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PhD 34 - Resolution analysis

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PhD Journal #34, 15/09/2026

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PhD34 - Resolution Analysis

PhD Journal #34, 15/09/2026

Introduction

- I. Resolution estimation results
 - A) Resolution calculation with Pseudo-inverse
 - B) Selecting a specific set of data
- II. Pseudo-inverse method limitations
 - A) Pseudo-experiments
 - B) Resolution as a function of beam position
 - C) Resolution as a function of bunch charge
- III. Calibration corrections
 - A) Compensating for stripline electronics amplitude difference
 - B) Inclusion of the profile monitors
 - C) ...

Conclusion

I. Resolution estimation results

A) Resolution calculation with Pseudo-inverse

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

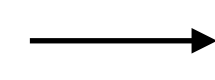
$P = 1000$ is the number of pulses

$M = 20$ is the number of BPMs used

Model Independent Analysis: [8]

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

cBPM measured values



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

← correlation coefficients

↑
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:

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

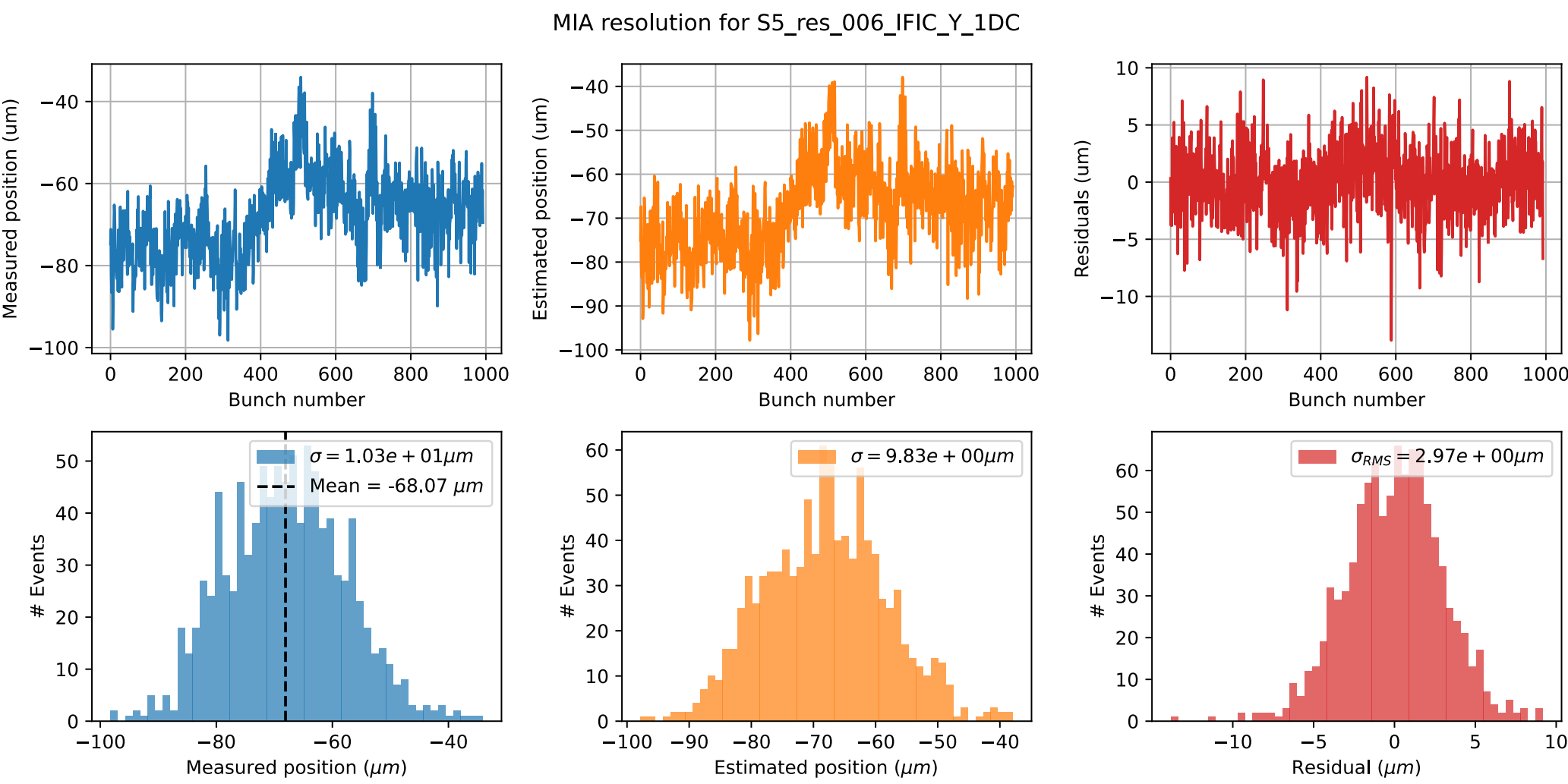
$$\begin{aligned} \mathbf{D}^{-1} &= \mathbf{V}^T \mathbf{S}^{-1} \mathbf{U}^T \\ &= \mathbf{V} \begin{pmatrix} 1/\sigma_1 & & \\ & \ddots & \\ & & 1/\sigma_M \end{pmatrix} \mathbf{U}^T \end{aligned}$$

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

I. Resolution estimation results

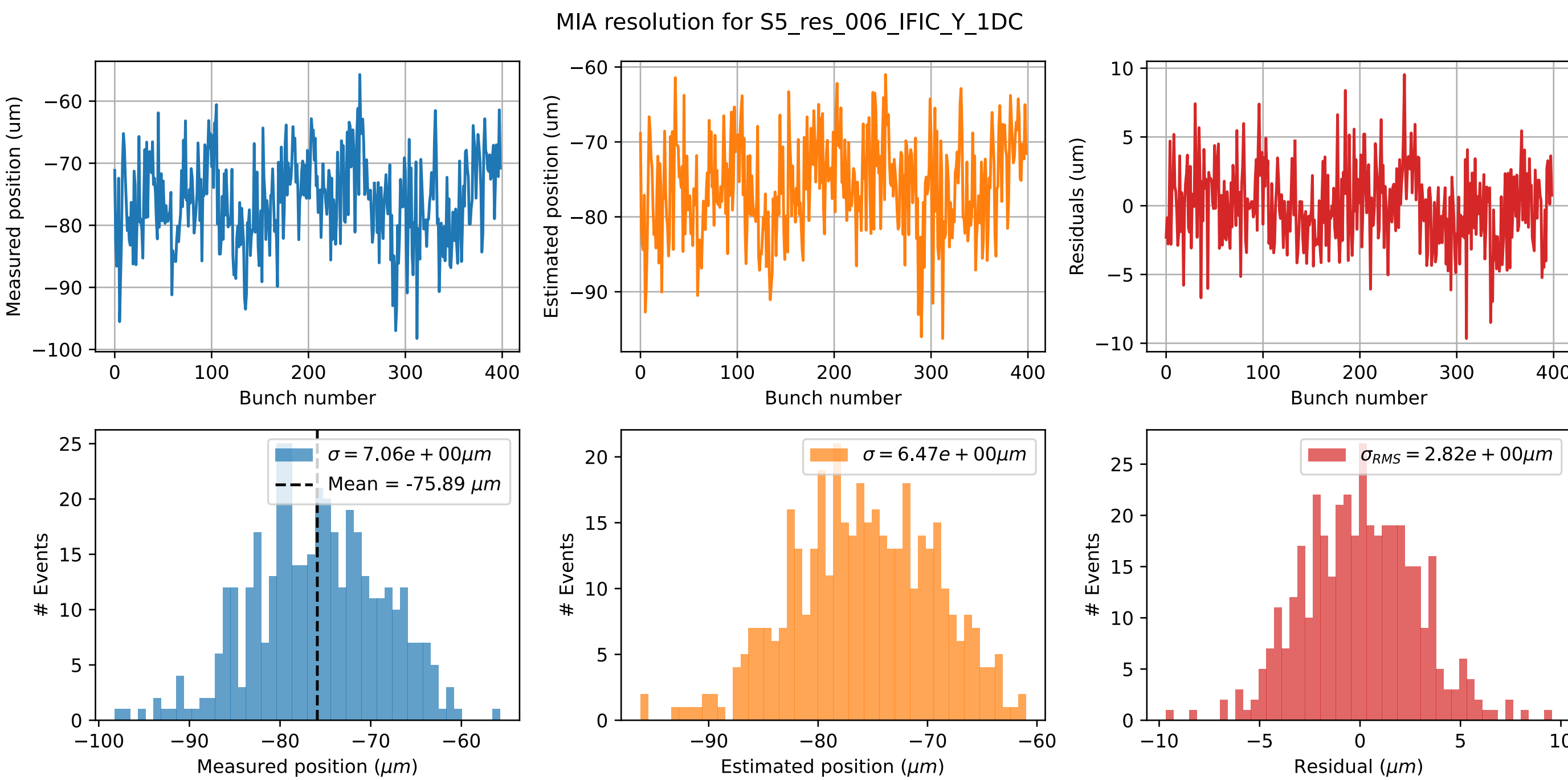
B) Selecting a specific part of the data

Full measurement



RESOLUTION with other cBPM			
resolution	res_err_n	res_err_c	res_err_2
(um)	(um)	(um)	(um)
2.97	2.34	0.59	2.46

First 400 bunches

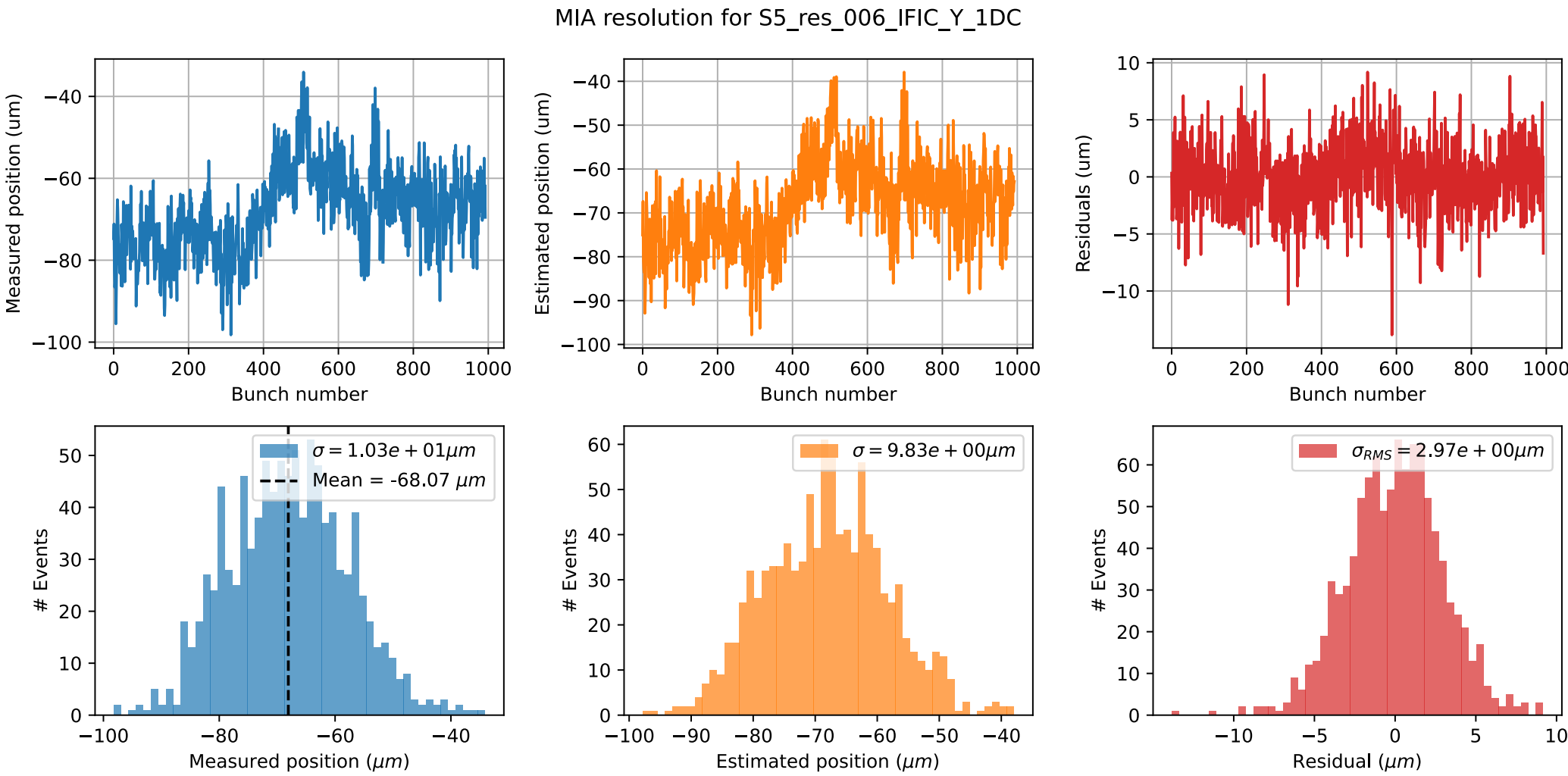


RESOLUTION with other cBPM			
resolution	res_err_n	res_err_c	res_err_2
(um)	(um)	(um)	(um)
2.82	2.20	0.82	2.46

I. Resolution estimation results

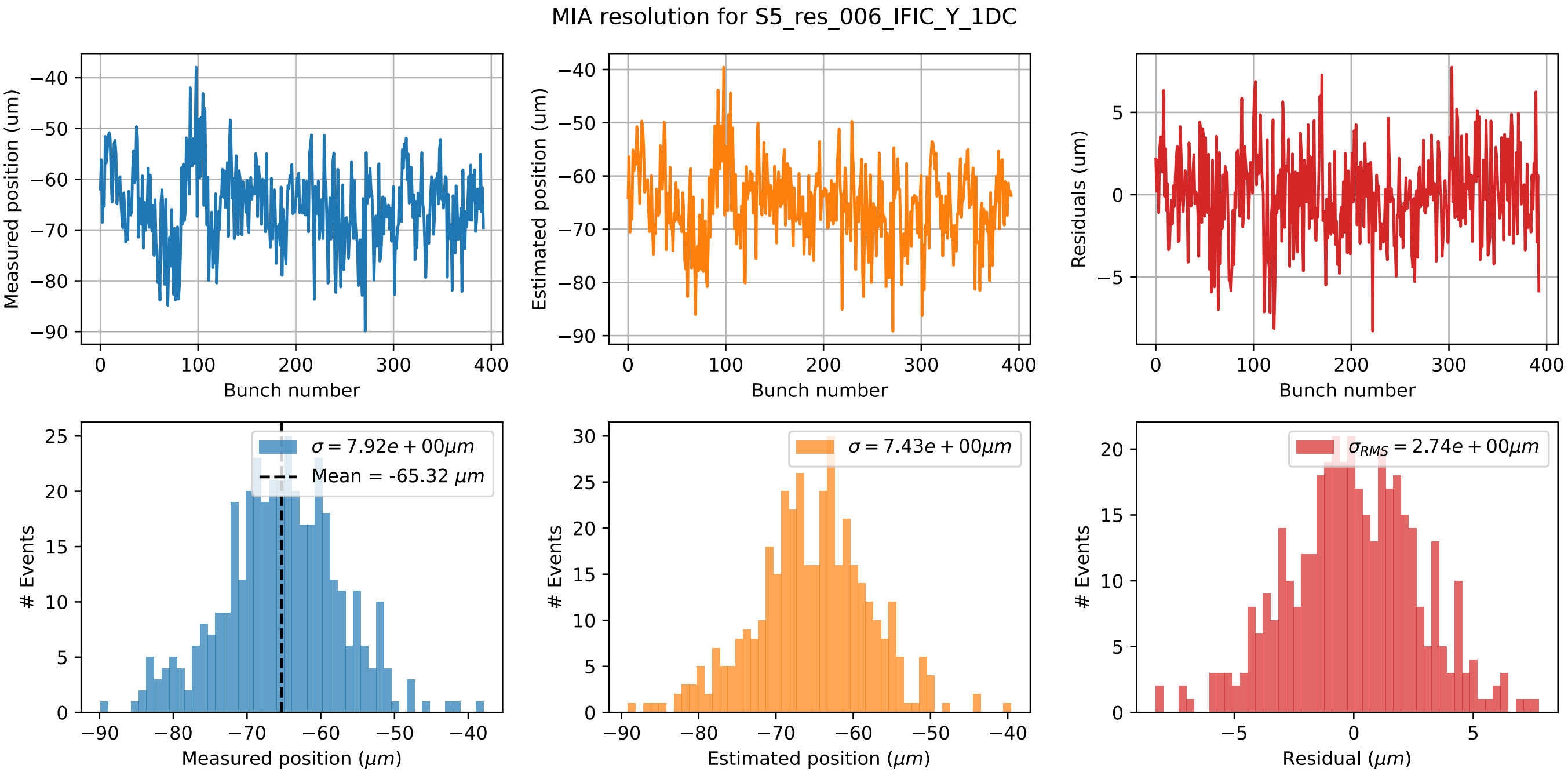
B) Selecting a specific part of the data

Full measurement



RESOLUTION with other cBPM			
resolution	res_err_n	res_err_c	res_err_2
(um)	(um)	(um)	(um)
2.97	2.34	0.59	2.46

Last 600 bunches



RESOLUTION with other cBPM			
resolution	res_err_n	res_err_c	res_err_2
(um)	(um)	(um)	(um)
2.74	2.39	0.91	2.64

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II. Pseudo-inverse method limitations

- A) Pseudo-experiments
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- C) Resolution as a function of bunch charge

III. Calibration corrections

- A) Compensating for stripline electronics amplitude difference
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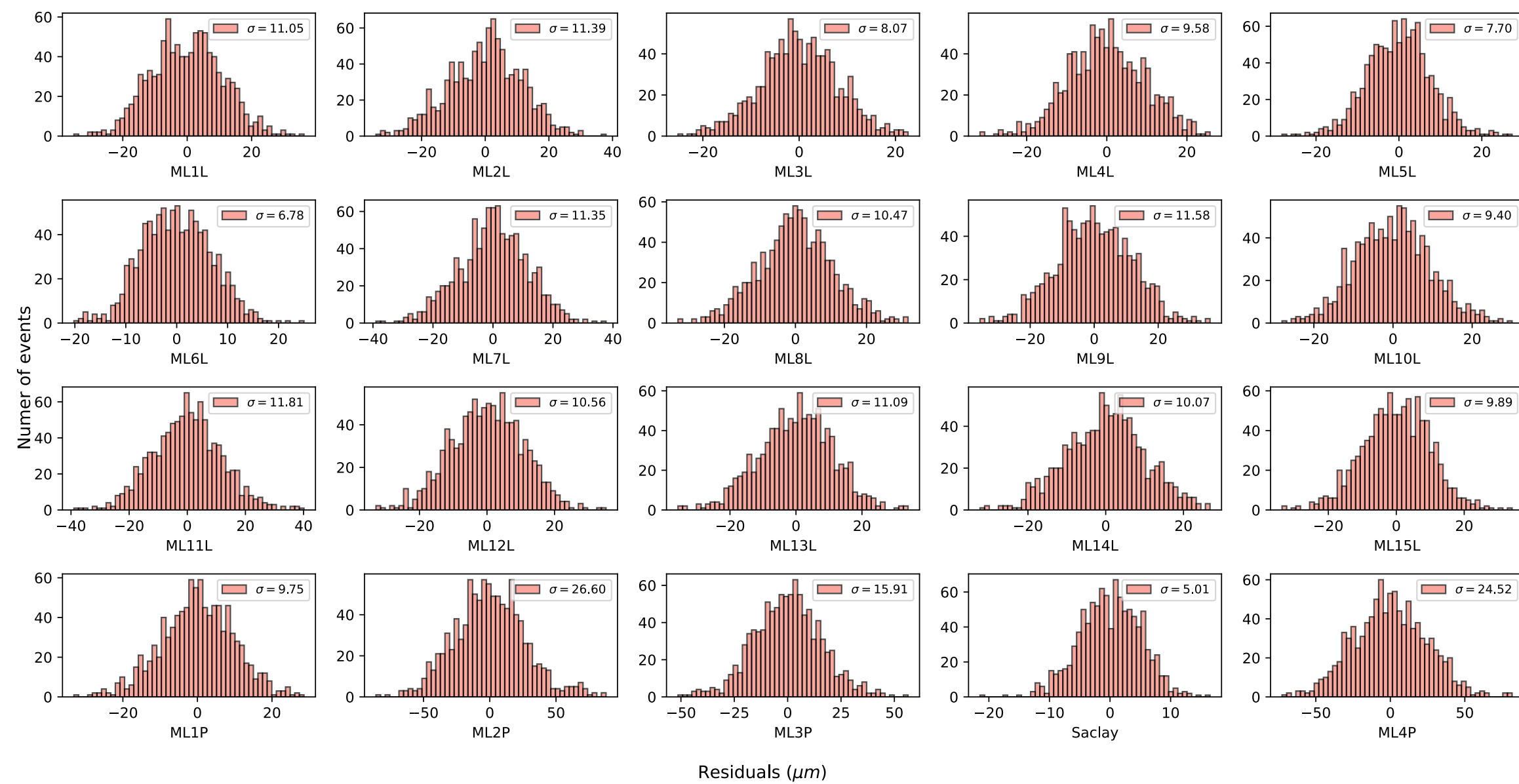
Conclusion

II. Pseudo-inverse method limitations

A) Pseudo-experiments

Contribution of the resolution of other BPMs:

The previous method is employed for all BPMs:



Stripline BPMs showed resolutions between $7 \mu\text{m}$ and $25 \mu\text{m}$, while the CEA-Saclay cBPM has shown to have a resolution of $3 \mu\text{m}$ under these beam conditions.

Uncertainties on the correlation coefficients from MIA:

- Analytically:**

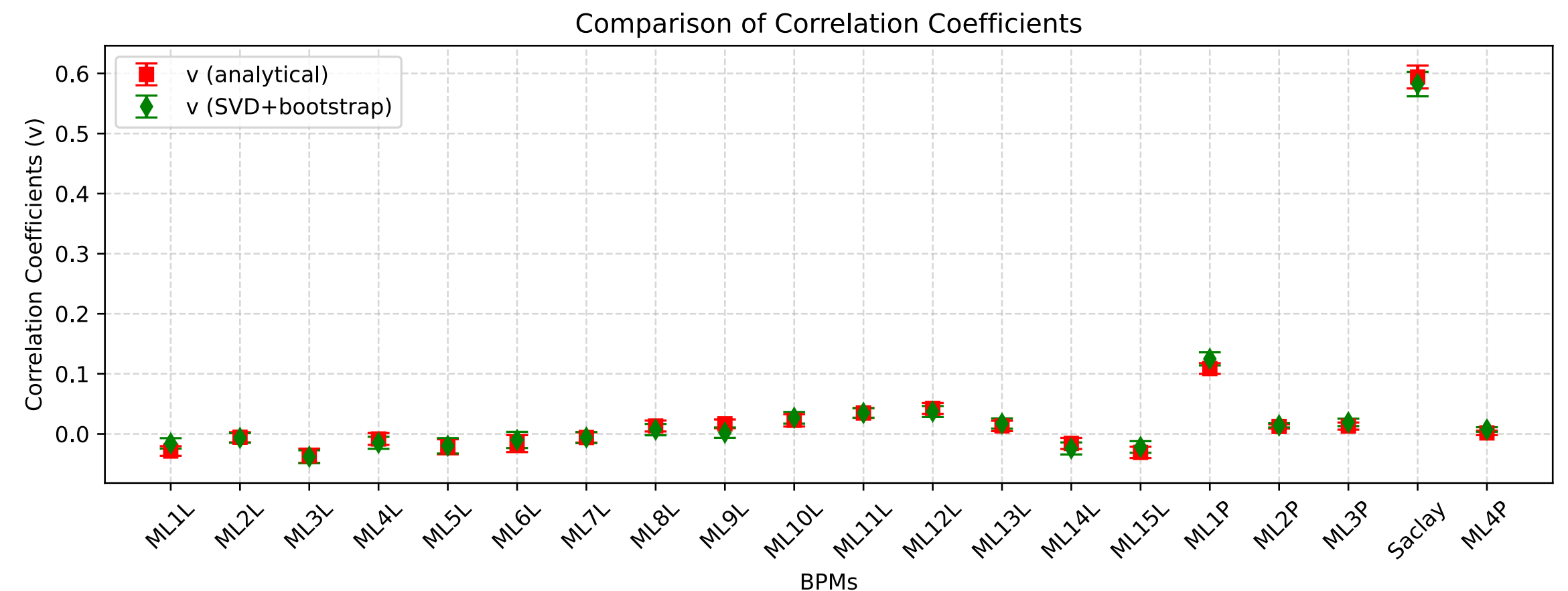
from the square root of the diagonal elements of the covariance matrix $Cov(\mathbf{v})$, where

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

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 $\mathbf{v} = \mathbf{D}^{-1} \cdot \mathbf{d}$



II. Pseudo-inverse method limitations

A) Pseudo-experiments

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:

$$\sigma_{residuals,i}(\mathbf{R}_{sim,l,i})$$

Performing simulations over several bunches,

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

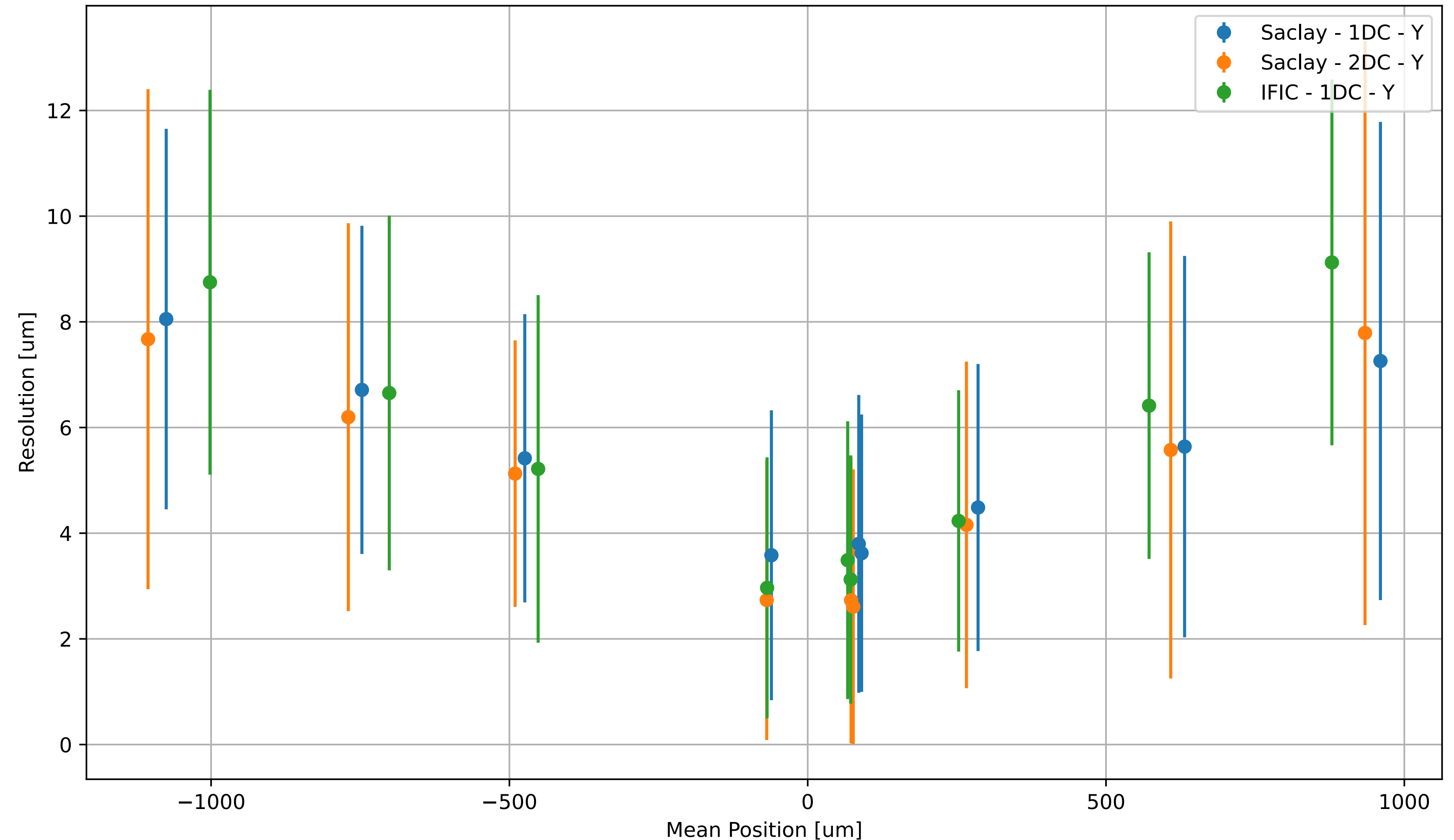
II. Pseudo-inverse method limitations

B) Resolution as a function of beam mean position

Runs no. 1 to 9 on shift 5 consisted on resolution measurements at different beam positions for both BPMs simultaneously.

The estimated resolution + the uncertainty on the resolution is plotted here.

To be studied: why Saclay 1DC and Saclay 2DC yield different positions for a similar run?



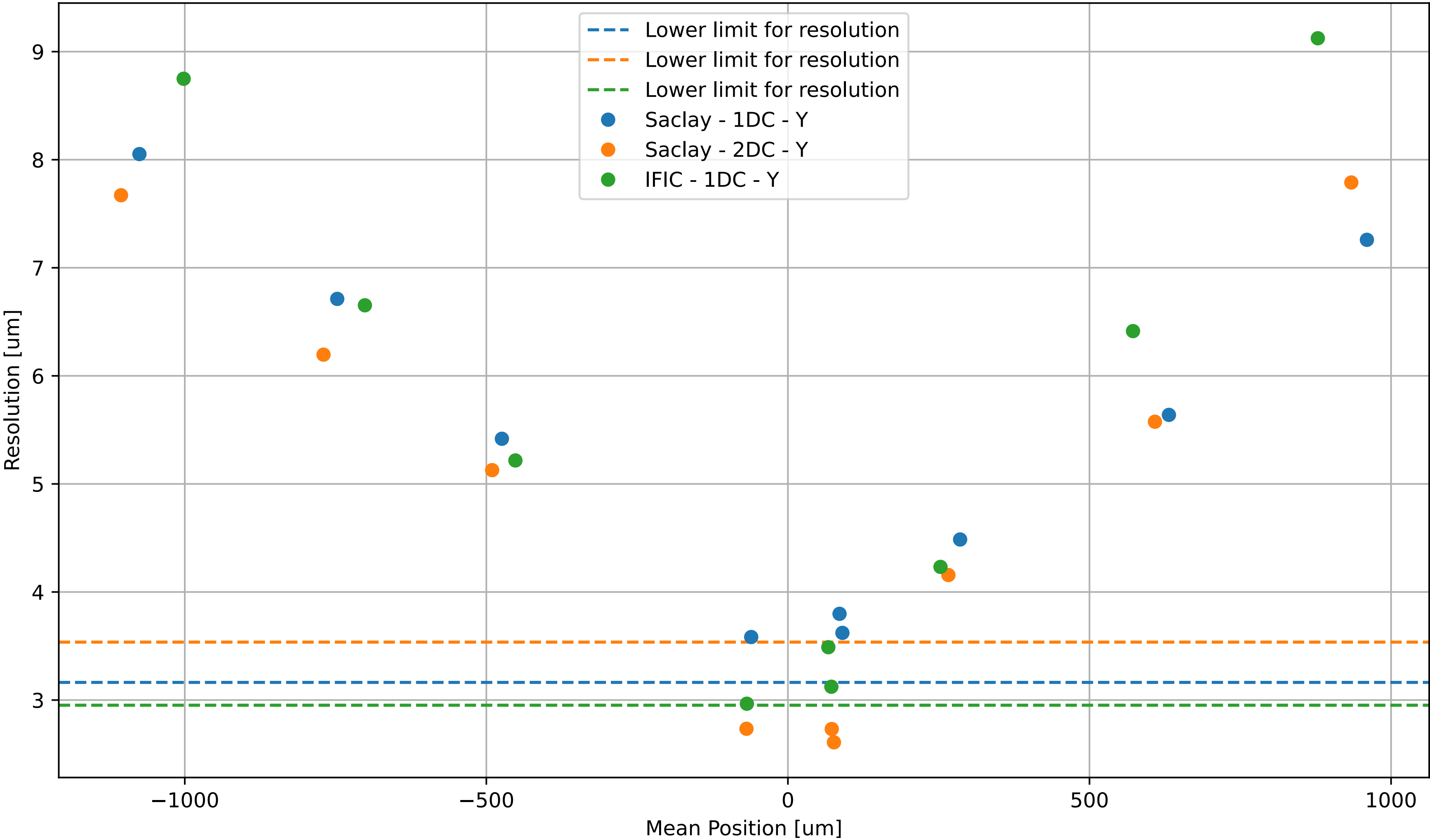
II. Pseudo-inverse method limitations

B) Resolution as a function of beam mean position

Runs no. 1 to 9 on shift 5 consisted on resolution measurements at different beam positions for both BPMs simultaneously.

The estimated resolution + the lower limit on the resolution estimation is plotted here.

We are also investigating the effect of the beam angle of attack on the resolution measurements.

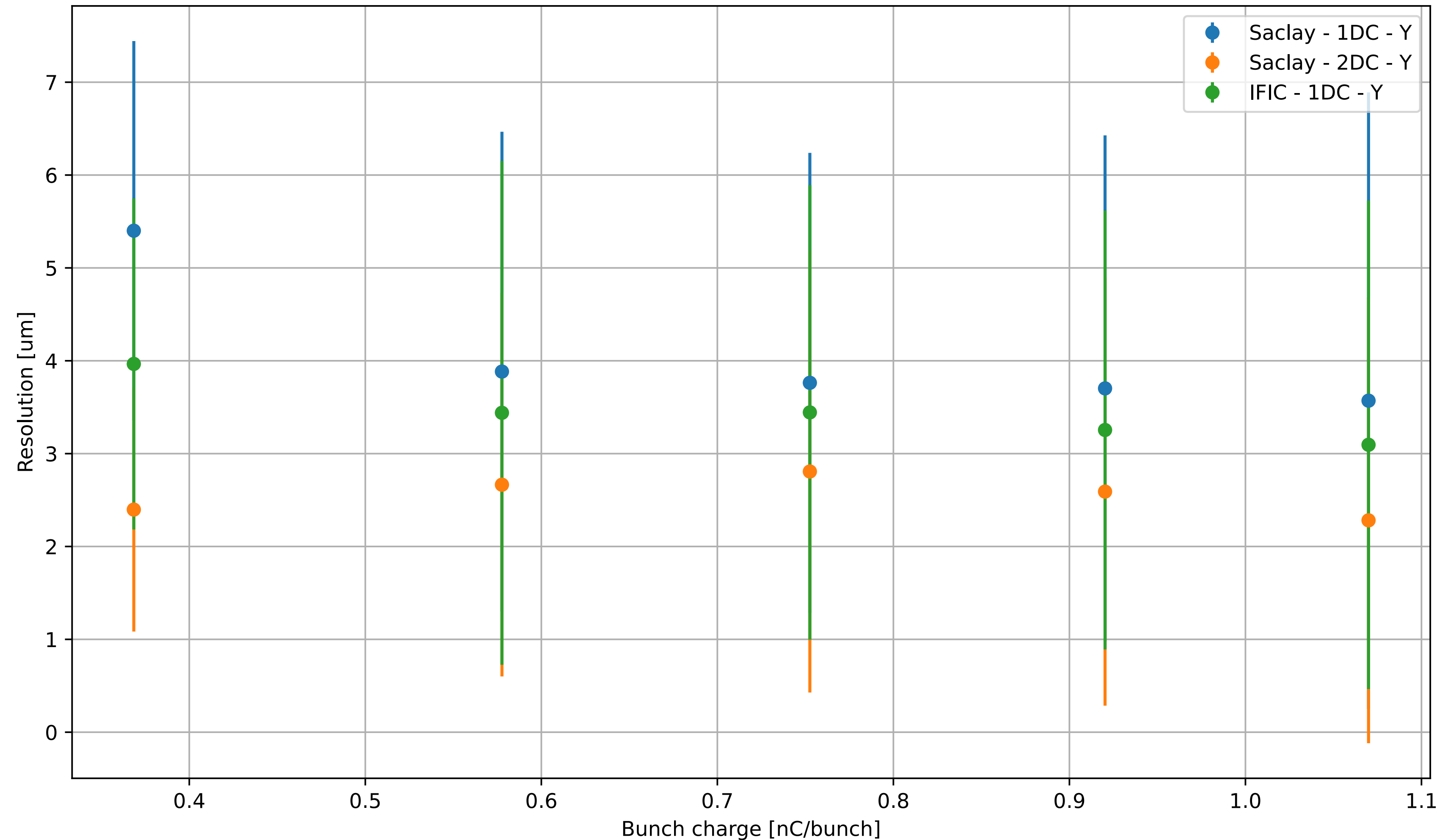


II. Pseudo-inverse method limitations

C) Resolution as a function of bunch charge

Runs no. 10 to 14 on shift 5 consisted on resolution measurements at different bunch charges for both BPMs simultaneously.

The estimated resolution + the uncertainty on the resolution is plotted here.



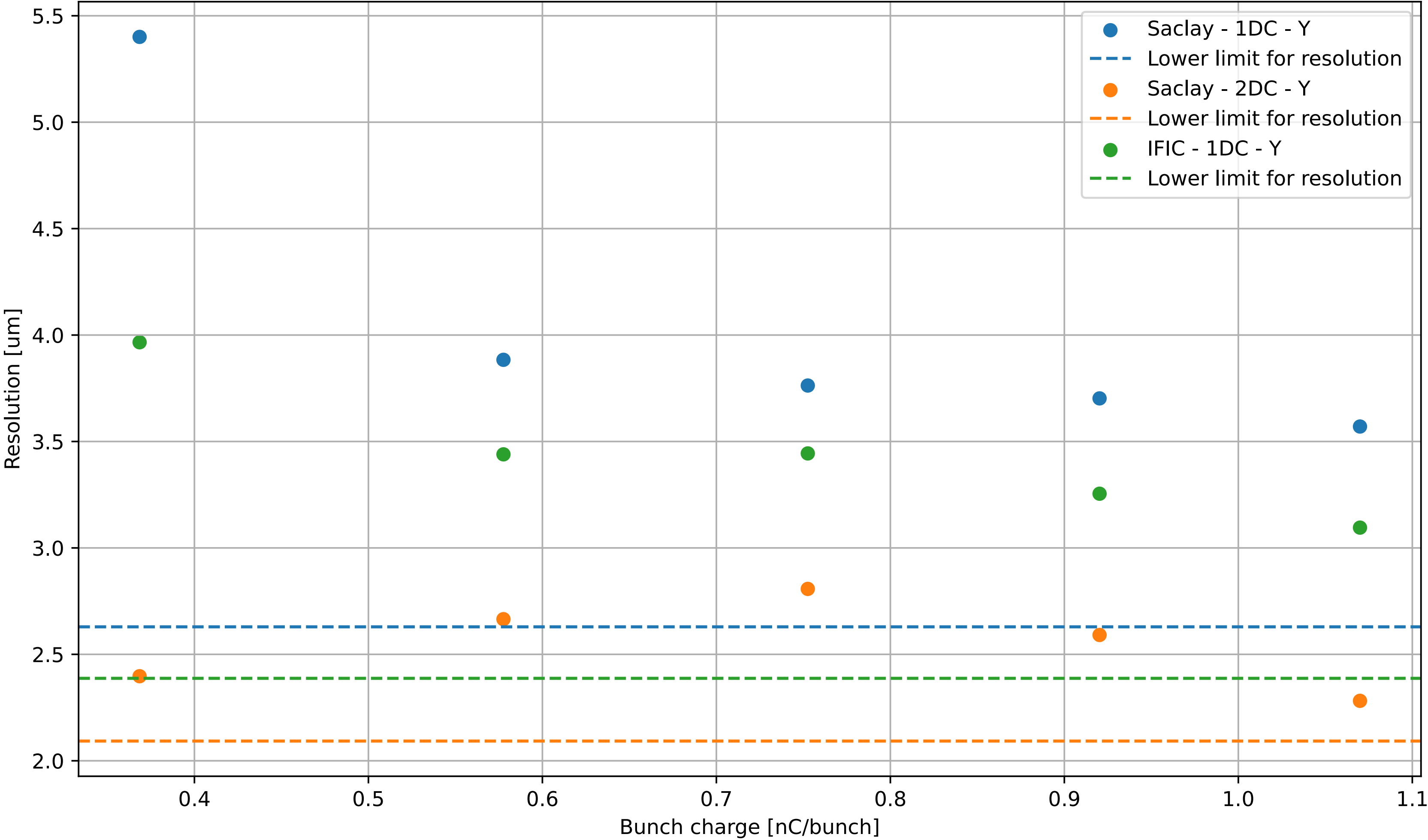
II. Pseudo-inverse method limitations

C) Resolution as a function of bunch charge

Runs no. 10 to 14 on shift 5 consisted on resolution measurements at different bunch charges for both BPMs simultaneously.

The estimated resolution + the lower limit on the resolution estimation is plotted here.

Differences between 1DC and 2DC are still under investigation via simulations.



II. Pseudo-inverse method limitations

D) Resolution as a function of the time window

Work in progress...

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Introduction

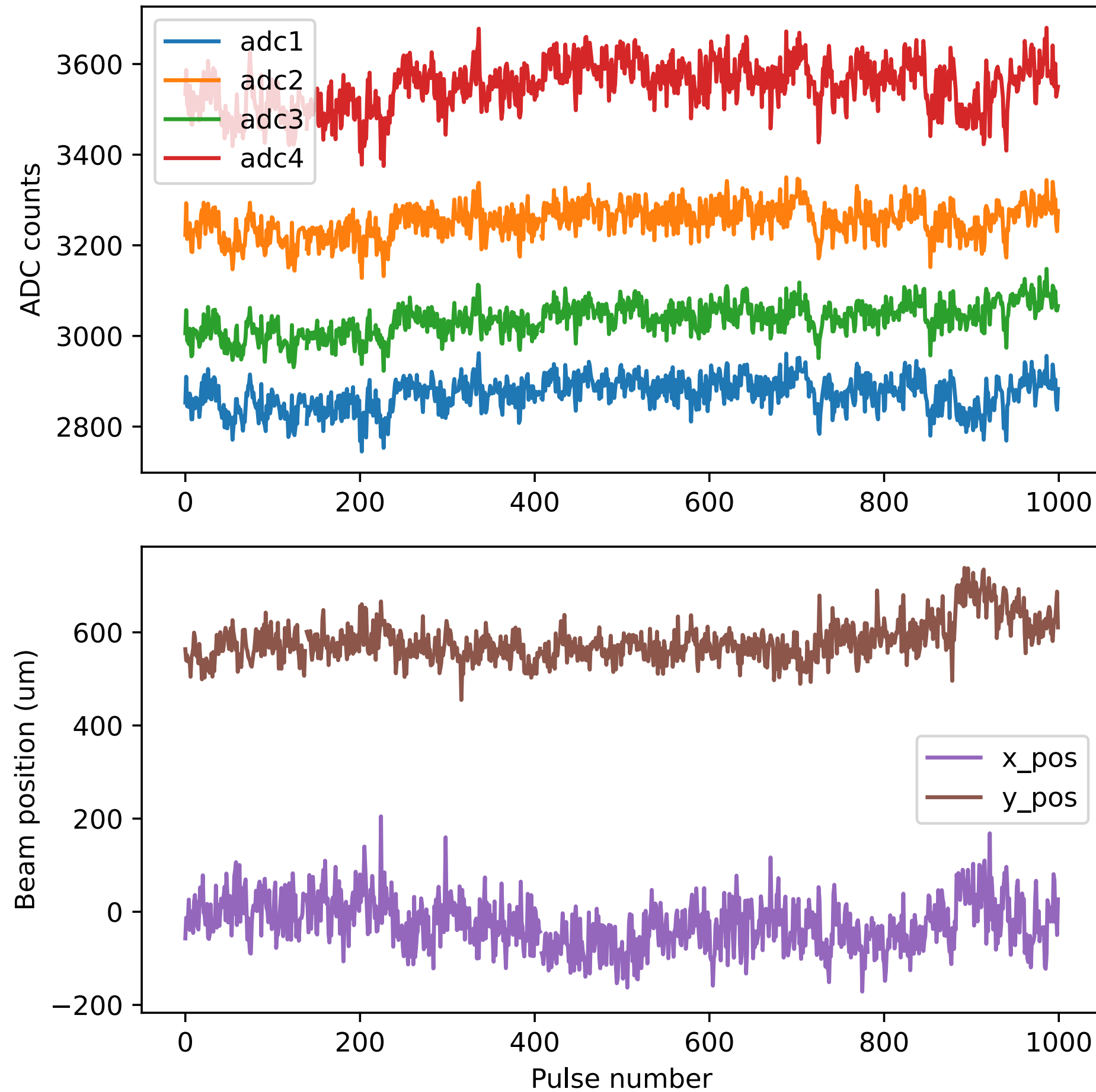
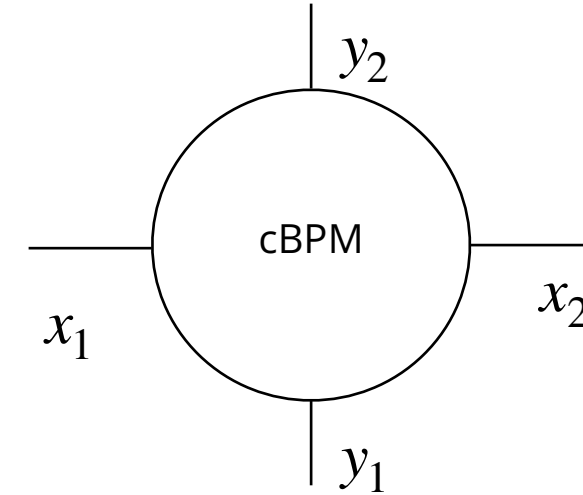
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Conclusion

III. Calibration corrections

A) Compensating for stripline electronics amplitude difference

How are the BPMs connected?



The beam position is reconstructed as follows:

$$x = S_x \frac{x_1 - x_2}{x_1 + x_2 + y_1 + y_2} \quad y = S_y \frac{y_1 - y_2}{x_1 + x_2 + y_1 + y_2}$$

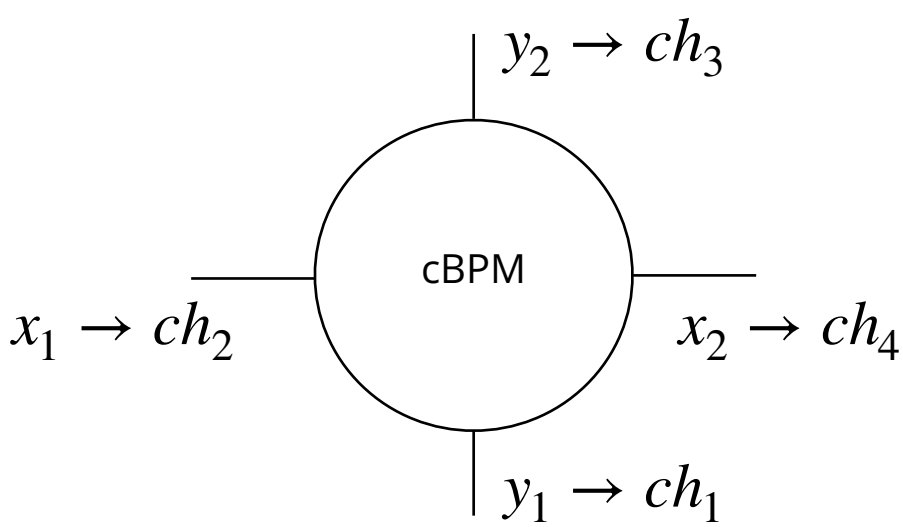
Having the ADC raw data (and pedestals) and the measured position, the Scaling factor can be determined for each bunch.

$$S_x = x \frac{x_1 + x_2 + y_1 + y_2}{x_1 - x_2} \quad S_y = y \frac{x_1 + x_2 + y_1 + y_2}{y_1 - y_2}$$

III. Calibration corrections

A) Compensating for stripline electronics amplitude difference

How are the BPMs connected?

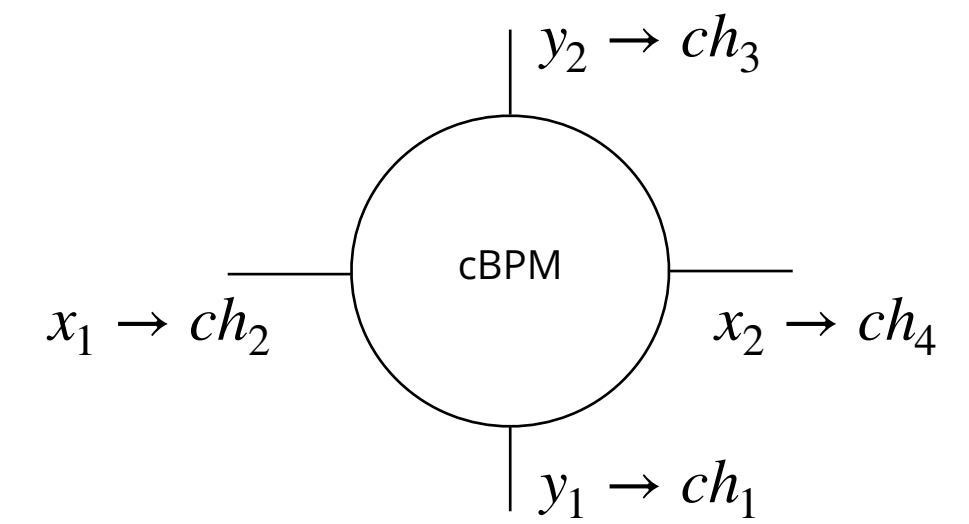


The relative error (in %) of the scaling factor can be evaluated ($\sigma(S)/\nu(S) * 100$) $\rightarrow$ it should be low (or 0?)

ADC configuration	X: ch1 and ch2 Y: ch3 and ch4	X: ch1 and ch3 Y: ch2 and ch4	X: ch1 and ch4 Y: ch2 and ch3	X: ch2 and ch3 Y: ch1 and ch4	X: ch2 and ch4 Y: ch1 and ch3	X: ch3 and ch4 Y: ch1 and ch2
BPM ML2P $\sigma(S_x)$ in %	204.4	202.7	220.9	209.7	351.9	241.6
BPM ML2P $\sigma(S_y)$ in %	14.1	21.4	14.7	7.1	1.3	5.4
BPM ML3P $\sigma(S_x)$ in %	2.4	2.5	3.7	1.7	0.7	4.3
BPM ML3P $\sigma(S_y)$ in %	2.2	3.5	1.7	5.3	1.4	4.1
BPM ML4P $\sigma(S_x)$ in %	1.7	2.5	9.3	10.8	0.8	2.0
BPM ML4P $\sigma(S_y)$ in %	0.7	1.8	8.8	7.4	0.3	1.1

III. Calibration corrections

A) Compensating for stripline electronics amplitude difference



The stripline electronics have slightly different gains for the 4 channels.

So for same RF input voltage the ADC readout gives different magnitudes.

This can be compensated on post processing by applying the correction factors to each ADC channel, compared to the channel that gives the highest gain.

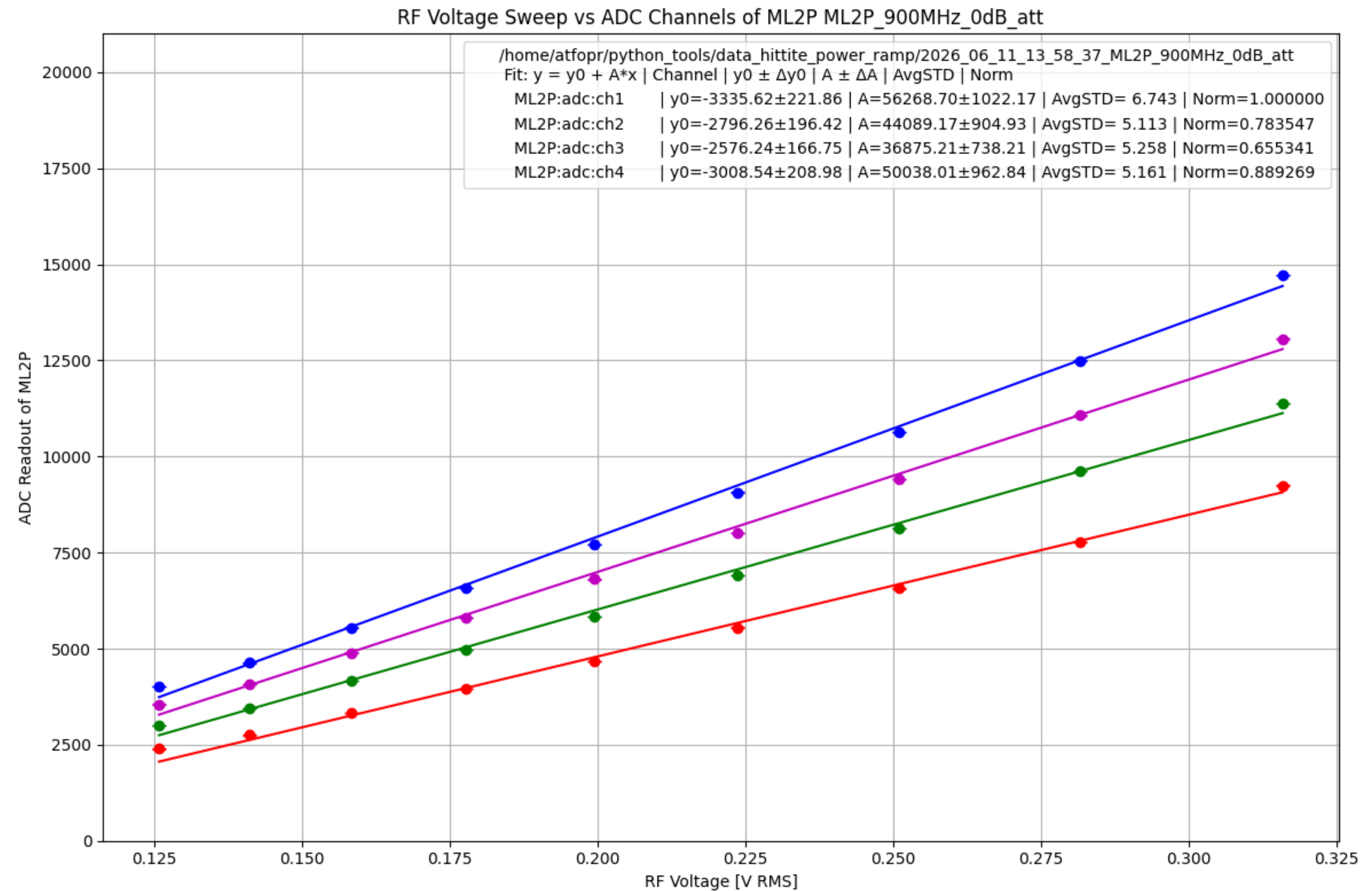
From the example of ML3P:

$$ch_{1,corr} = ch_1$$

$$ch_{2,corr} = ch_2/0.783547$$

$$ch_{3,corr} = ch_3/0.655341$$

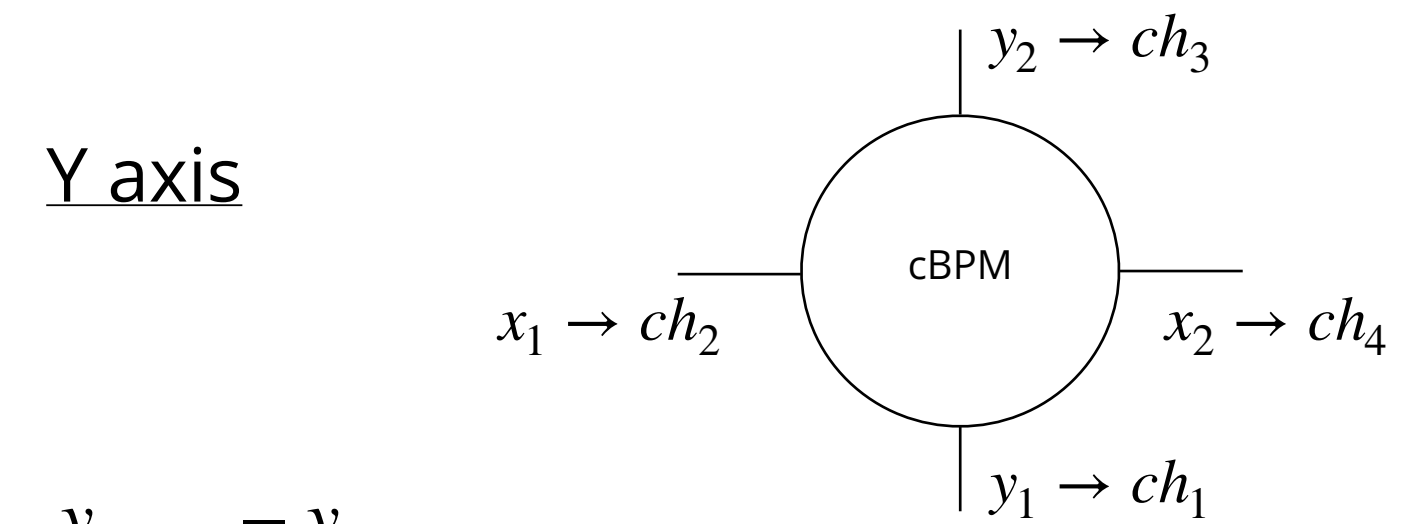
$$ch_{4,corr} = ch_4/0.889269$$



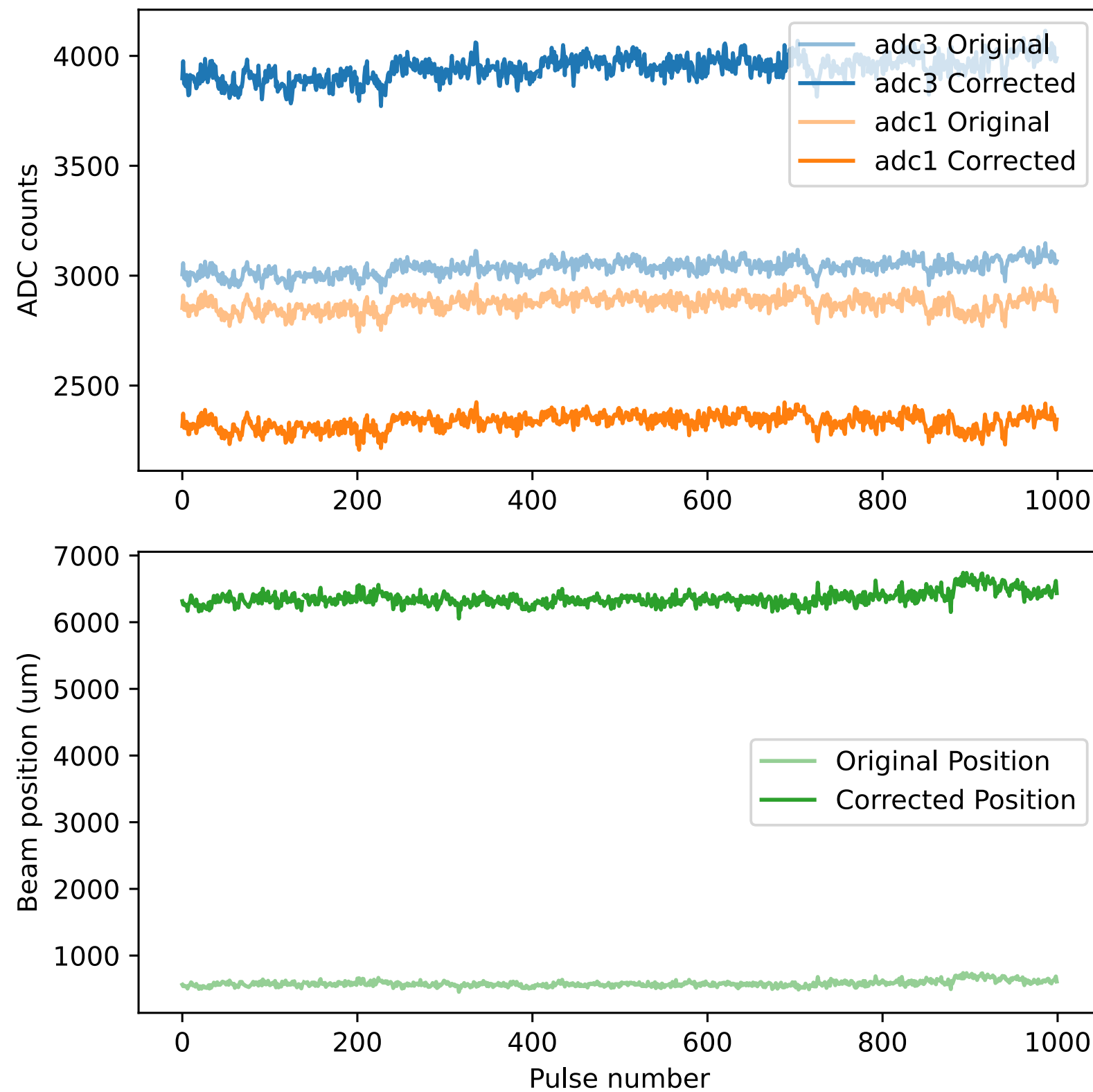
III. Calibration corrections

A) Compensating for stripline electronics amplitude difference

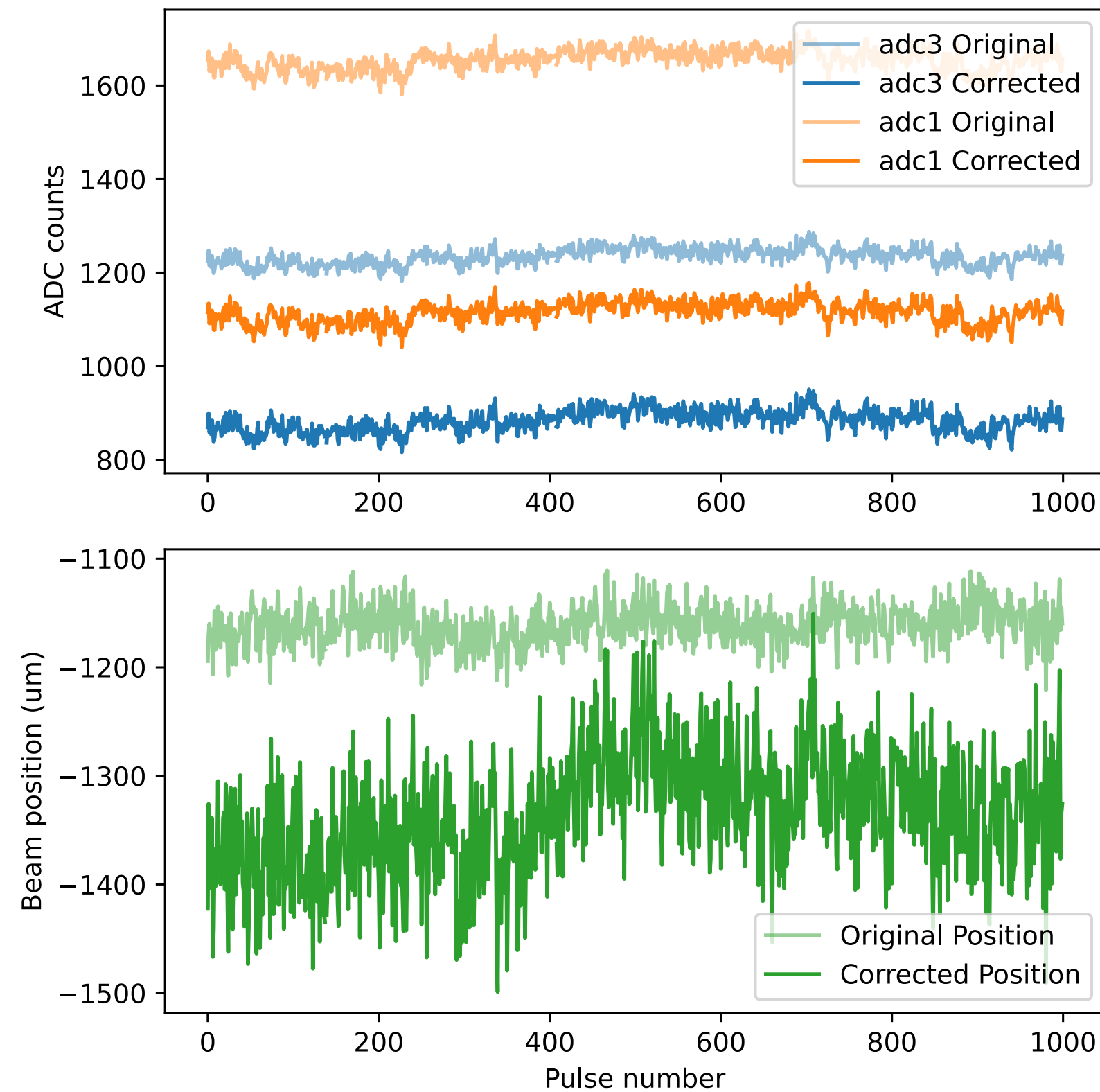
Procedure: $y_i = ch_i - ped_i \Rightarrow S_y = y \frac{x_1 + x_2 + y_1 + y_2}{y_1 - y_2} \Rightarrow y_{i,corr} = y_i / CF_i \Rightarrow y_{corr} = \nu(S_y) \frac{y_{1,corr} - y_{2,corr}}{x_{1,corr} + x_{2,corr} + y_{1,corr} + y_{2,corr}}$



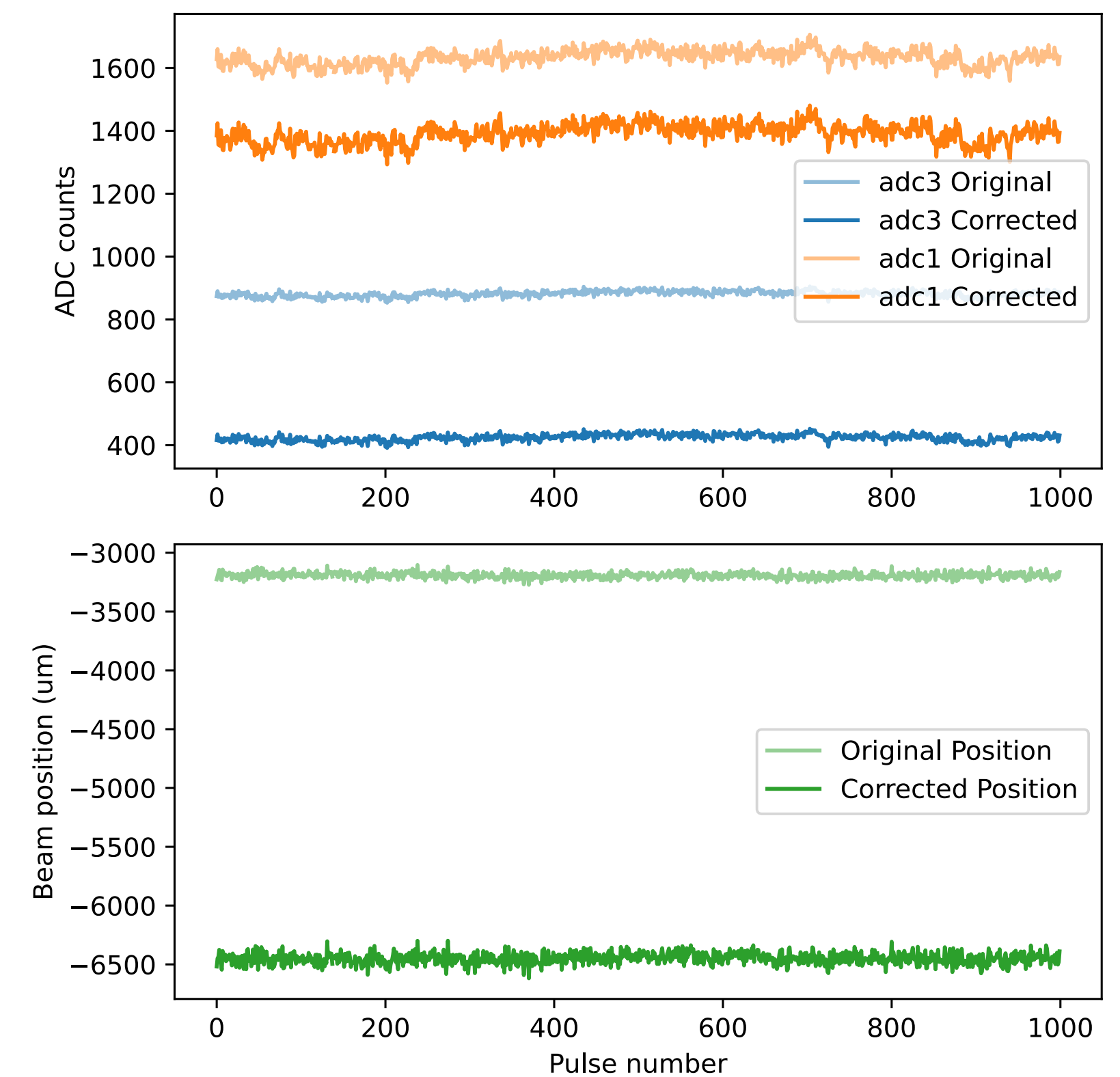
ML2P



ML3P



ML4P



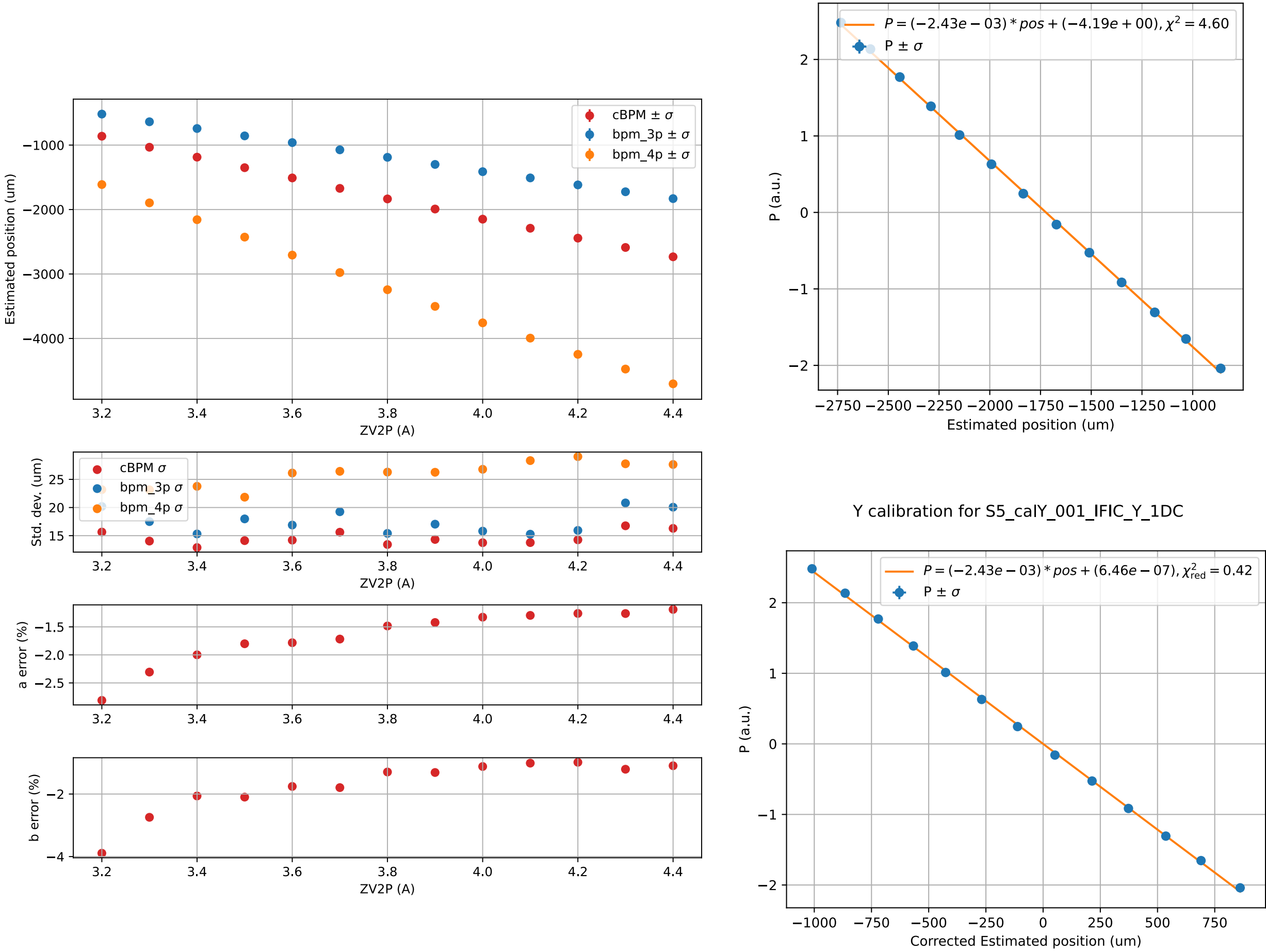
III. Calibration corrections

Y axis

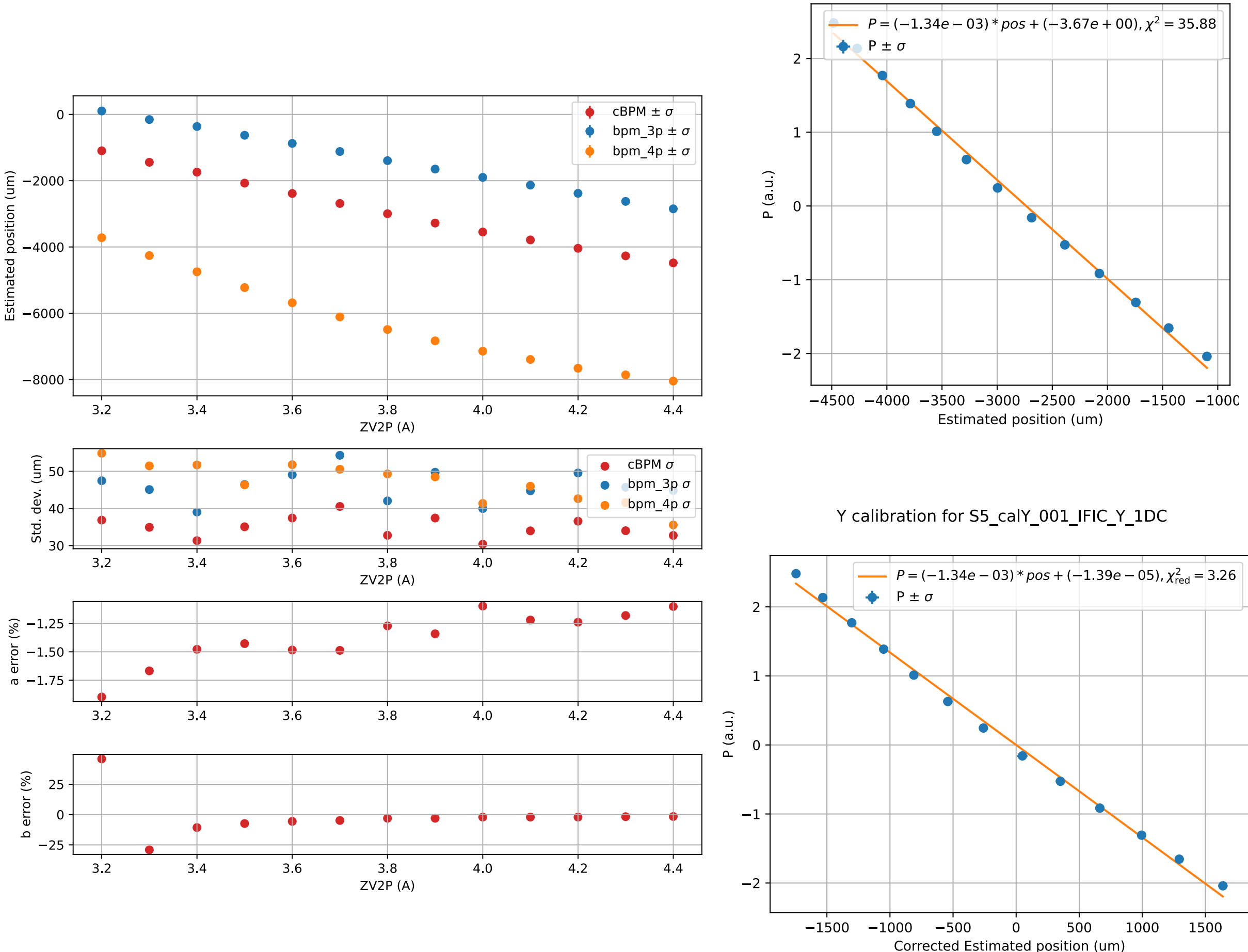
A) Compensating for stripline electronics amplitude difference

Only applying CF to ML3P and ML4P

Calibration results **without** correction:



Calibration results **with** correction:



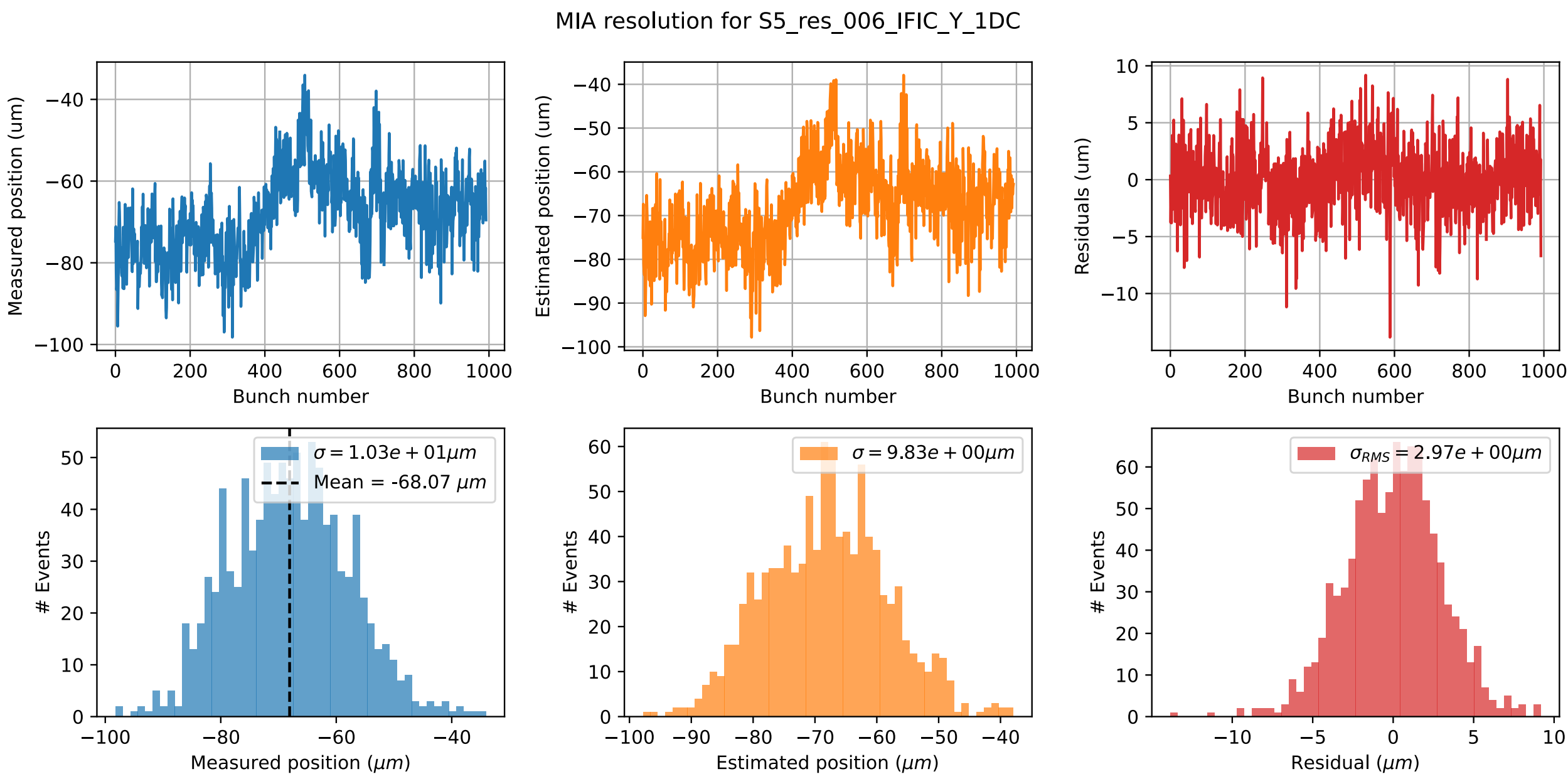
III. Calibration corrections

Y axis

A) Compensating for stripline electronics amplitude difference

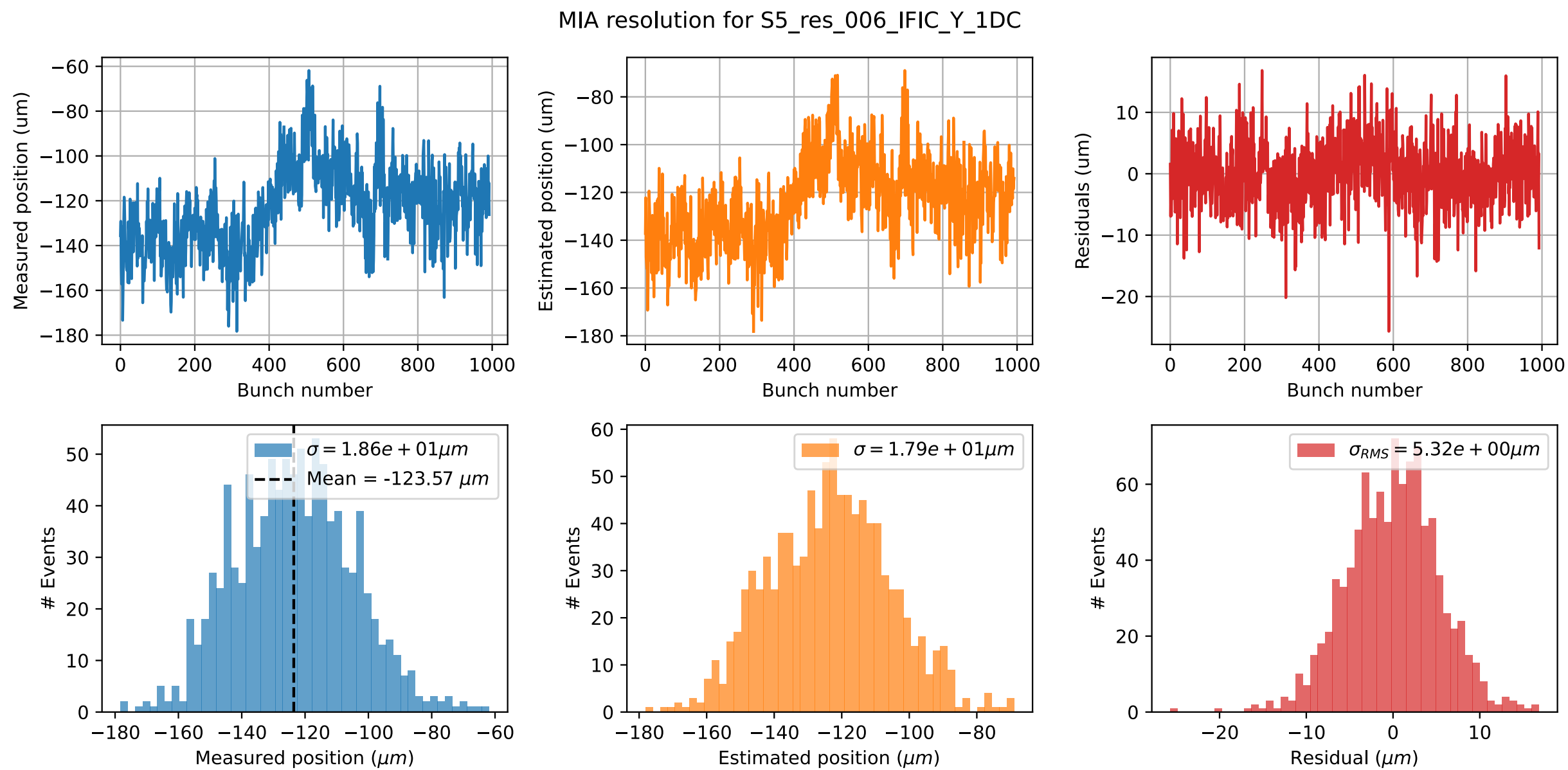
Only applying *CF* to ML2P, ML3P and ML4P

Resolution results **without** correction:



2.97 μm

Resolution results **with** correction:



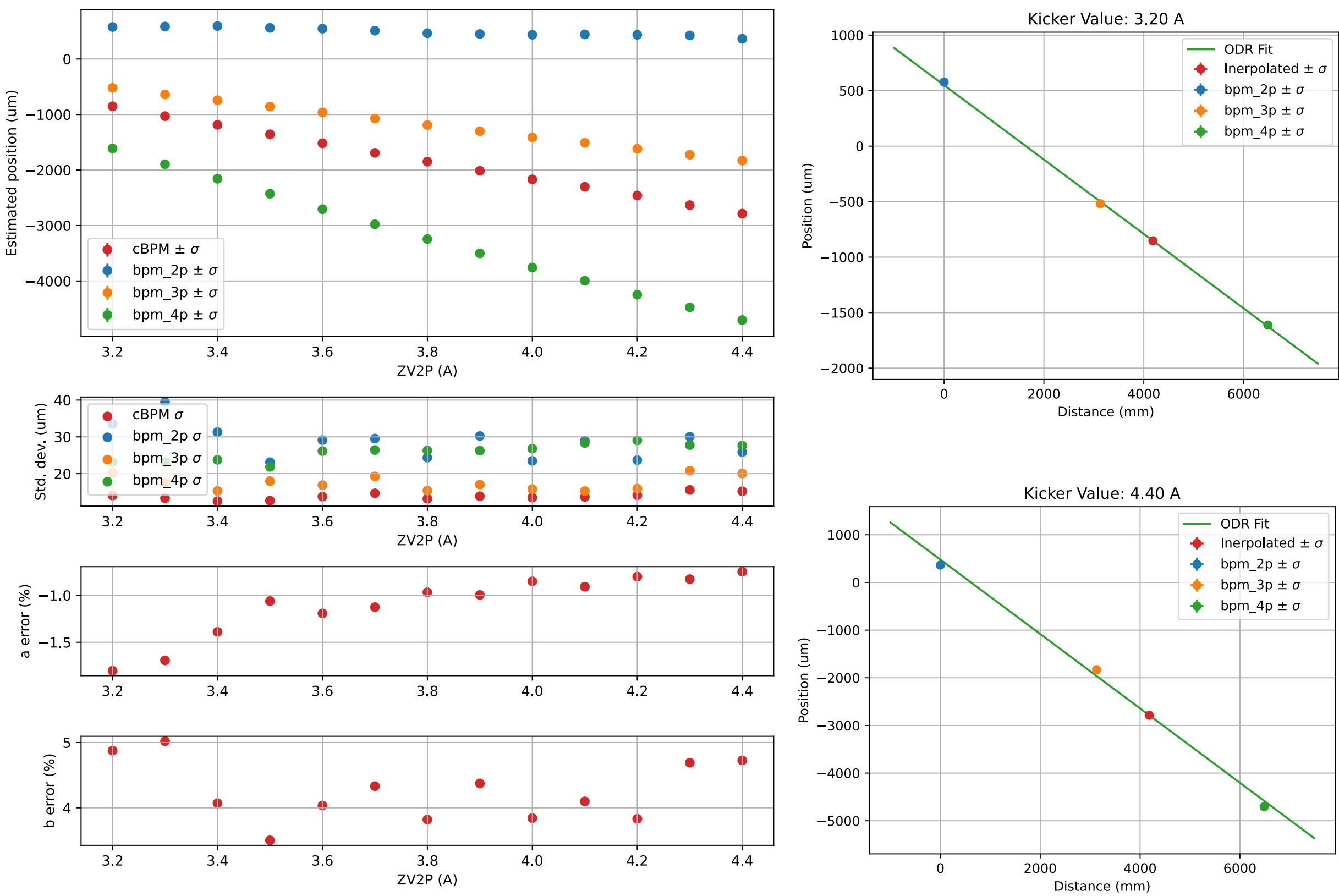
5.97 μm

III. Calibration corrections

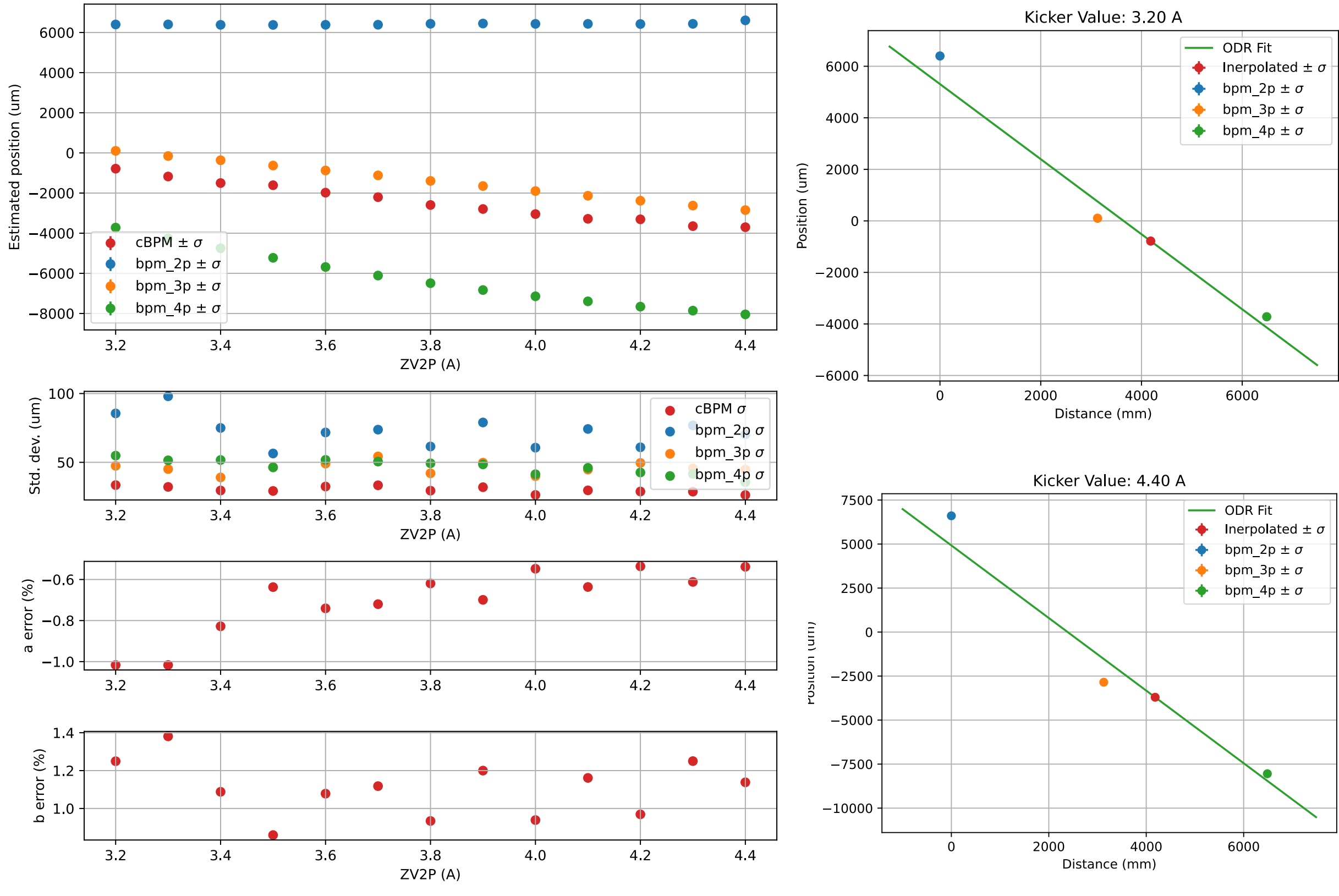
A) Compensating for stripline electronics amplitude difference

Only applying *CF* to ML2P, ML3P and ML4P

Calibration results **without** correction:



Calibration results **with** correction:



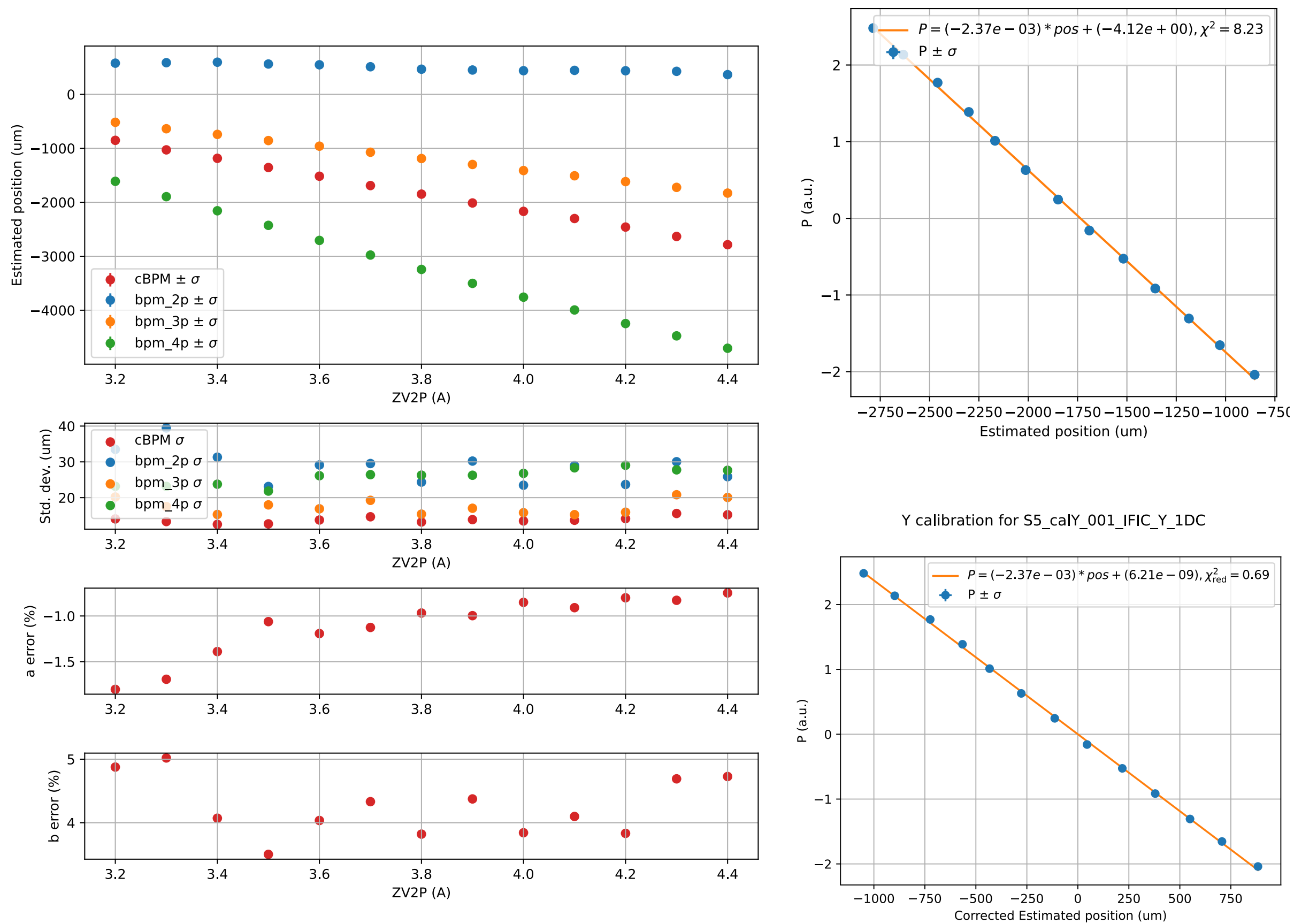
III. Calibration corrections

Y axis

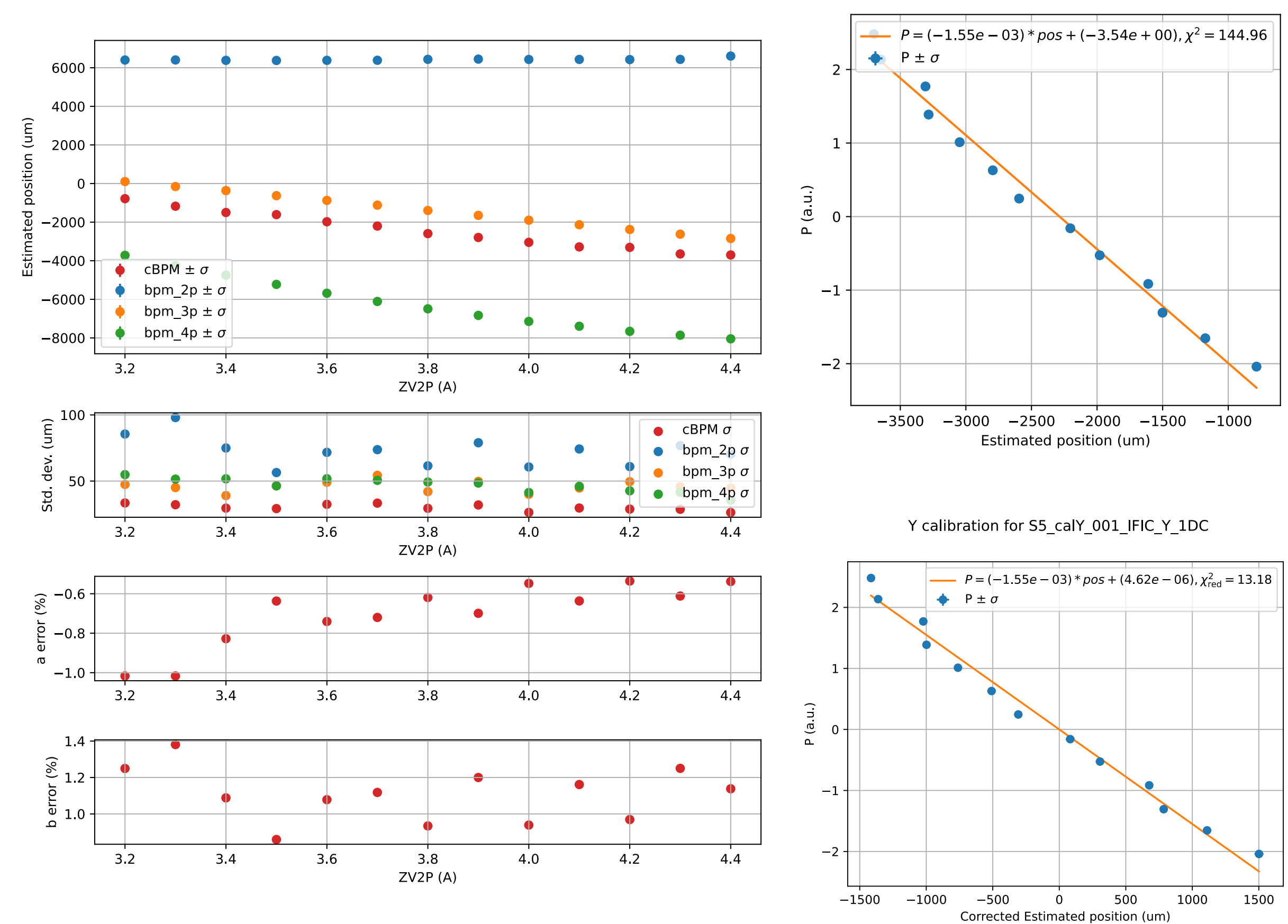
A) Compensating for stripline electronics amplitude difference

Only applying *CF* to ML2P, ML3P and ML4P

Calibration results **without** correction:



Calibration results **with** correction:



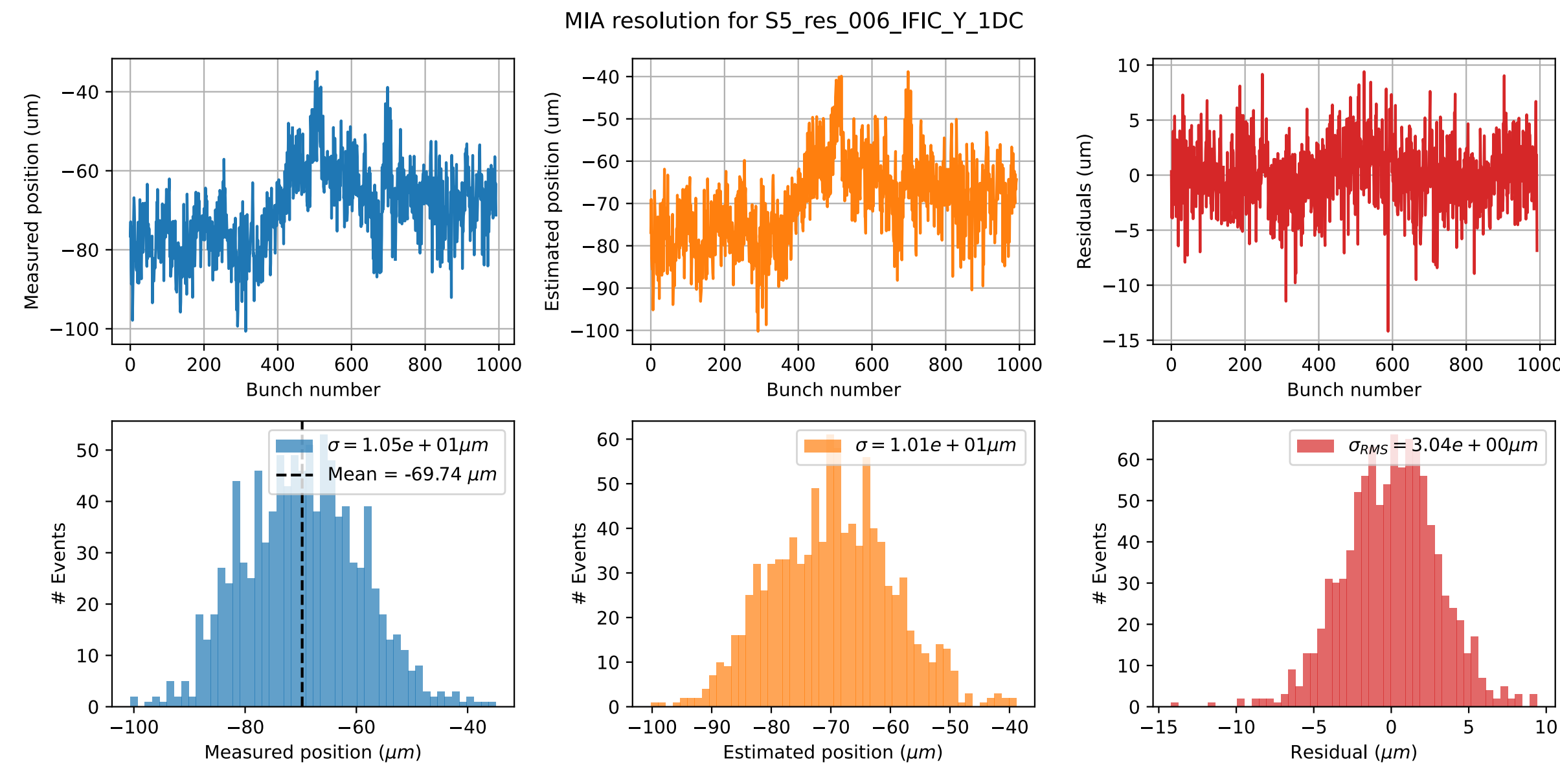
III. Calibration corrections

Y axis

A) Compensating for stripline electronics amplitude difference

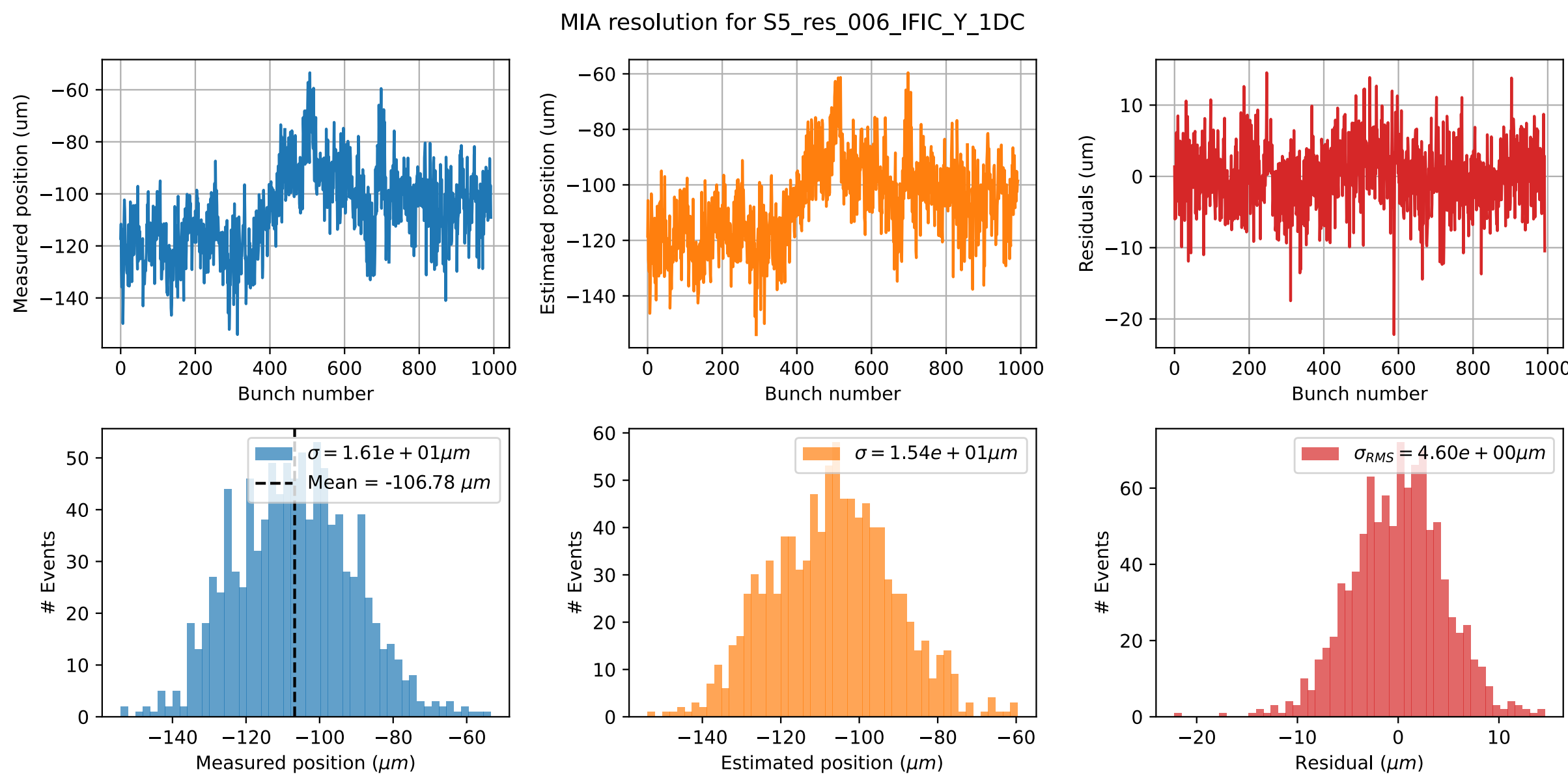
Only applying *CF* to ML2P, ML3P and ML4P

Resolution results **without** correction:



3.04 μm

Resolution results **with** correction:

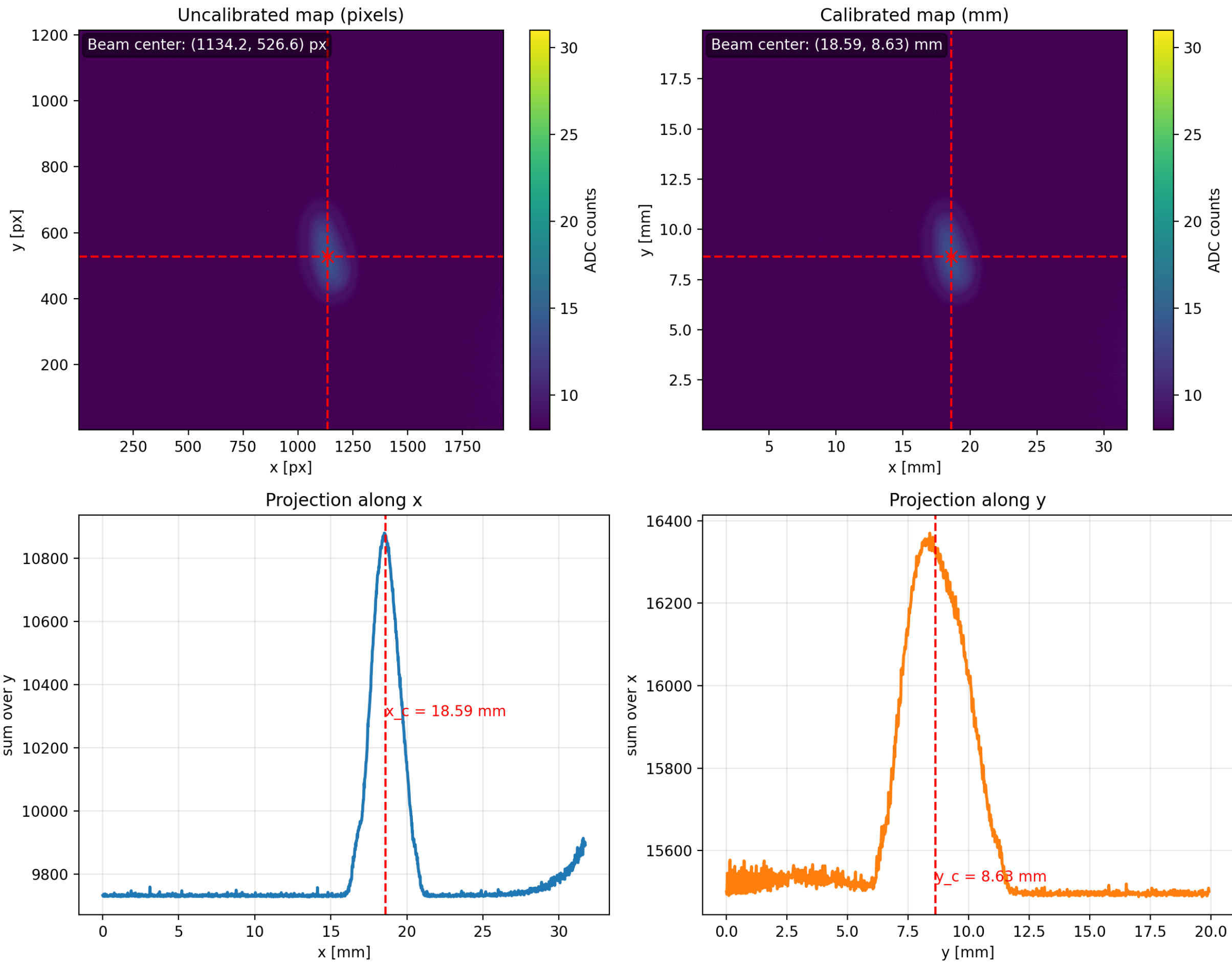


4.60 μm

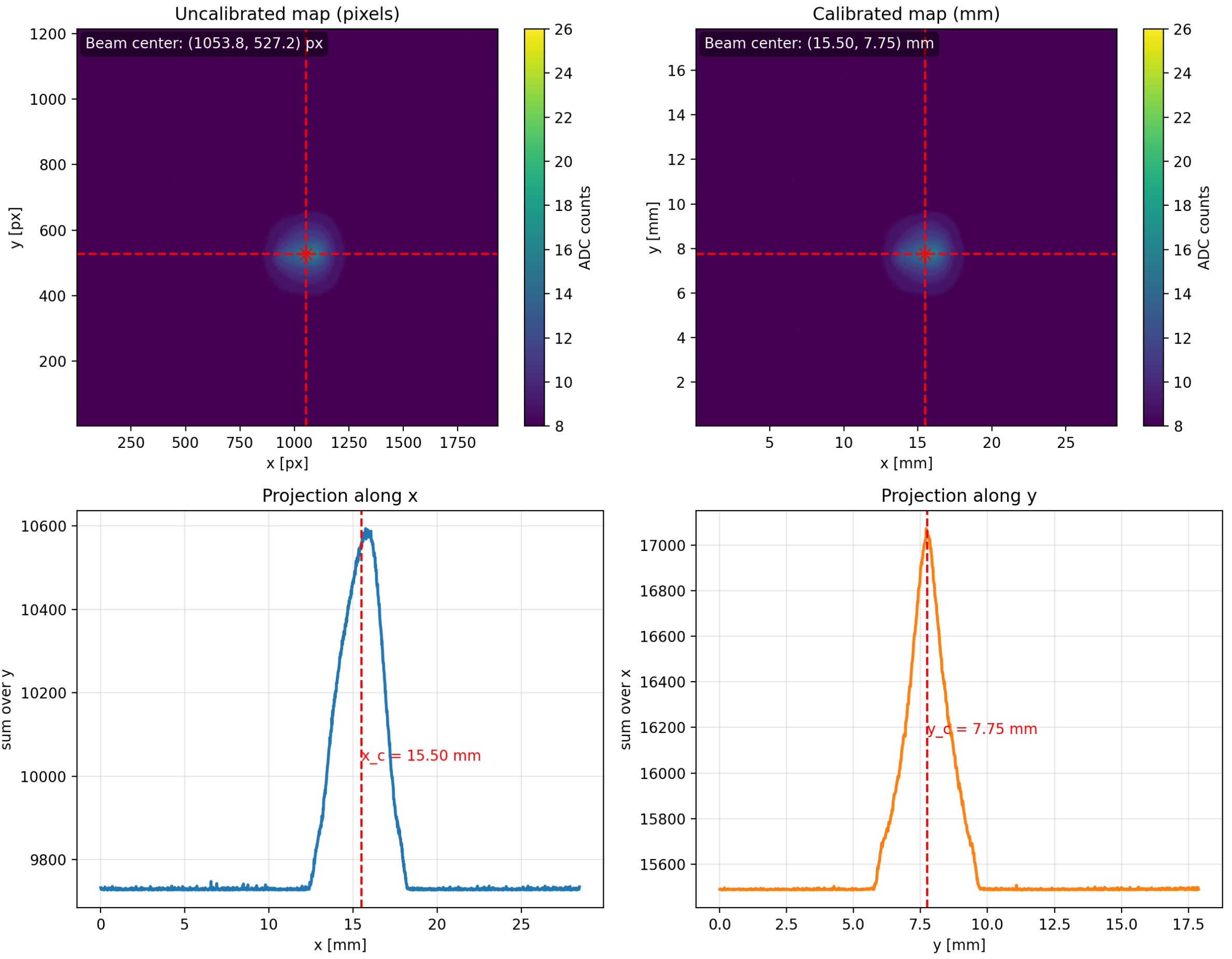
III. Calibration corrections

B) Including the profile monitors

Screen MS2P / steering ZV2P / sample 1



Screen MS3P / steering ZV2P / sample 1





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Thank you for your attention

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Backup-slides

I. Resolution estimation results

A) Resolution calculation with Pseudo-inverse