BPM's.
  - Non-destructive measurements.
  - Device compactness (typically 10-15 cm in length).

- **Cons:**
  - Complex read-out electronics is required.
  - Short time intervals between bunches could be a problem.
  - Not suitable for rings (they could affect beam orbit).

Cavity Beam Position Monitor and EuPRAXIA

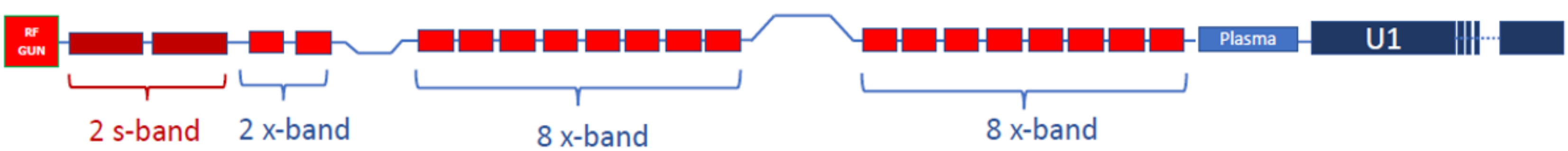
EuPRAXIA is a new accelerator complex to be built at INFN-LNF, that pursues two major goals:

- to have a FEL, based on a 1GeV compact, X-band LINAC;
- to test plasma wakefield acceleration and to possibly exploit it in order to reach higher energy.

<u>Timeline</u>:

- 2020: CDR published.
- 2025: publish the TDR.
- 2027: completion of the building, start of machine installation.

Possible layout

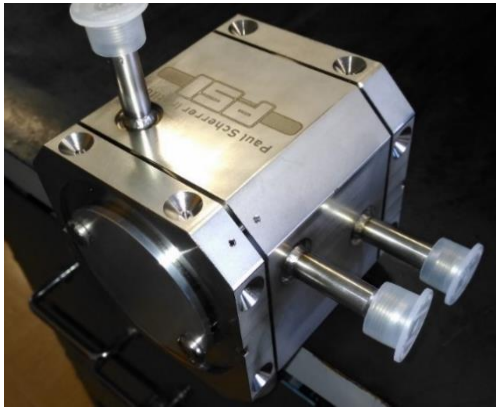


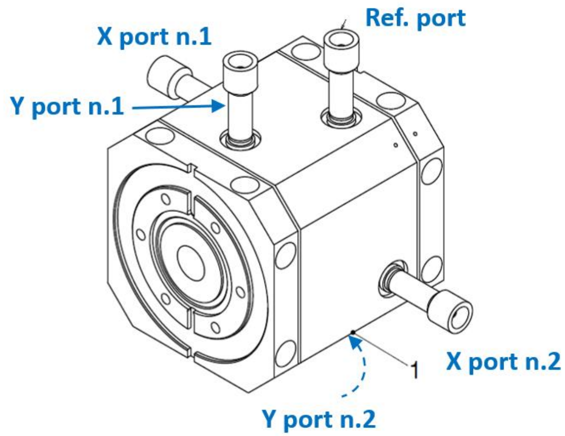
$L_{max} \simeq 60$ m (without Undulators)

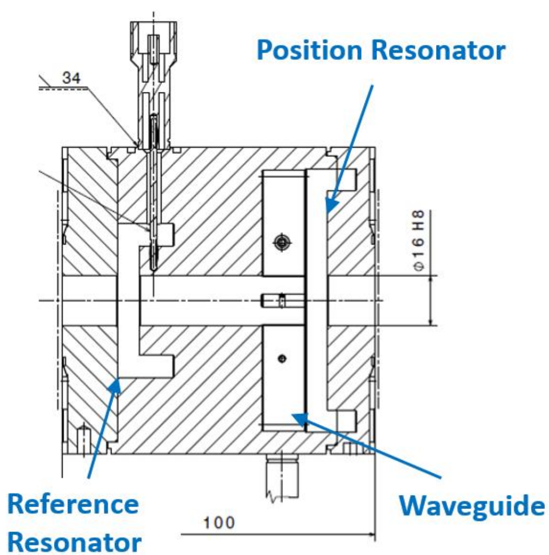
R&D on diagnostics is ongoing.
Cavity Beam Position monitors are one of the devices under study.

see: R.W. Assmann et al., "EuPRAXIA Conceptual Design Report", Eur.Phys. J. Special Tipics 229, 3675-4284 (2020)

Cavity BPM (PSI BPM16 Model)







General Pickup Parameters

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

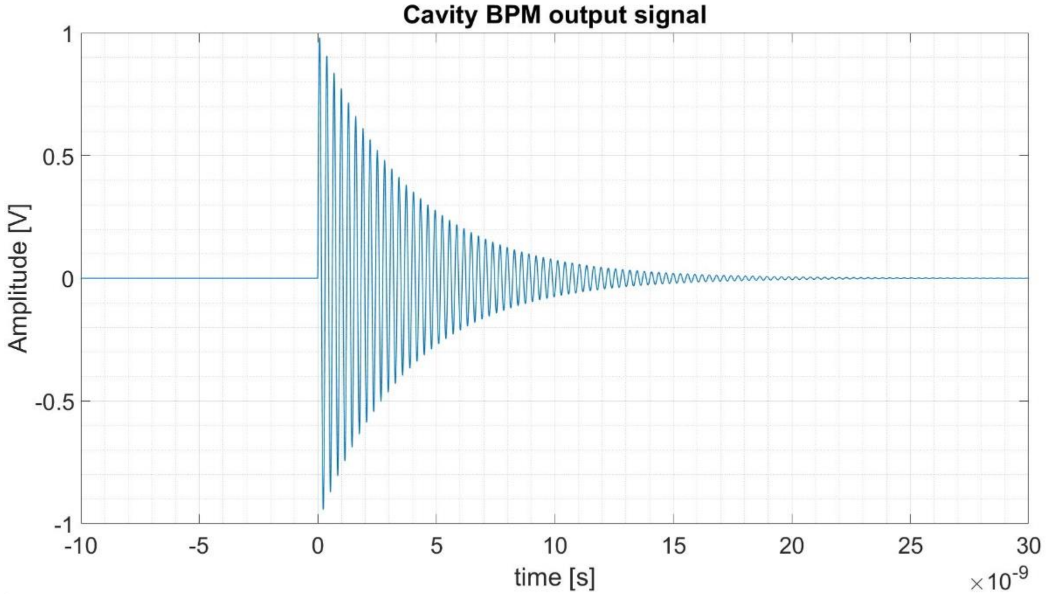
Position Resonator

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

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



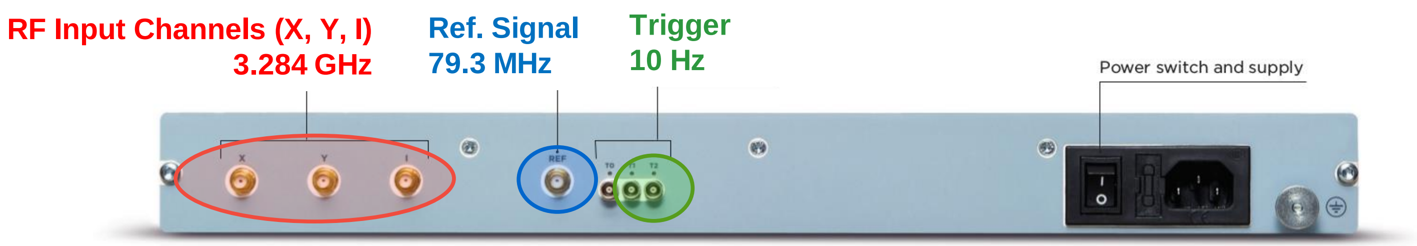
$$V_{out}(t) = A \cdot \sin(2\pi f_{res} t + \theta) \cdot e^{-t/\tau}$$

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

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**).

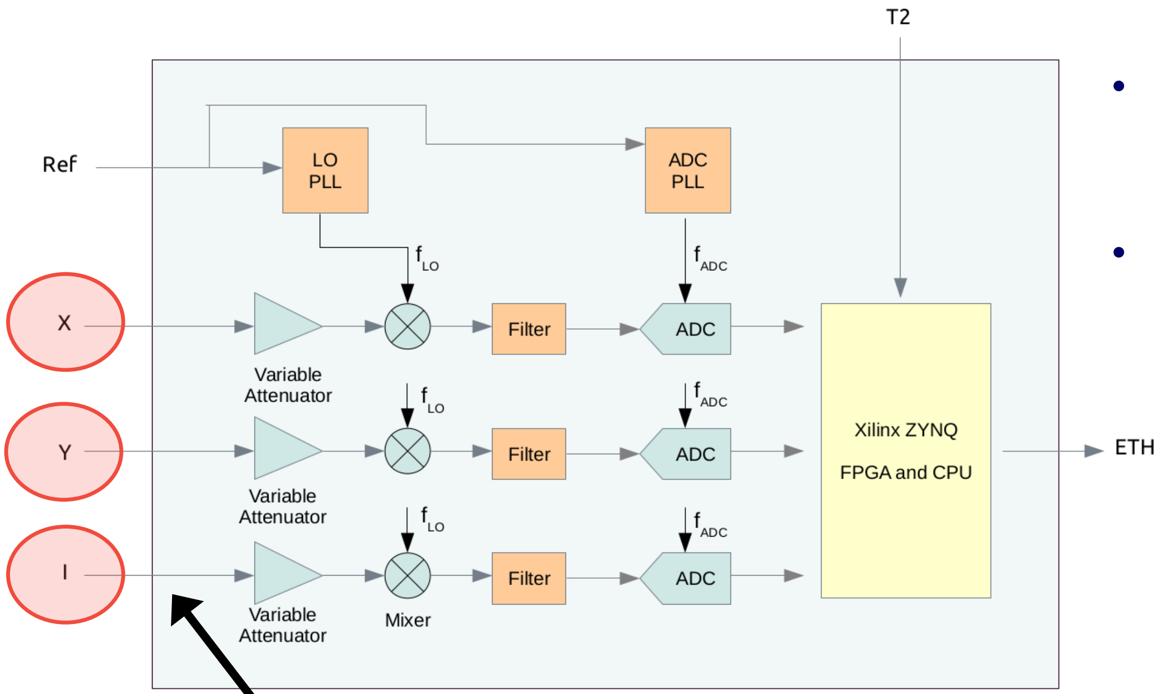
Readout Electronics 'LIBERA CavityBPM'



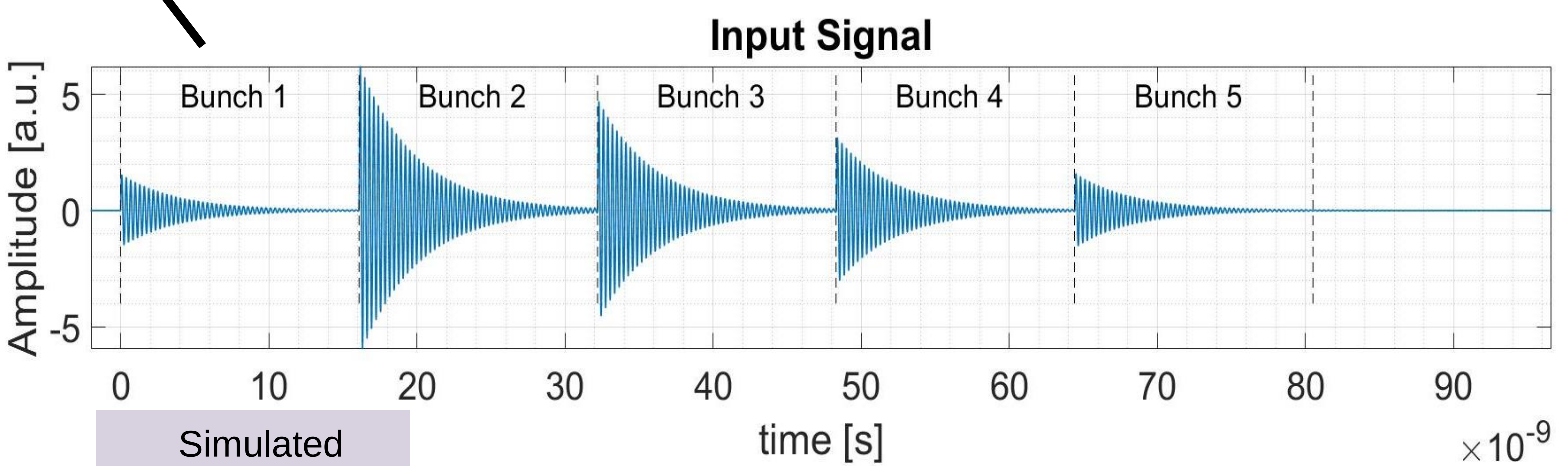
Main Specifications

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

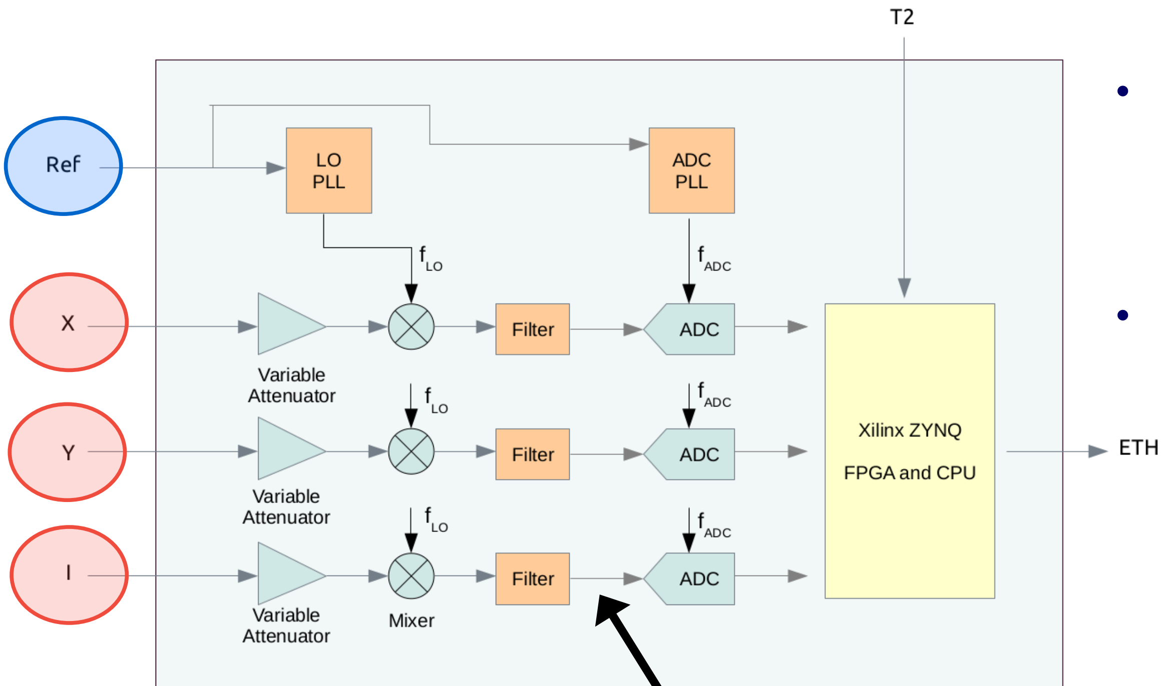
Signal processing (1/3)



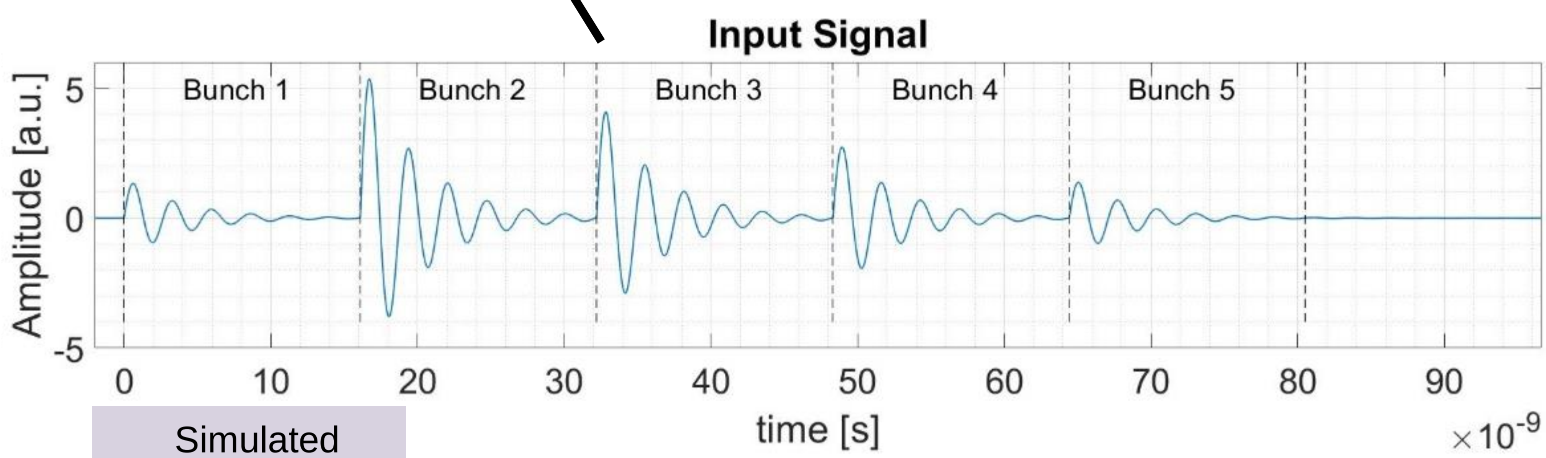
- RF signals (X, Y, I) use three identical and independent channels.
- They are filtered and attenuated by means of three configurable attenuators (0 / 31 dB).



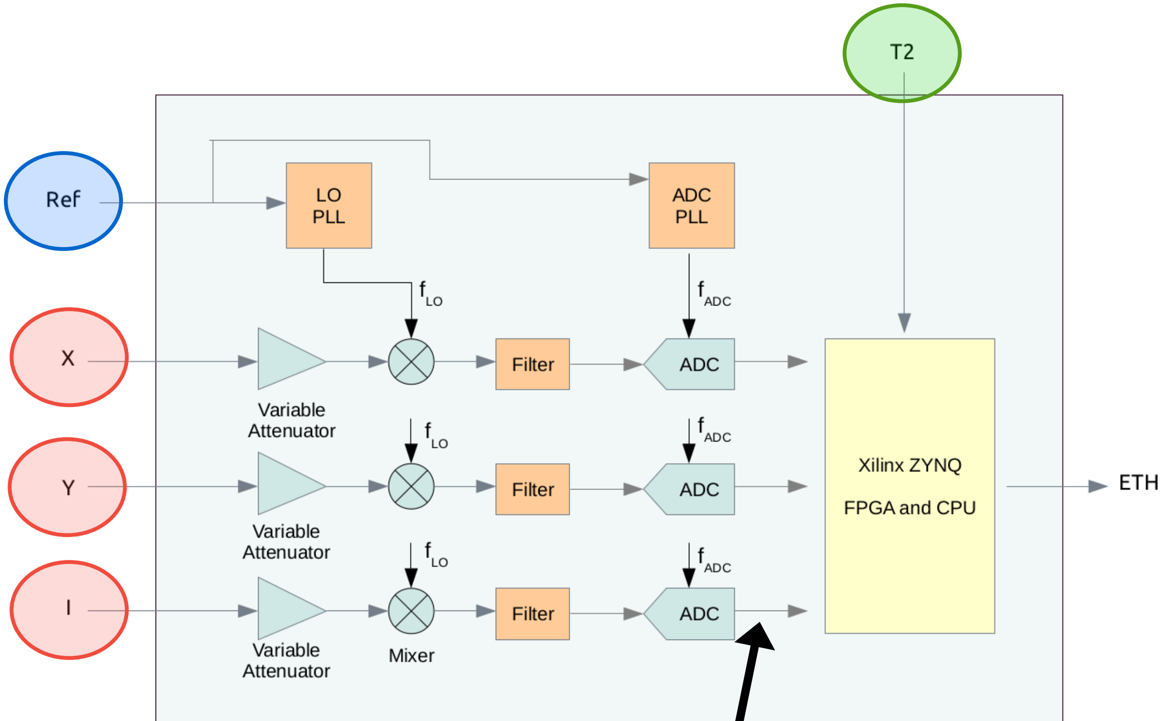
Signal processing (2/3)



- Reference signal (79.3 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.



Signal processing (3/3)



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

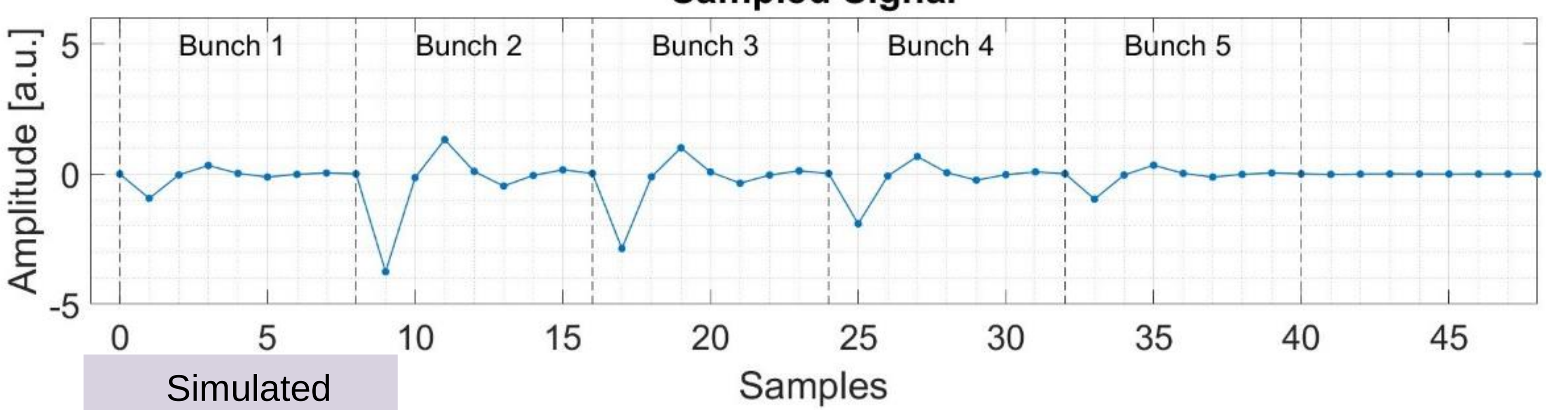
$$V_{Y_b} = \sqrt{\sum_{bth\ bunch\ window} {y_n}^2}$$

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

Calc. beam position

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

Sampled Signal



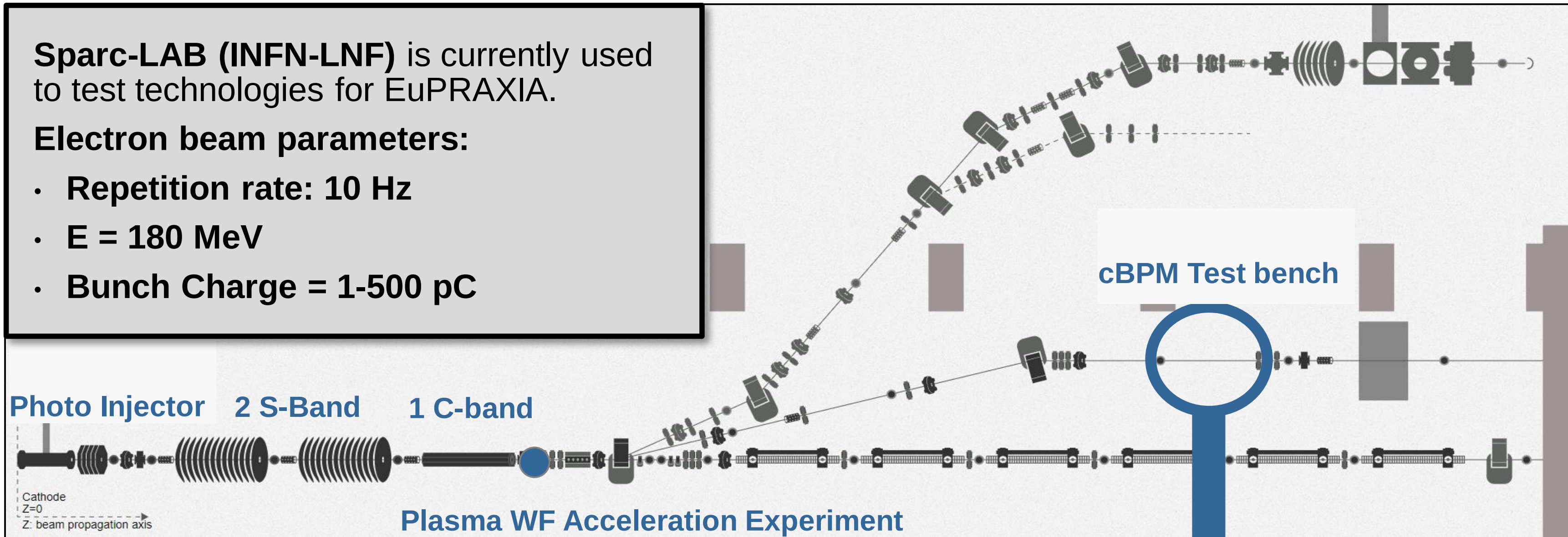
Simulated

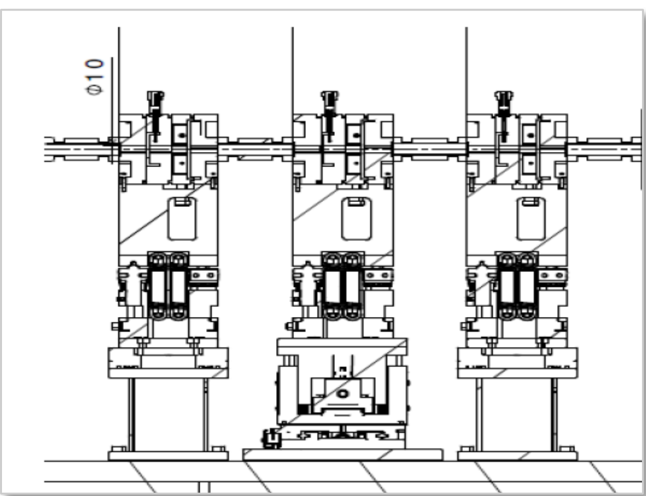
Test Bench at SPARC-LAB

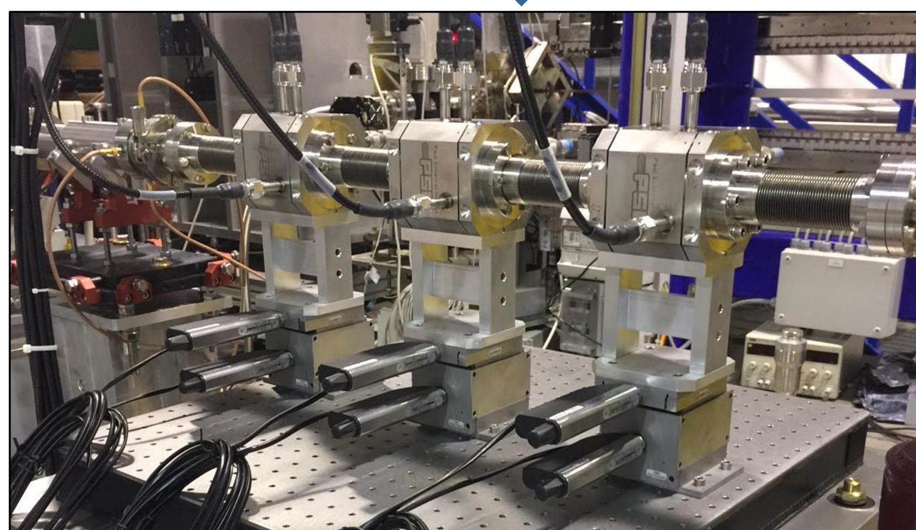
Sparc-LAB (INFN-LNF) is currently used to test technologies for EuPRAXIA.

Electron beam parameters:

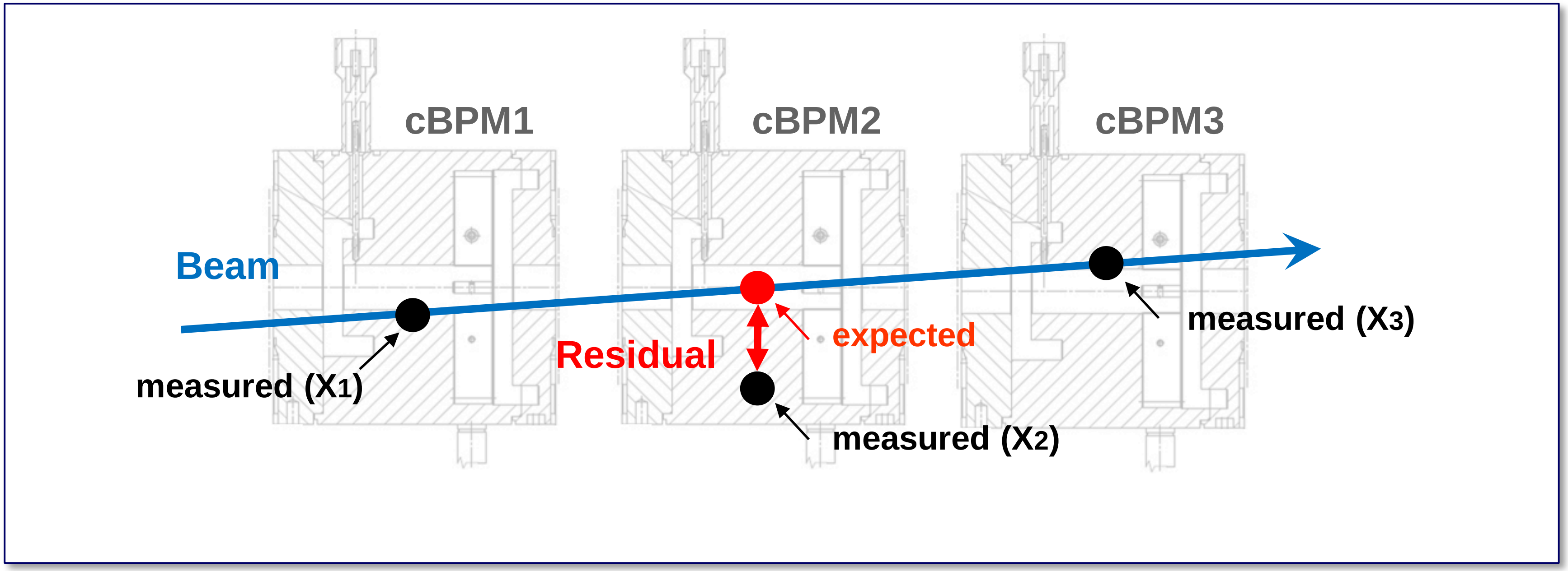
- **Repetition rate: 10 Hz**
- **E = 180 MeV**
- **Bunch Charge = 1-500 pC**







Resolution Measurements

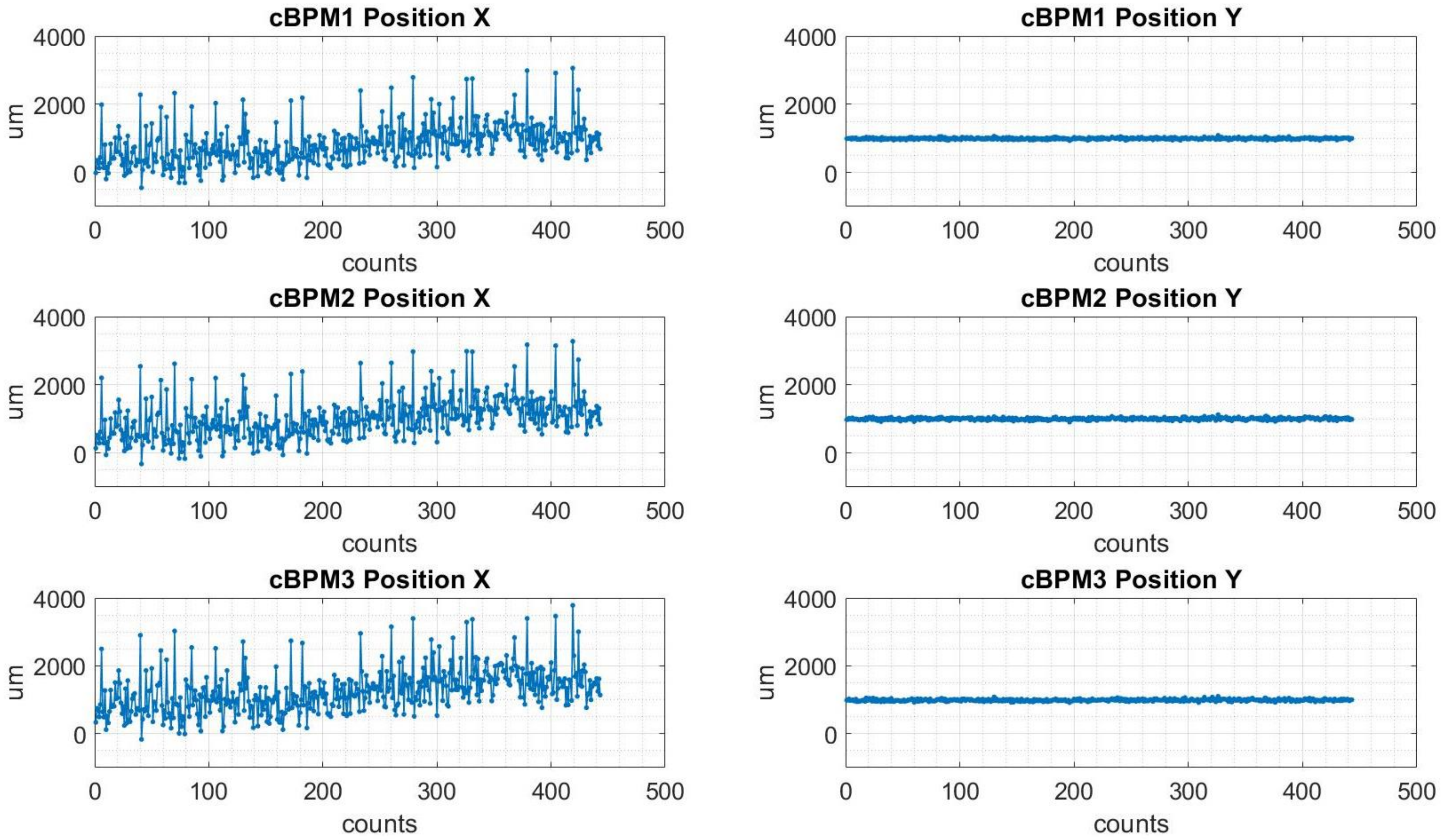


$$ResX_2 = X_2 - \frac{X_1 + X_3}{2}$$

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

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).

all cBPMs – Q=20pC



- Position X is much more unstable than Y.
- We focused on Position Y for resolution measurements.

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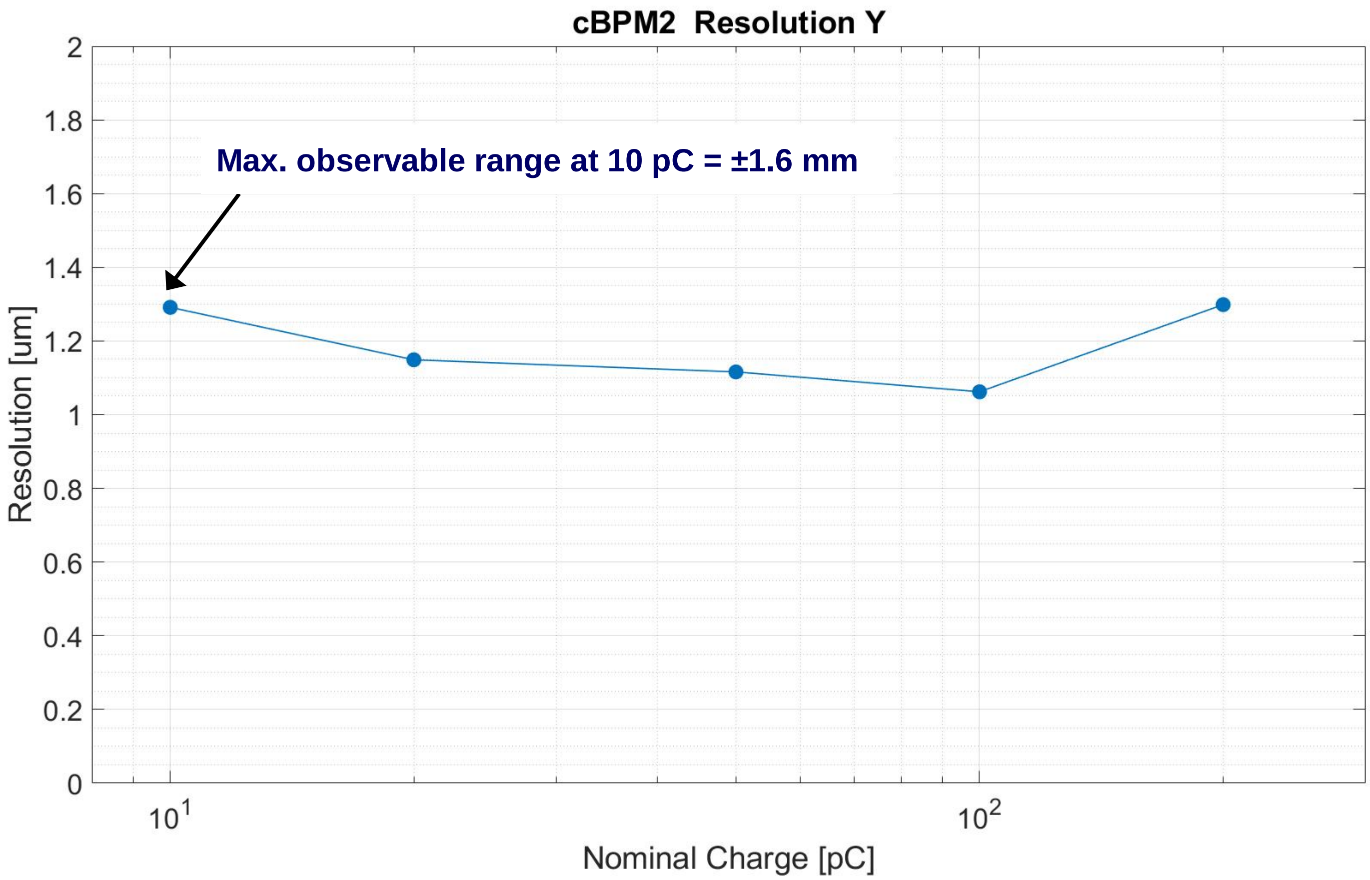
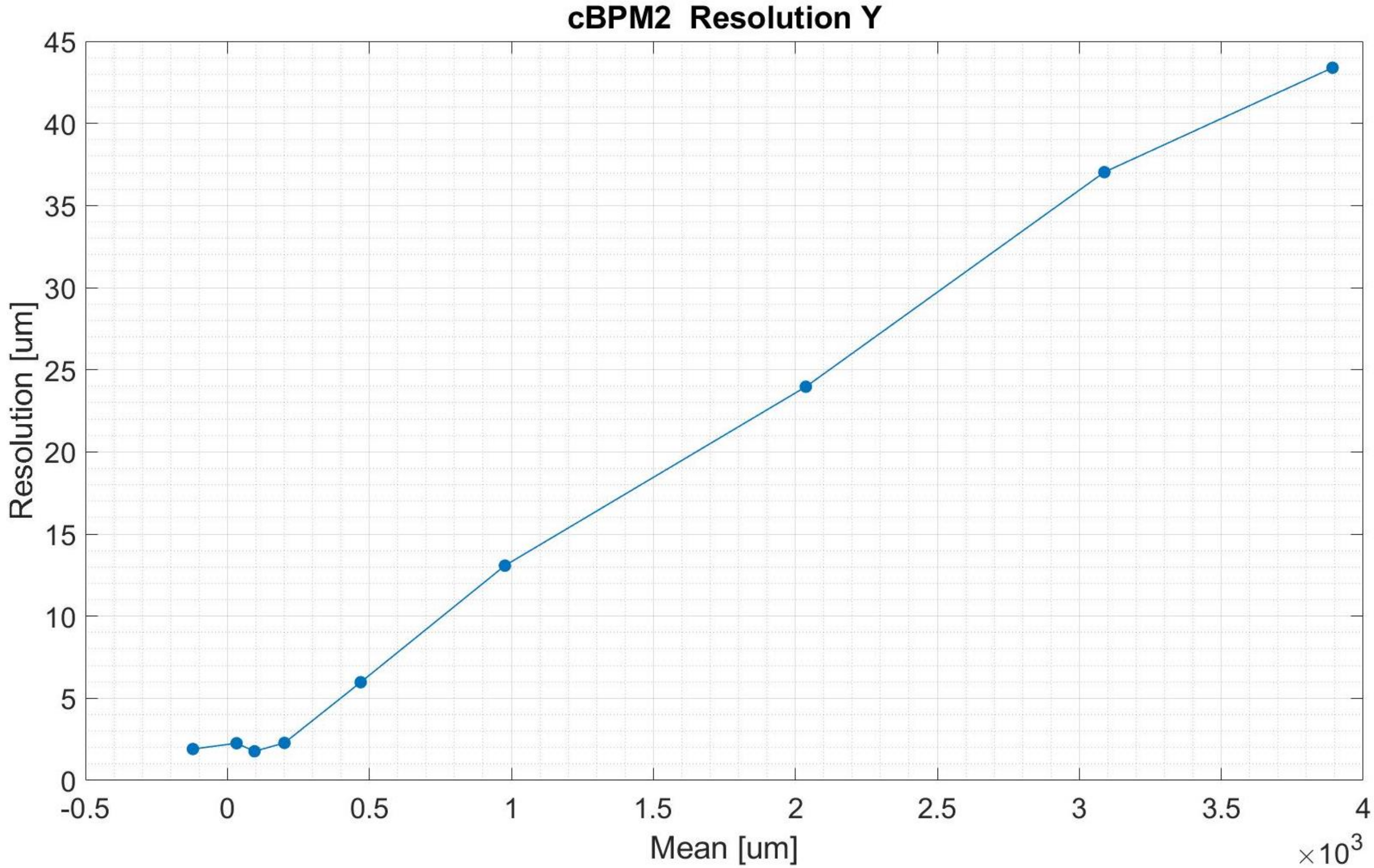
Resolution on Y – Charge sweep at Y=0.1 mm



- Resolution measured with the method of residuals.
- Resolution was calculated on hundreds of acquisitions for each bunch charge value.
- Attenuations were adjusted for each bunch charge value (maximum observable range changes for each bunch charge value).

Resolution on Y – Position Y sweep – Q=20pC



- Resolution depends on beam position (linear dependency).
- At low beam positions (<0.2 mm), resolution is almost costant.
- **A possible explanation is that the measuring system is phase-noise dominated.**

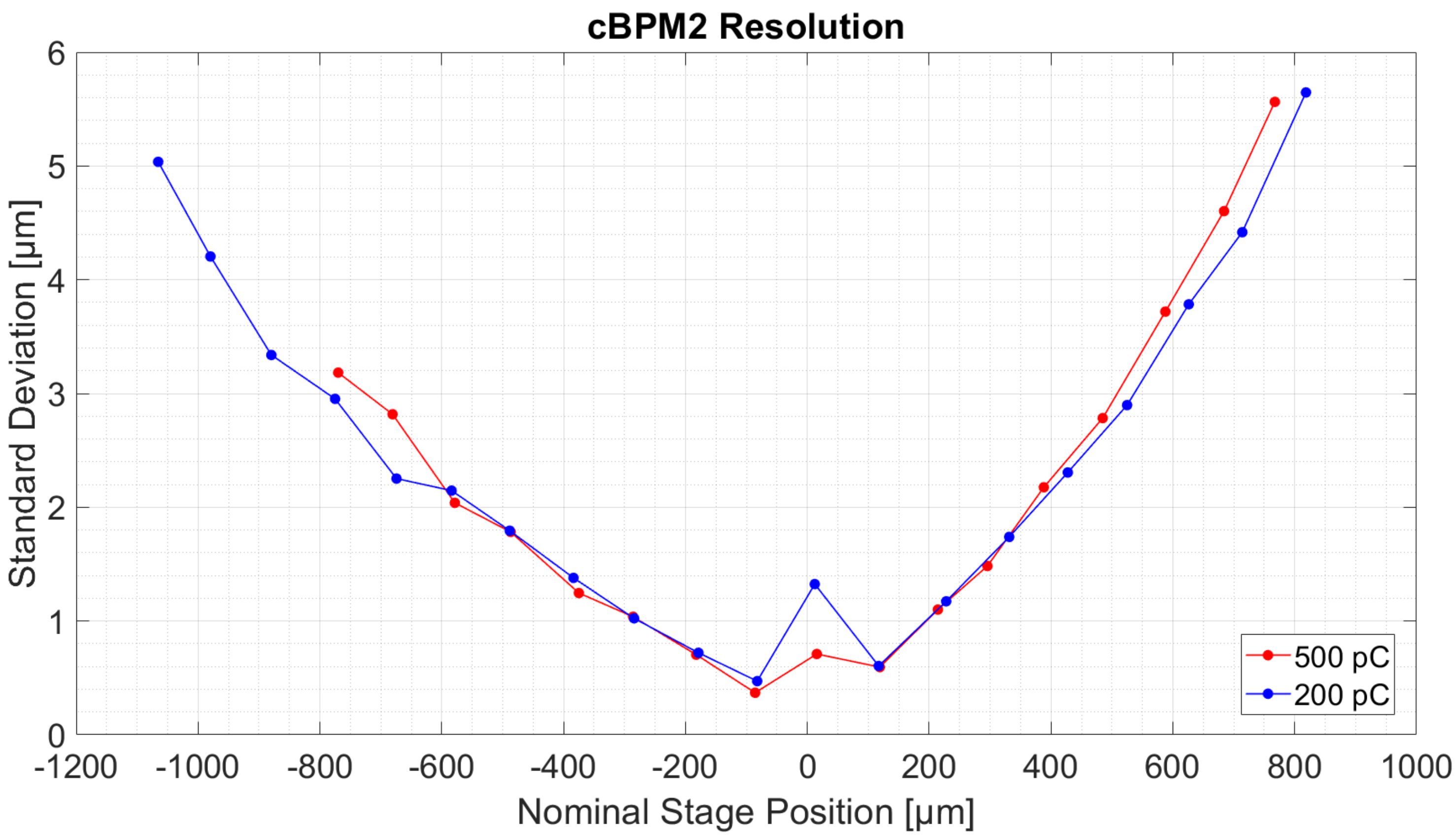
Measurements at FLASH1 (DESY) - 2017

Courtesy of
D. Lipka

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

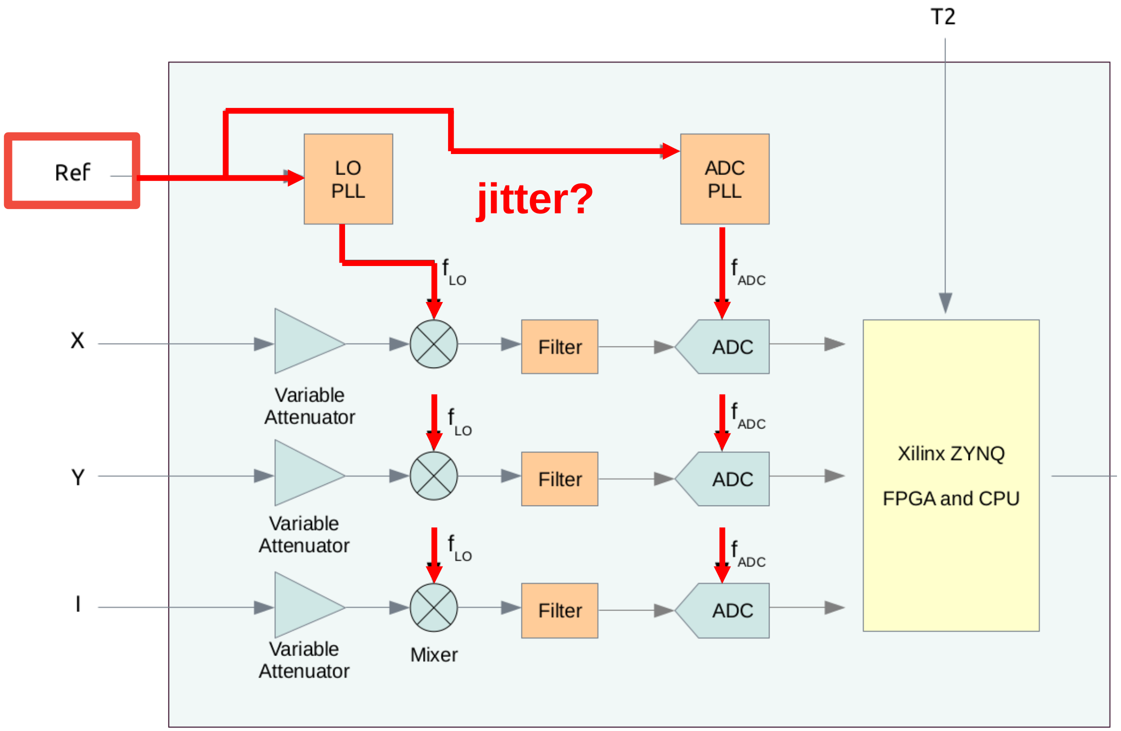
see: G. Franzini et al., "Measurements with the ELI-NP Cavity beam Position Monitor Read-out Electronics at FLASH", Proceedings of IPAC'18, 2169-2172, Vancouver, Canada (April 2018)

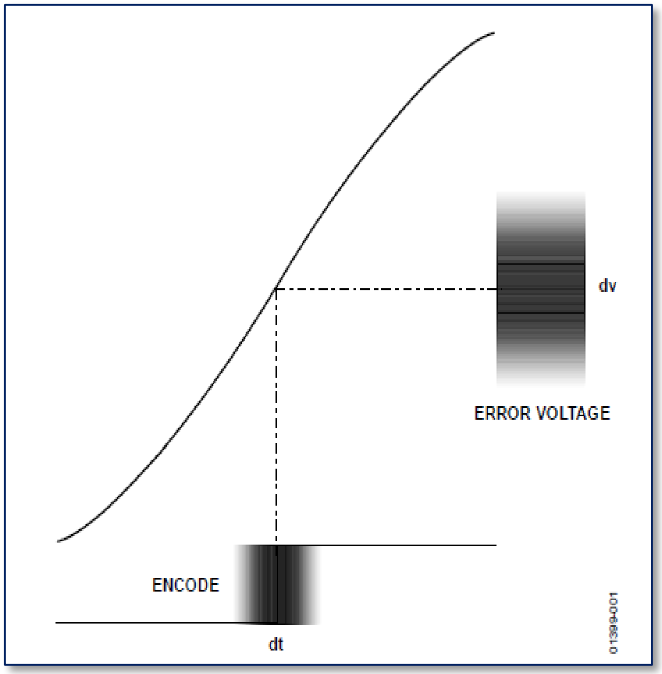
Resolution Measurements at FLASH1 (DESY)



- **Resolution measurements performed at DESY show the same behaviour** (although the resolution was overall better on similar conditions).
- **Resolution get worse at the center for a known problem of the electronics**: the latter is not capable to recognize the sign of the signals coming from the cBPM when the signals are small (i.e. position is around e.m. center of cBPM).

Hypothesis: Measurement resolution affected by jitter

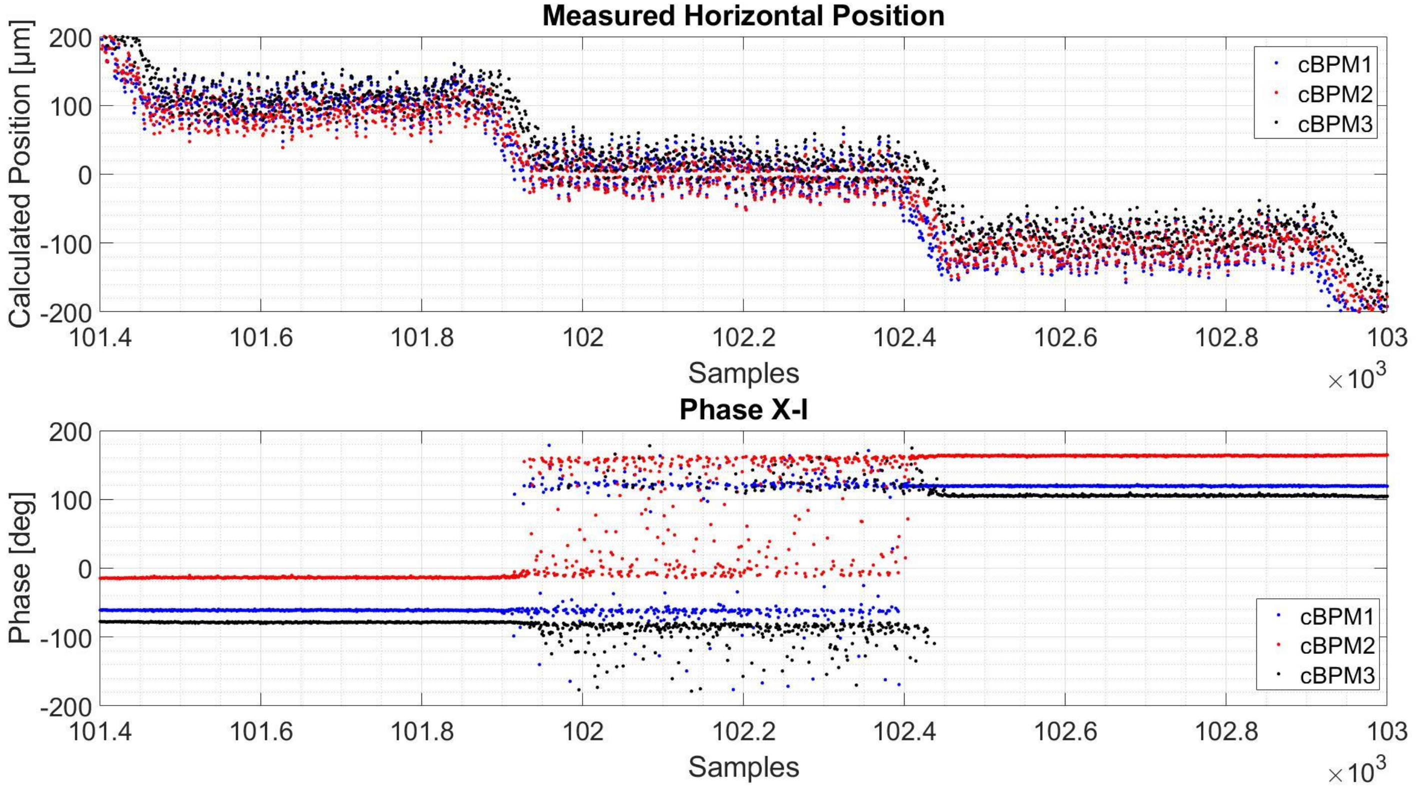




Noise induced by jitter: $V_{err} = 2\pi \cdot A \cdot f \cdot t_{jit}$

- **Noise induced by jitter could explain the resolution dependency on the signal level**
- A jitter on the reference signal (or introduced by the electronics) is translated to an **amplitude-dependent noise**.
- **Reference signal Jitter at DESY: 3.2 ps; at SPARC-LAB: 0.7 ps.**

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 compensates 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).**

Ideas and Conclusions

- Resolution of the system is heavily affected by noise proportional to the signal amplitude.
- We did not find a clear explanation for it, although we believe it could be related to phase noise.
- High-Q cBPM would be less affected by it, because the signals would be longer in time.
- Further testing will be done in the future. To reduce this type of noise a possible solution is to guarantee that X,Y,I input signals have the same phase (suggestion from Borut Baricevic).
- Other types of behaviours (e.g. crosstalk, gain differences) of the measuring system have been measured and could be digitally compensated.

Thank you for your attention!

Spares

Other behaviours

GAIN

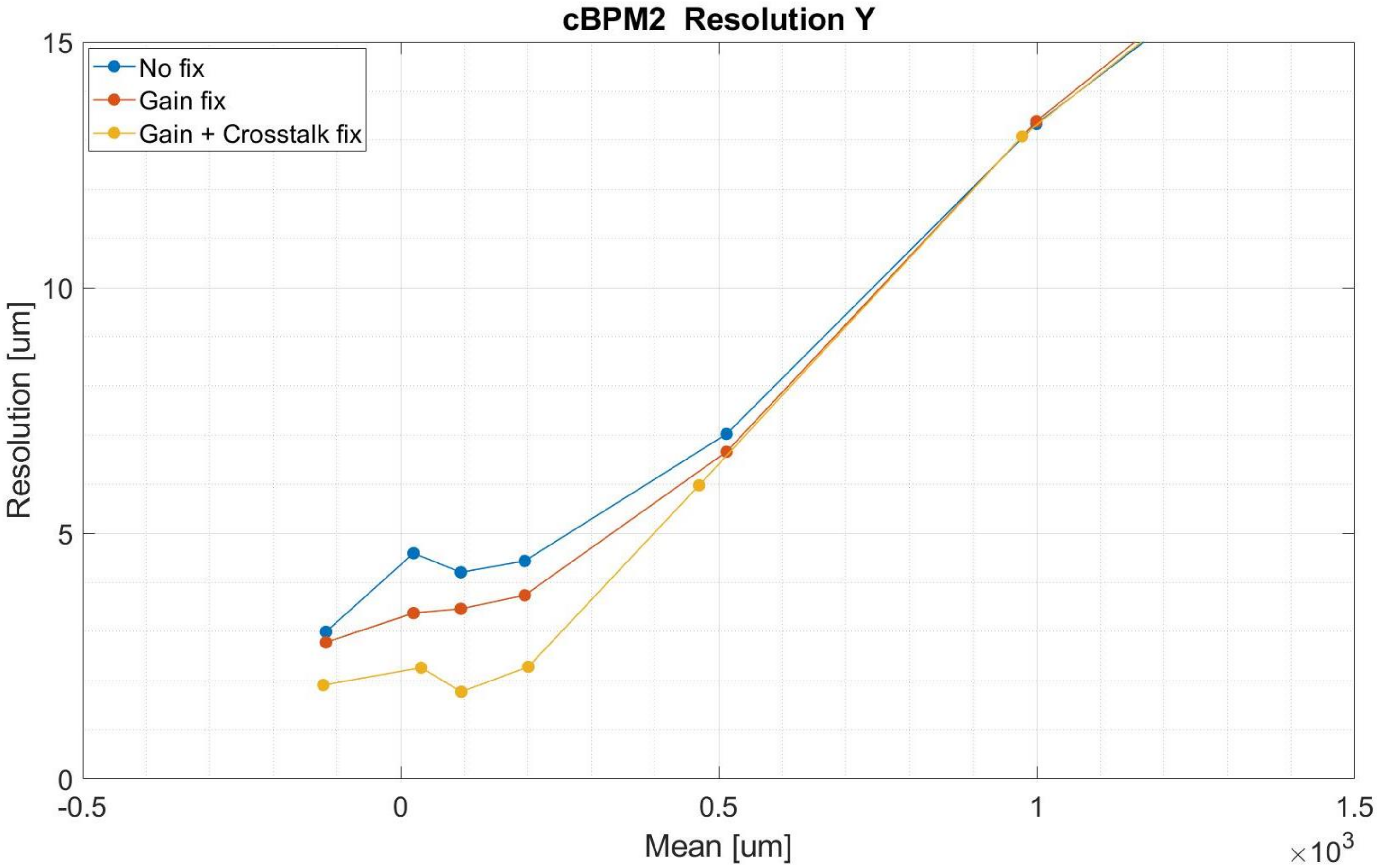
- **We noiticed a substantial difference in Gain between the three cBPMs.**
- Calculated gain ratio:
  - cBPM1 / cBPM2 = 0.88
  - cBPM3 / cBPM2 = 0.93
- The gain difference could be related both to the cBPM and the Electronics (should be tested further).

CROSSTALK

- We noticed a dependency between the Y position and the X position.
- Calculated Dependency:
  - cBPM1: $Y = 0.0013 \cdot X$
  - cBPM2: $Y = 0.0074 \cdot X$
  - cBPM3: $Y = 0.0046 \cdot X$
- This is probably related to a mechanical misalignment of the cBPM's.

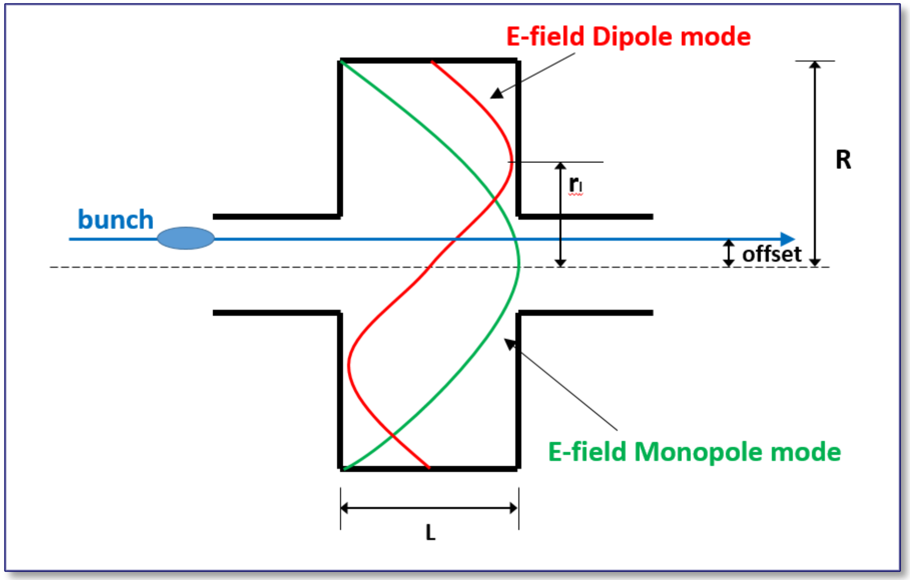
- **These two behaviours affect the resolution measurements.**

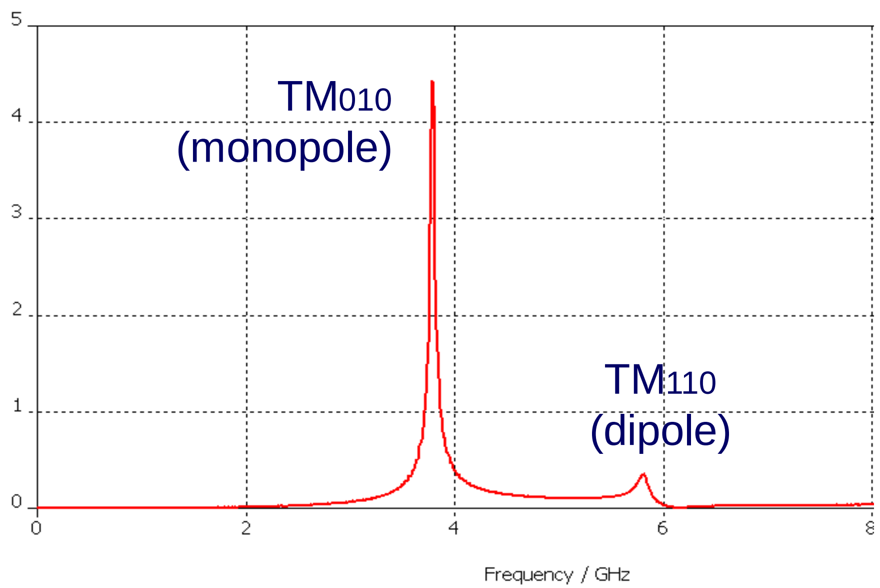
Resolution on Y – Q=20pC - data elaborations



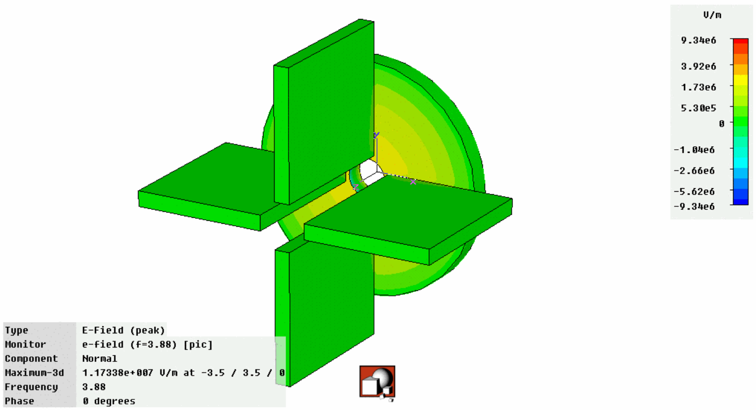
- Compensation of gain differences and crosstalk was performed on collected data.
- Their effects are masked for positions higher than 0.2 mm, because the amplitude-dependent noise is dominant.

Cavity BPM (pillbox resonator)

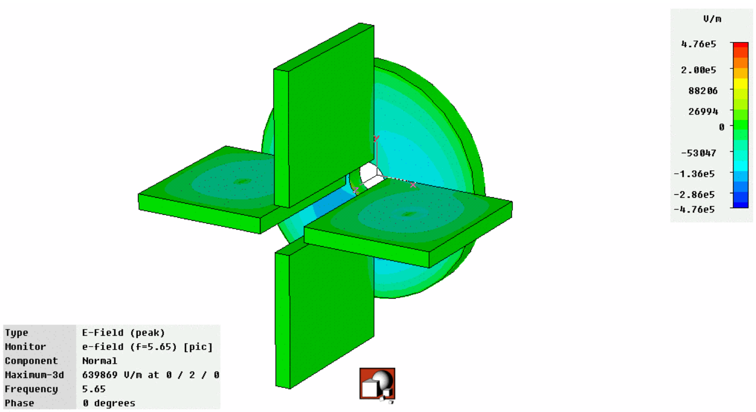




monopole mode

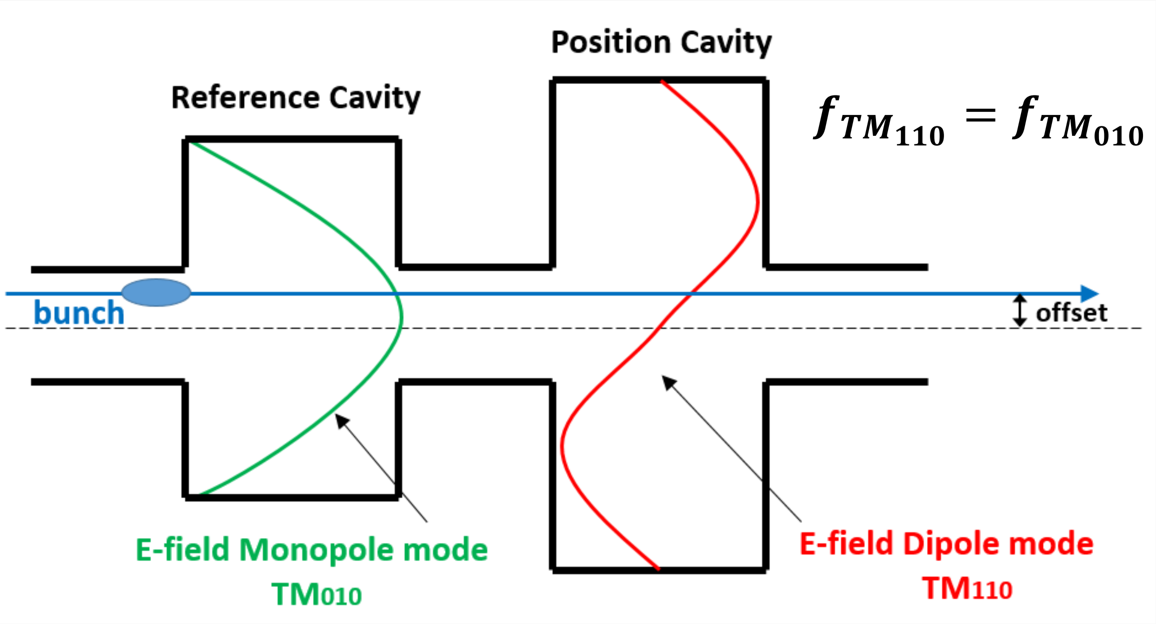


dipole mode



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.