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# Resolution and static waveform studies in IP BPMs

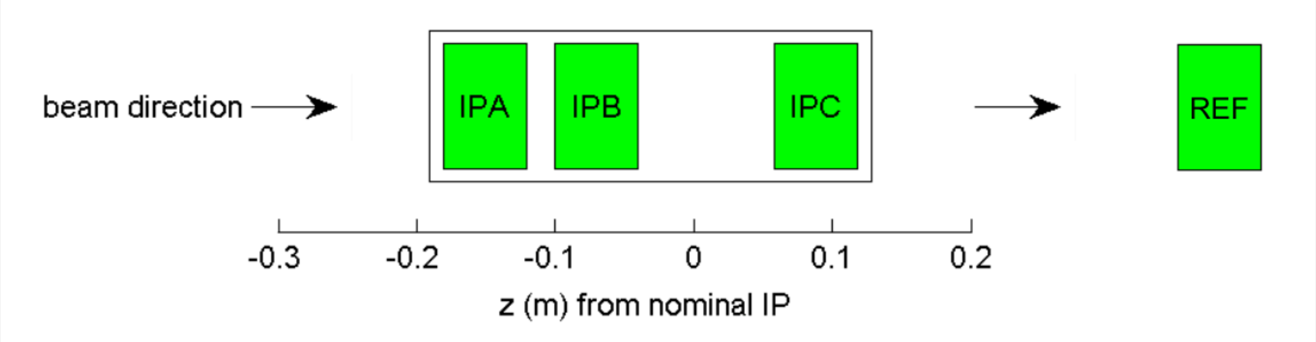
N. Blaskovic, T. Bromwich, P. Burrows, G. Christian, C. Perry, R. Ramjiawan
*FONT, John Adams Institute, University of Oxford*

Thanks also to the IPBPM collaboration group, particularly T. Tauchi (ATF) and S. Yang (KNU) for their help with these studies

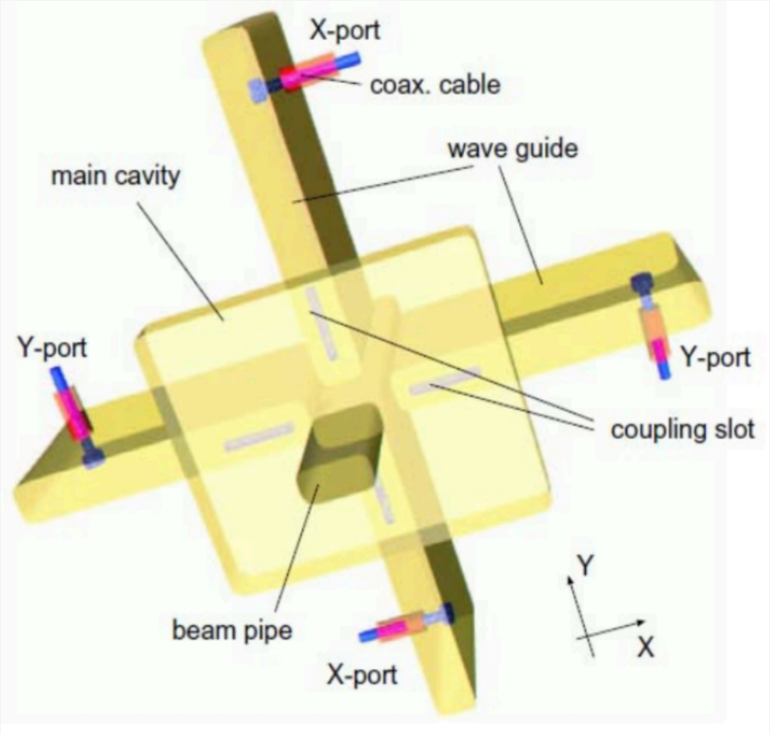
# Outline

- Summary of IP BPMs and associated electronics
- 3BPM resolution analysis
- Unwanted static waveform studies
  - BPFs on electronics
  - Cable mismatches from the dipole cavity to the outside of the chamber
  - Delay cables
  - Symmetric modes in dipole cavity using splitter instead of hybrid
  - Amplitude of 60 MHz waveform with changing charge
  - 2-port on IPBY
- Position sensitivity to phase in IP BPMs

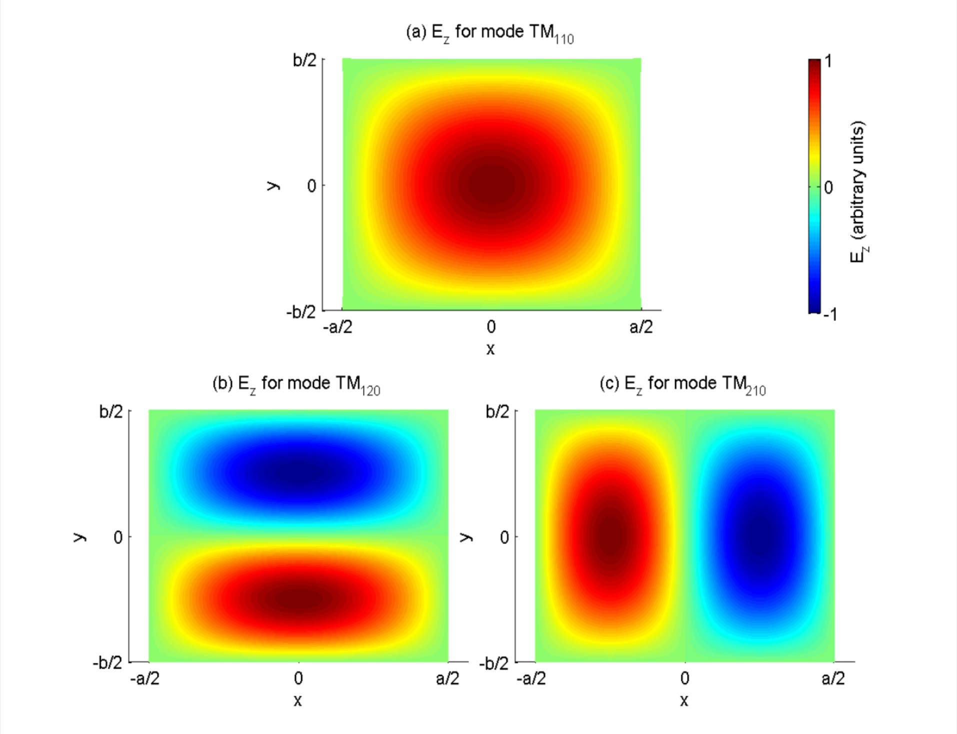
# The ATF IP cavity BPMs




Relative positions (z) of BPMs in the ATF beamline. (Image credit: Neven Blaskovic Kraljevic, PhD Thesis, University of Oxford, 2015)




IP dipole cavity BPM waveguide design. (Image credit: Tomoya Nakamura, Masters Thesis, University of Tokyo, Feb 3, 2008)




Cavity modes. (Image credit: Neven Blaskovic Kraljevic, PhD Thesis, University of Oxford, 2015)

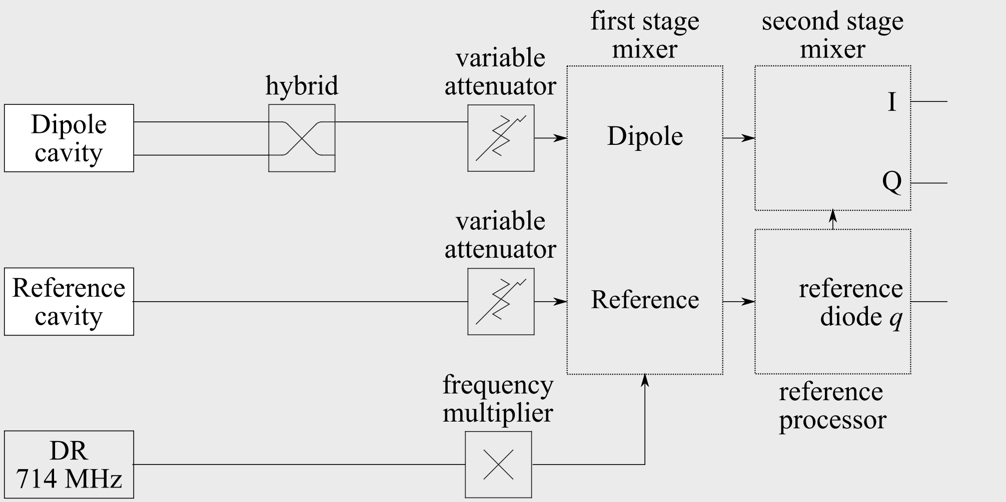
# IP BPM associated electronics

**Dipole cavity** designed for position-dependent dipole mode, **reference cavity** for charge-dependent monopole mode.

Two ports of dipole cavity combined by **hybrid**, doubling power and cancelling monopole.

**Variable attenuators**
0 to 70dB in 10dB steps.

**First stage** reduces frequency by combining up-multiplied DR local oscillator with cavity signals to output a 714 MHz.

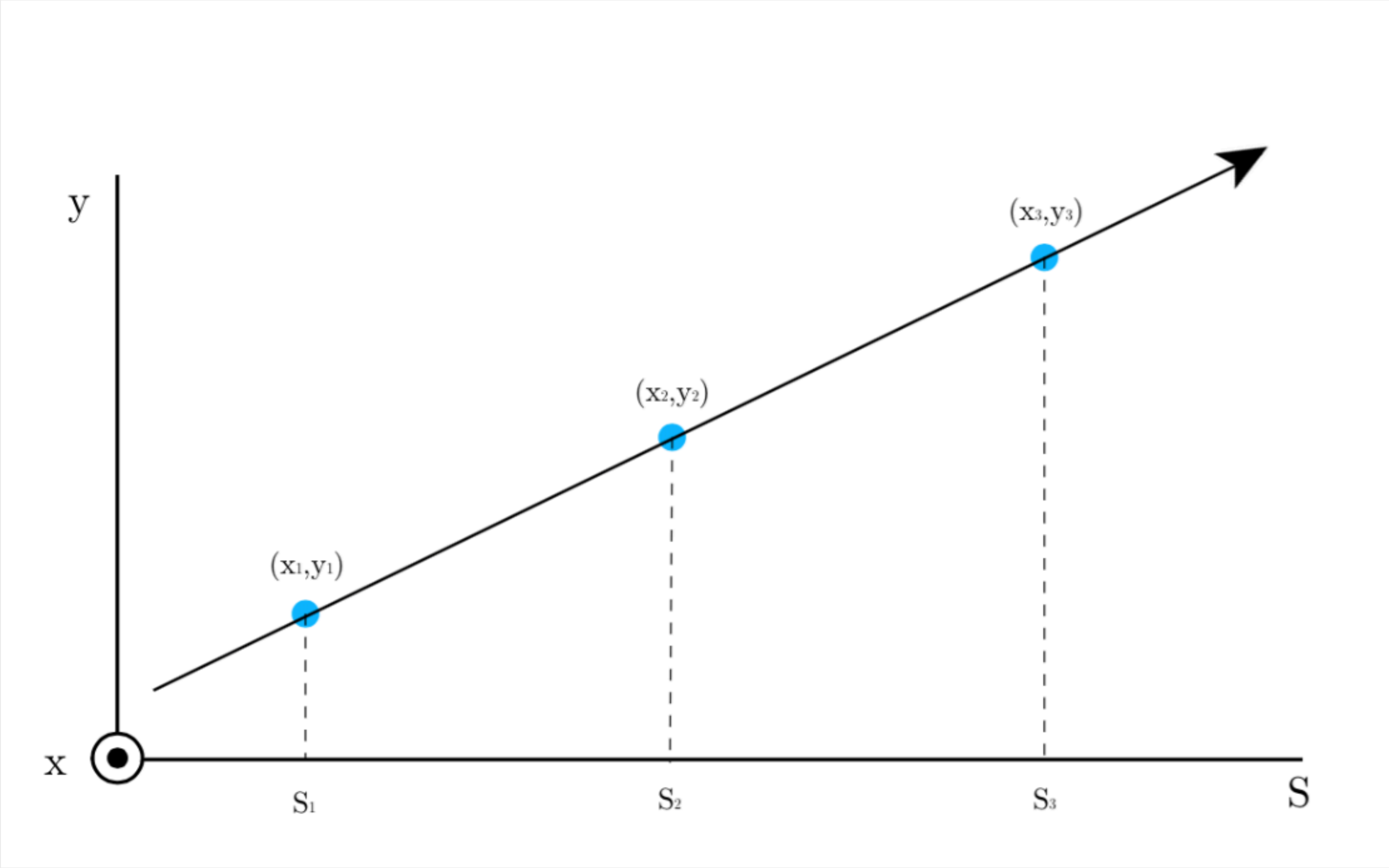



IP BPM processing electronics
Image credit: Neven Blaskovic Kraljevic

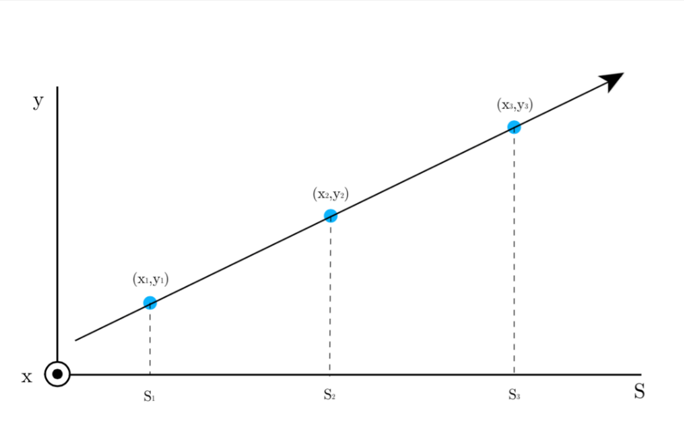
**Second stage** multiplies reference and dipole for **I signal** (position dependent), and 90° phase-shifted reference with the dipole for **Q signal** (angle dependent). I, Q, and **q**, are digitised to extract the beam position.

# 3BPM resolution

Use the measured signal at two IP BPMs to predict the position at the third. Then compare the prediction with what was actually measured at the third BPM.



# Geometric method




Use known separations of the BPMs to predict vertical position at BPM 2:

$$\hat{y}_2 = y_1\left(1 - \frac{s_2 - s_1}{s_3 - s_1}\right) + y_3\left(\frac{s_2 - s_1}{s_3 - s_1}\right).$$

Residual is the difference between the predicted and measured position:

$$\Delta_{y_2} = y_2 - \hat{y}_2, \quad = y_2 + y_1\left(\frac{s_2 - s_1}{s_3 - s_1} - 1\right) - y_3\left(\frac{s_2 - s_1}{s_3 - s_1}\right).$$

Apply error propagation to find standard deviation of the residual in terms of the resolution at the BPMs:

$$\sigma^2_{\Delta_{y_2}} = \left(\frac{s_2 - s_1}{s_3 - s_1} - 1\right)^2 \sigma^2_{y_1} + \left(1\right)^2 \sigma^2_{y_2} + \left(-\frac{s_2 - s_1}{s_3 - s_1}\right)^2 \sigma^2_{y_3}.$$

Assume resolution the same at all three BPMs and rearrange:

$$\sigma_G = \frac{\sigma_{\Delta_{y_2}}}{\sqrt{\left(\frac{s_2 - s_1}{s_3 - s_1} - 1\right)^2 + 1 + \left(\frac{s_2 - s_1}{s_3 - s_1}\right)^2}}$$

# Fitting method

Instead of constraining the position prediction to the known geometric separations, apply a linear fit:

$$\hat{y}_2 = \alpha_2 y_1 + \beta_2 y_3 + \gamma_2.$$

Following exactly the same logic as for the geometric method, the resolution becomes:

$$\sigma_{F2} = \frac{\sigma_{\Delta_{y2}}}{\sqrt{1 + (\alpha_2)^2 + (\beta_2)^2}}.$$

Allowing the fitting coefficients for different BPMs to be unconstrained, means the three different calculations for residuals at different BPMs will result in three different BPM vertical position resolutions (unlike the geometric method which produces only one).

# Fitting before calibrating

Instead of converting signals into a position, y, and then applying the geometric or fitting method to find the resolution, others in the ATF IPBPM collaboration instead apply a fit to the I' and Q' or raw I and Q signals, and convert to a position measurement after the residual has been determined.

Fitting with I and Q means using only one calibration constant for the BPM where you are predicting, instead of all three required to convert to positions at the beginning.
It also means any remaining position dependence in the Q' signal is incorporated.

$$\hat{I}'_2 = \alpha_2 I_1 + \beta_2 Q_1 + \rho_2 I_3 + \eta_2 Q_3.$$

$$\sigma_{y_2} = \frac{k_2 \sigma_{\Delta_{I'_2}}}{\sqrt{1 + \left(1 - \frac{s_2 - s_1}{s_3 - s_1}\right)^2 + \left(\frac{s_2 - s_1}{s_3 - s_1}\right)^2}}$$

# Multi-parameter fit

It is possible to include additional fit terms, such as x-port signals, or the beam charge.

$$\hat{I}'_{y2} = \alpha_2 I_{y1} + \beta_2 Q_{y1} + \rho_2 I_{y3} + \eta_2 Q_{y3} + \lambda_2 I_{x1} + \xi_2 Q_{x1} + \tau_2 I_{x3} + \mu_2 Q_{x3} + \nu_2 REF_y.$$

This involves making separate assumptions about the predicted position signal and actual position. Here, for example, you include x and and q in the definition of predicted y:

$$\hat{y}_2 = A_2 y_1 + B_2 y_3 + C_2 x_1 + D_2 x_3 + E_2 REF_y,$$

But once the fit has been performed, the resolution must then be calculated by adopting a geometric-dependent model of the actual position:

$$\hat{y}_2 = y_1 \left(1 - \frac{s_2 - s_1}{s_3 - s_1}\right) + y_3 \left(\frac{s_2 - s_1}{s_3 - s_1}\right).$$

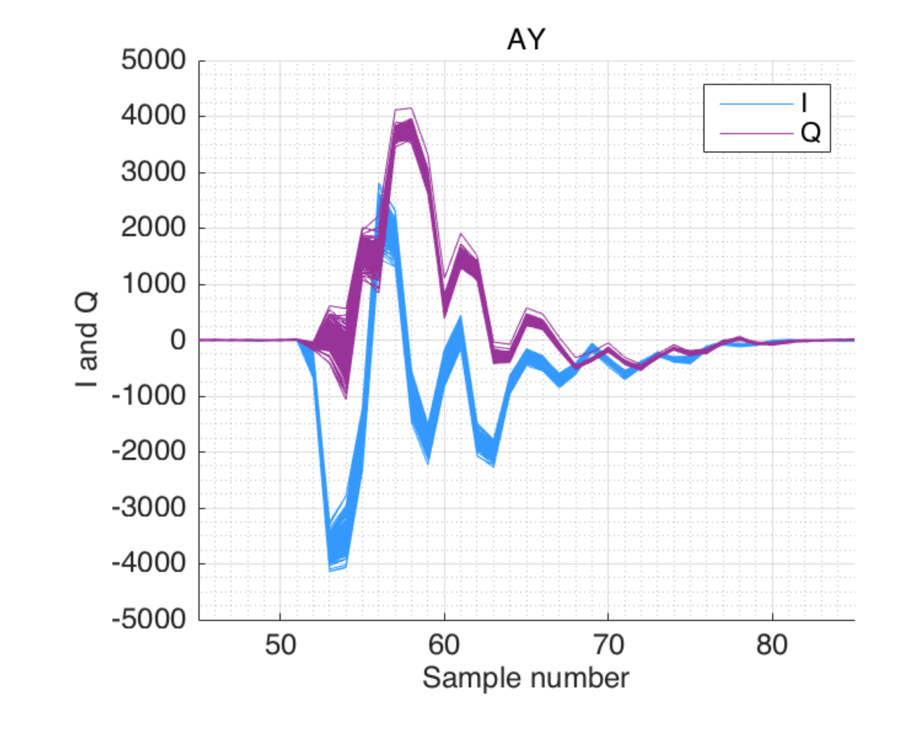
You have no choice but to do this if you include additional parameters, and it is not clear that these two separate assumptions are not contradictory.

# Different sampling

*Single sample* – use one sample from each pulse – calibrate and find position from I and Q signals.

*Multi-sample averaging* – use multiple samples from each pulse – calibrate each sample individually to find positions, then average the positions.

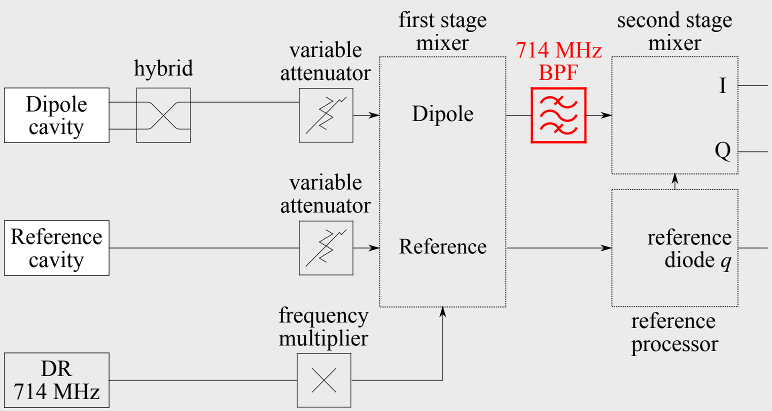
*Integration* – use the sum of multiple samples from one pulse – calibrate the combined samples into one position.

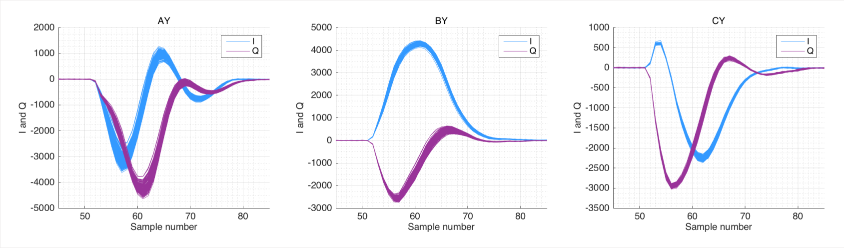



Example of I and Q signal waveforms sampled at the IP by the SIS digitiser at 238 MHz (one sample every 4.2 ns).

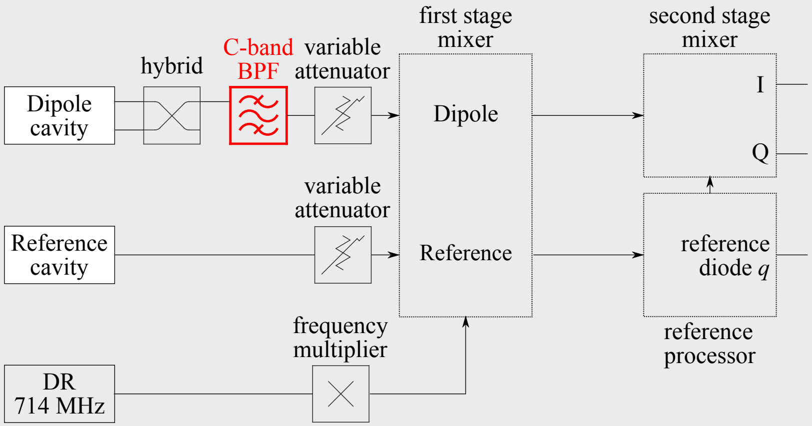
# Band-pass-filter tests

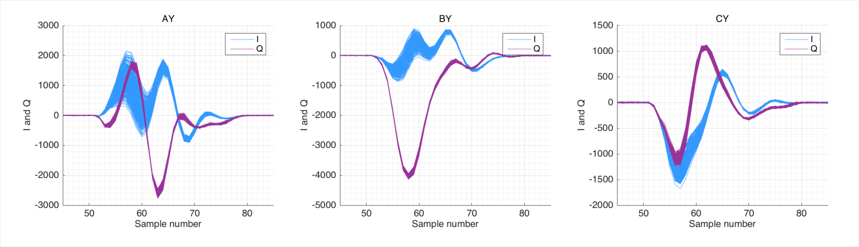
## 714 MHz BPF




## C-band BPFs



# 3BPM resolution study

*Filtering experiments*

- *No BPFs*
- *714 MHz BPFs*
- *C-band BPFs*

SAMPLING METHOD

- Single sample
- Multi-sample averaging
- Integration

*ANALYSIS METHOD*

(1) Geometric method

Fitting methods:

(2) $\hat{y}_2 = Ay_1 + By_3$
(3) $\hat{y}_2 = Ay_1 + By_3 + C$
(4) $\hat{y}_2 = Ay_1 + By_3 + Cy'_1 + Dy'_3 + E$

(5) $\hat{I}'_2 = AI'_1 + BI'_3$
(6) $\hat{I}'_2 = AI'_1 + BI'_3 + C$
(7) $\hat{I}'_2 = AI'_1 + BI'_3 + CQ'_1 + DQ'_3 + E$
(8) $\hat{I}'_2 = AI_1 + BI_3 + CQ_1 + DQ_3 + E$

# Optimisation example

**Single Sample**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| IPA | 101 | 90 | 90 | 52 | 66 | 66 | 52 | 39 |
| IPB | 101 | 92 | 94 | 66 | 144 | 139 | 66 | 43 |
| IPC | 101 | 89 | 91 | 35 | 43 | 43 | 35 | 46 |
| Average | 101 | 90 | 92 | 51 | 85 | 83 | 51 | 43 |
| Sample no. | 57 | 58 | 58 | 57 | 58 | 58 | 57 | 54 |

**Integration**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| IPA | 76 | 51 | 51 | 31 | 44 | 44 | 26 | 18 |
| IPB | 76 | 51 | 51 | 33 | 53 | 52 | 26 | 26 |
| IPC | 76 | 51 | 54 | 32 | 65 | 58 | 42 | 42 |
| Average | 76 | 51 | 52 | 32 | 54 | 52 | 32 | 28 |
| Sample start | 56 | 57 | 57 | 54 | 57 | 57 | 53 | 53 |
| Sample finish | 58 | 61 | 61 | 59 | 61 | 61 | 59 | 59 |

**Multi-Sample Averaging**

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| IPA | 54 | 50 | 49 | 29 |
| IPB | 54 | 49 | 49 | 37 |
| IPC | 54 | 49 | 51 | 32 |
| Average | 54 | 49 | 50 | 33 |
| Sample start | 56 | 56 | 56 | 54 |
| Sample finish | 58 | 58 | 58 | 59 |

jitRun3_0dB_ipbpm_150612

# Resolution analysis results

- The fitting analysis method with raw I and Q data, sampled using integration, always produces the smallest resolution.
- The addition of Q to a multi-parameter fit has largest impact on reducing resolution result.

$$\hat{I}'_2 = AI_1 + BI_3 + CQ_1 + DQ_3 + E$$

| | Single sample | Integration | Multi-sample | Charge (x $10^{10}$) |
|---|---|---|---|---|
| No BPFs | 43 | 28 | 33 | 0.69 |
| 714 MHz | 43 | 41 | 56 | 0.73 |
| C-band | 38 | 35 | 41 | 0.46 |

*In agreement with analysis results by Siwon Jang, 22 July 2015, ATF IPBPM/FONT meeting (http://atf.kek.jp/twiki/pub/ATF/IPBPMmeetings2/IPBPM_resolution_test_results_at_June_2015.pdf ). Uncertainty of ± 1nm from propagated calibration uncertainties – uncertainty from fit parameters yet to be incorporated.*

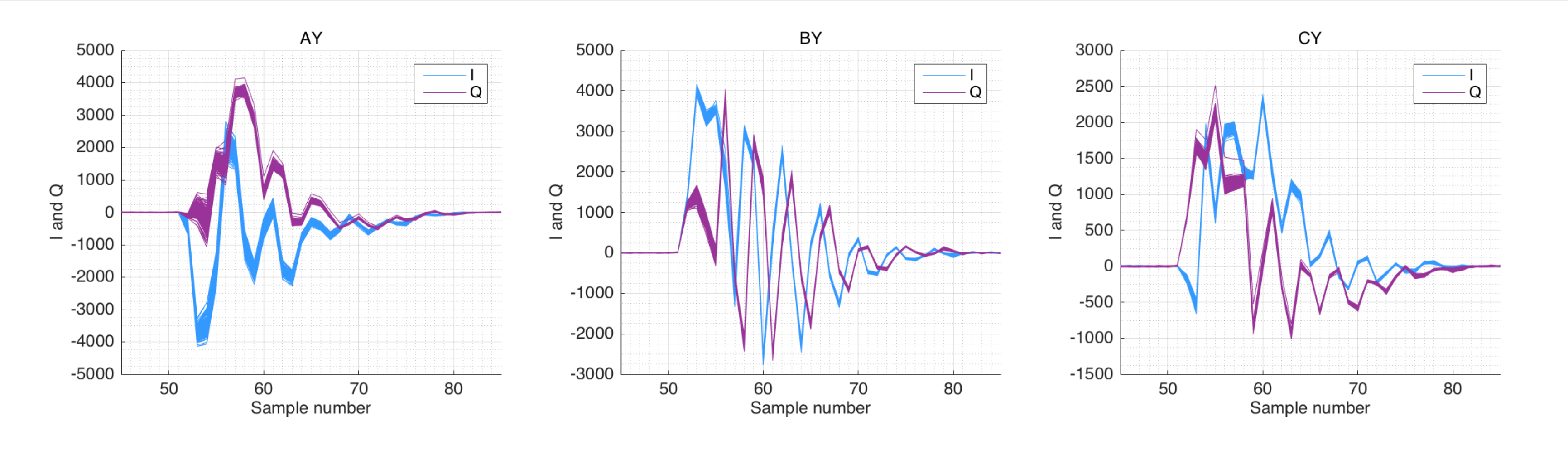
# BPM static waveform

Signals from the cavity BPMs contain an unwanted waveform of unknown origin.

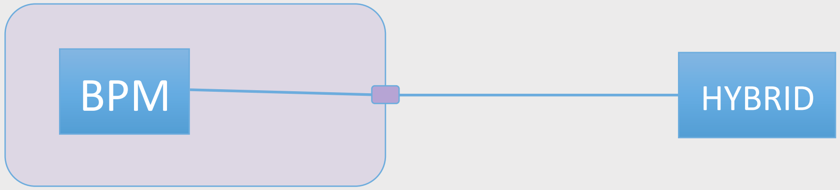
Causes complications in

- calibrating BPMs
- sampling the pulses for feedback
- measuring BPM resolution

May be a limiting factor in achieving nanometre-level position measurements at the IP for beam stabilisation (Goal 2).



# Cable mismatch




Measured cable lengths from IP BPM dipole cavities inside the IP vacuum chamber to the hybrid prior to the processing electronics using TDR.

| BPM ports | Cavity to hybrid(ns) | Cavity to hybrid (m) | Δ Length (cm) | δ (cm) | Error (cm) |
|---|---|---|---|---|---|
| IPA-X1 | 9.91 | 2.360 | 11.43 | 1.08 | 0.04 |
| IPA-X2 | 10.39 | 2.474 | | | |
| IPB-X1 | 10.39 | 2.475 | 0.011 | 0.11 | 0.06 |
| IPB-X2 | 10.39 | 2.474 | | | |
| IPC-X1 | 9.92 | 2.362 | 11.21 | 1.29 | 0.06 |
| IPC-X2 | 10.39 | 2.474 | | | |
| IPA-Y1 | 9.92 | 2.361 | 11.32 | 0.21 | 0.05 |
| IPA-Y2 | 10.39 | 2.474 | | | |
| IPB-Y1 | 10.40 | 2.476 | 0.38 | 0.38 | 0.06 |
| IPB-Y2 | 10.39 | 2.473 | | | |
| IPC-Y1 | 9.91 | 2.361 | 11.32 | 0.21 | 0.04 |
| IPC-Y2 | 10.39 | 2.474 | | | |

| BPM port | Frequency (GHz) | Wavelength (m) |
|---|---|---|
| Y port | 6426 | 0.037 |
| X port | 5712 | 0.042 |

- Cable velocity 2.381 x $10^8$ m/s.
- 100 waveforms averaged on the TDR.
- δ is the phase difference after removing integer wavelength differences.

Cables mismatched inside chamber.

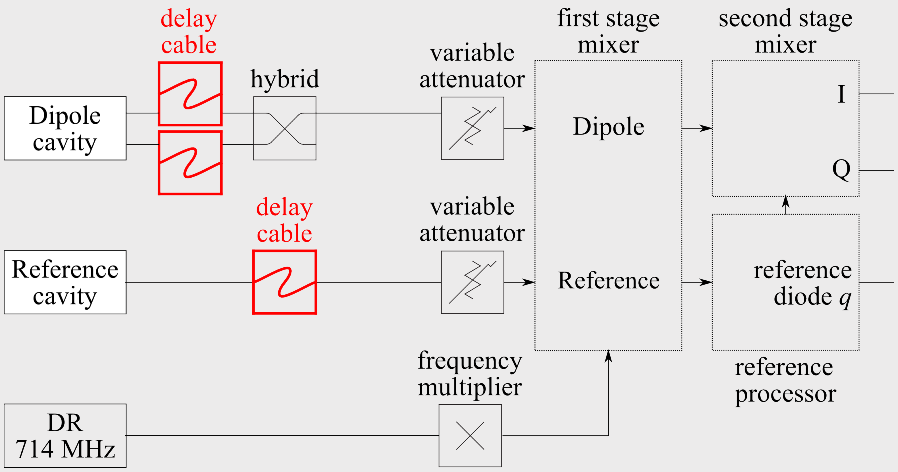
**Y: Within 0.38cm (10% of wavelength)**

**X: Within1.29 cm (31% of wavelength)**

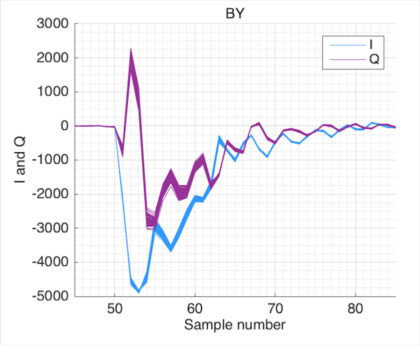
# Delay cables

Look for reflections inside the chamber by introducing delay cables outside before the electronics and observing if the static signal moves within the pulse.

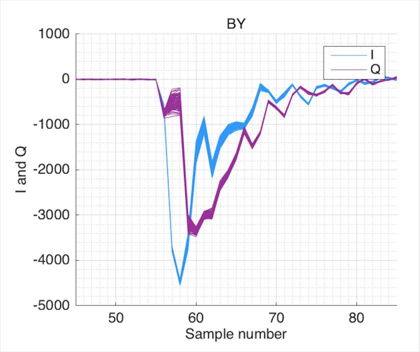
Matched 5.5 m (28 ns) delay cables introduced on both ports of IPBY and the reference cavity.




***No delay cables***



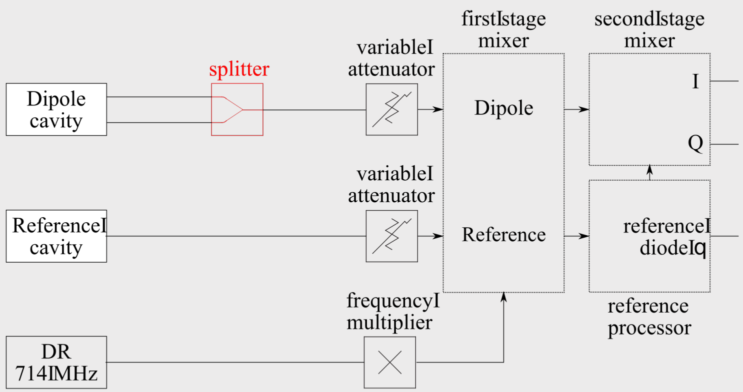

***Delay cables***




**Results:**
SIS digitiser (4.2 ns per sample), expect delay of 6.5 samples with 5.5 m cables. Signals delayed as expected.

Static feature does not move noticeably within the pulse.

# Symmetric modes

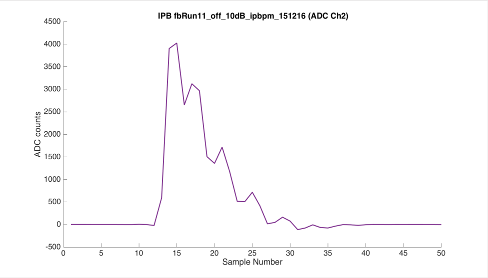


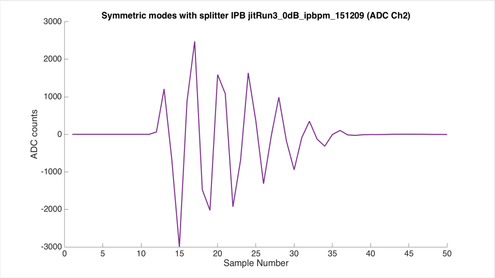

IPB hybrid replaced with a splitter to cancel dipole modes and combine symmetric modes.

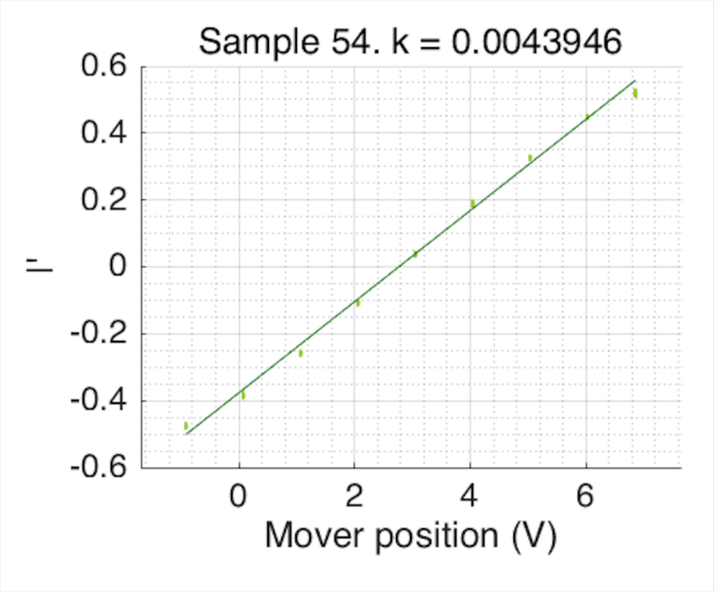
- 60 MHz signal seen in symmetric modes.
- Slight position dependence measured in mover scan with symmetric modes: k = 0.004 (k typically ~0.1 in dipole modes)

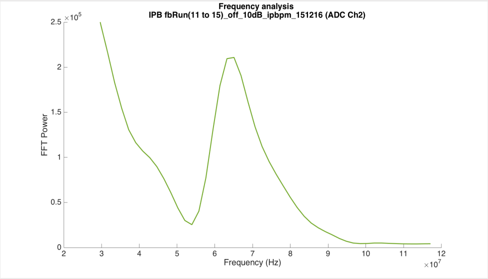
Dipole modes (normal set-up)

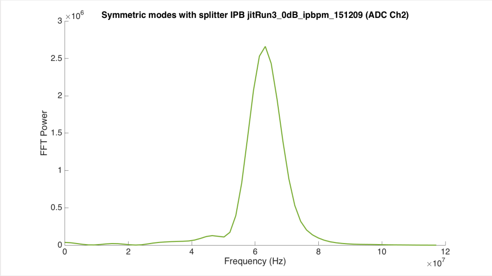
Symmetric modes



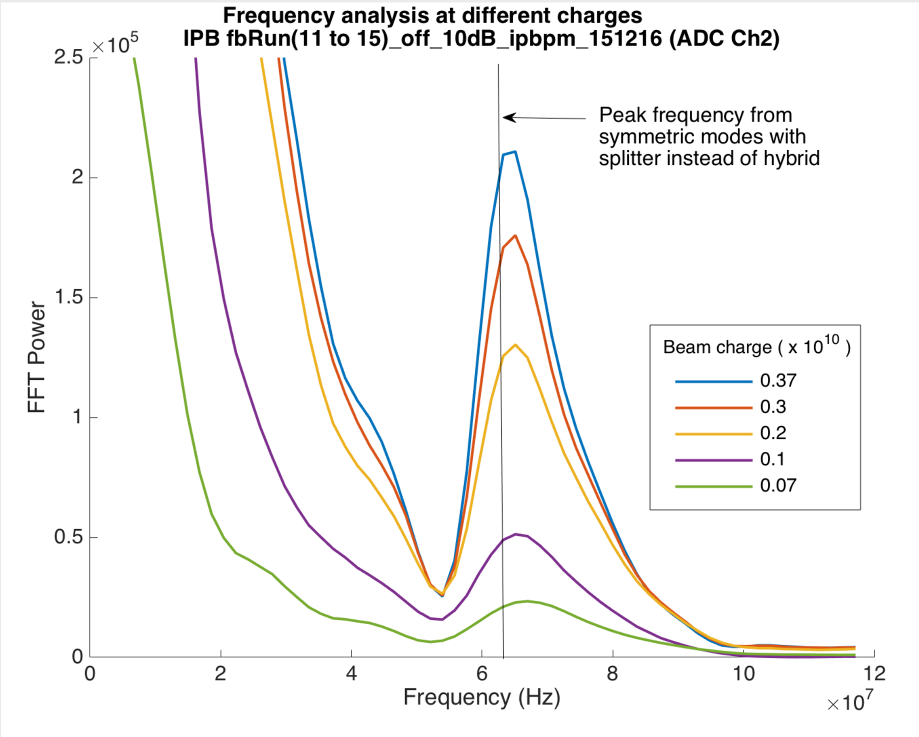



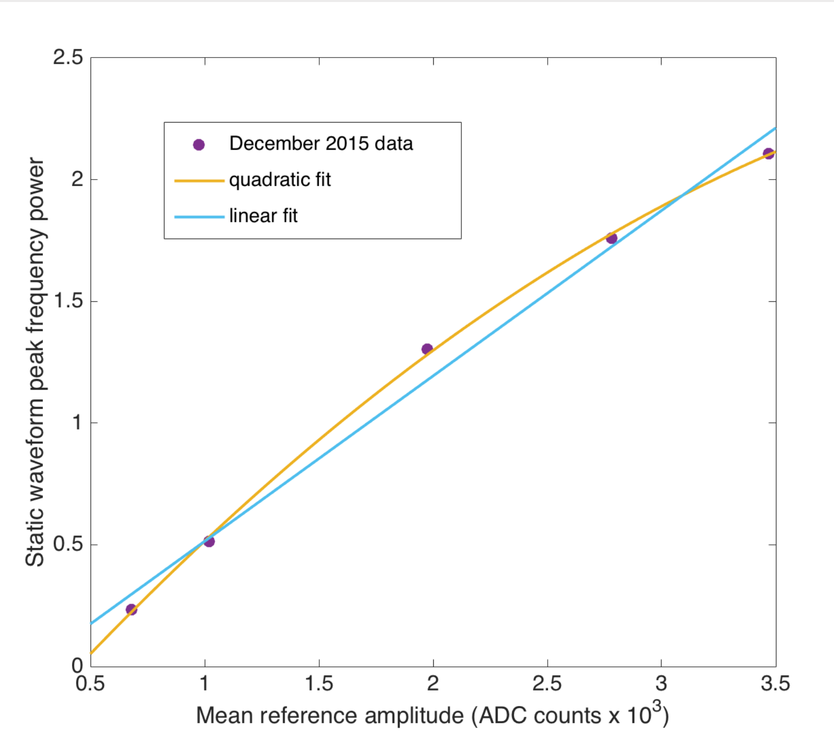



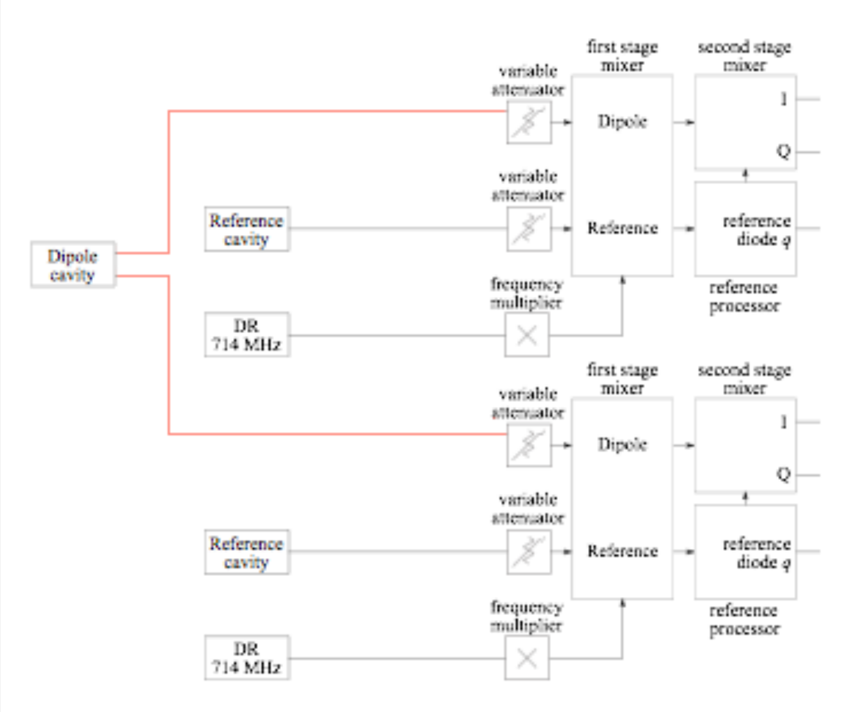
# 60 MHz amplitude with charge




60MHz signal amplitude in dipole waveforms increases with charge. However, this data is with normal dipole set-up and may be confused by the dominant position-dependence. Need to repeat experiment with symmetric modes.

# 2-port study

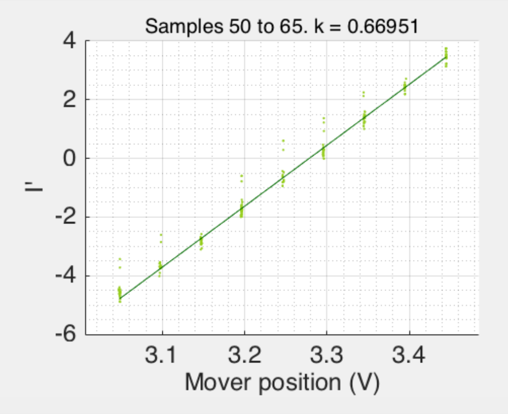



Send the two dipole cavity ports from IPBY through separate electronics. Calibrate signals for position, expecting values to be the same for both ports.

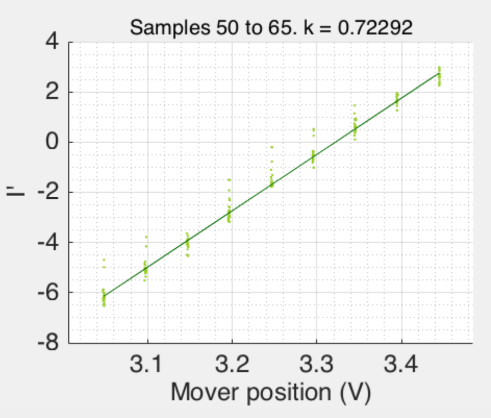
Integrated samples 50:65. Results are a weighted mean of 7 repeat calibration runs with the weighted standard deviation quoted as an uncertainty.

| | |
|---|---|
| IPBY Port 1 *k* | 0.62 ± 0.04 |
| IPBY Port 2 *k* | 0.76 ± 0.02 |

***Port 1 example***




***Port 2 example***



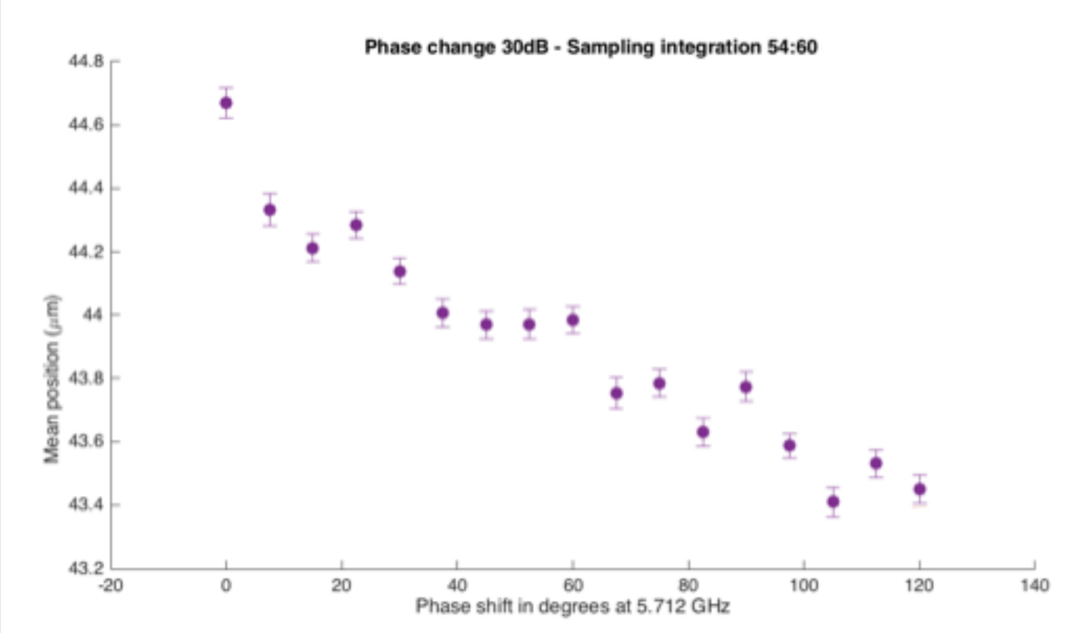
# Phase sensitivity

IP BPMs position measurements should have no sensitivity to the bunch phase. To check this, we manually changed the LO phase relative to the bunch.

Analysis shows ~10 nm/degree sensitivity at 30dB at 5.712 GHz. Given known upstream bunch phase jitter, this corresponds to **~1 nm apparent position jitter at 0dB due to phase sensitivity – not significant effect.**

However, the expected sinusoidal waveform is not observed in data and may be effected by sampling method.

More analysis needed.



# Conclusions

**3BPM Resolution Calculations**

- Including Q in a fit to the raw signals has the largest impact on the resolution.
- Optimised integration sampling always produces the lowest resolution result.
- Best resolution calculated as 28 nm at a charge of $0.7 \times 10^{10}$.

**Unwanted static waveform**

- BPFs at various locations in the electronics do not improve position resolution.
- IP BPM cables inside the vacuum chamber are mismatched to ~10% of wavelength in Y and ~30% in X.
- Strong symmetric modes present in dipole cavity, where static waveform appears more dominantly, as demonstrated using a resistive splitter.
- Static waveform amplitude decreases with beam charge.
- 2-port study on IPBY shows small difference in gain between two BPM ports.
- Position measured at the IP is sensitive to bunch phase, but only on nm level.