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PhD 34 - Resolution analysis

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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. SVD Analysis simulations
 - A) Using lower resolution BPMs
 - B) Inclusion of the charge information
 - C) ...

Conclusion

I. Resolution estimation results

A) Resolution calculation with Pseudo-inverse

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

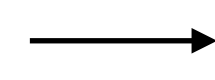
$P = 1000$ is the number of pulses

$M = 20$ 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:

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

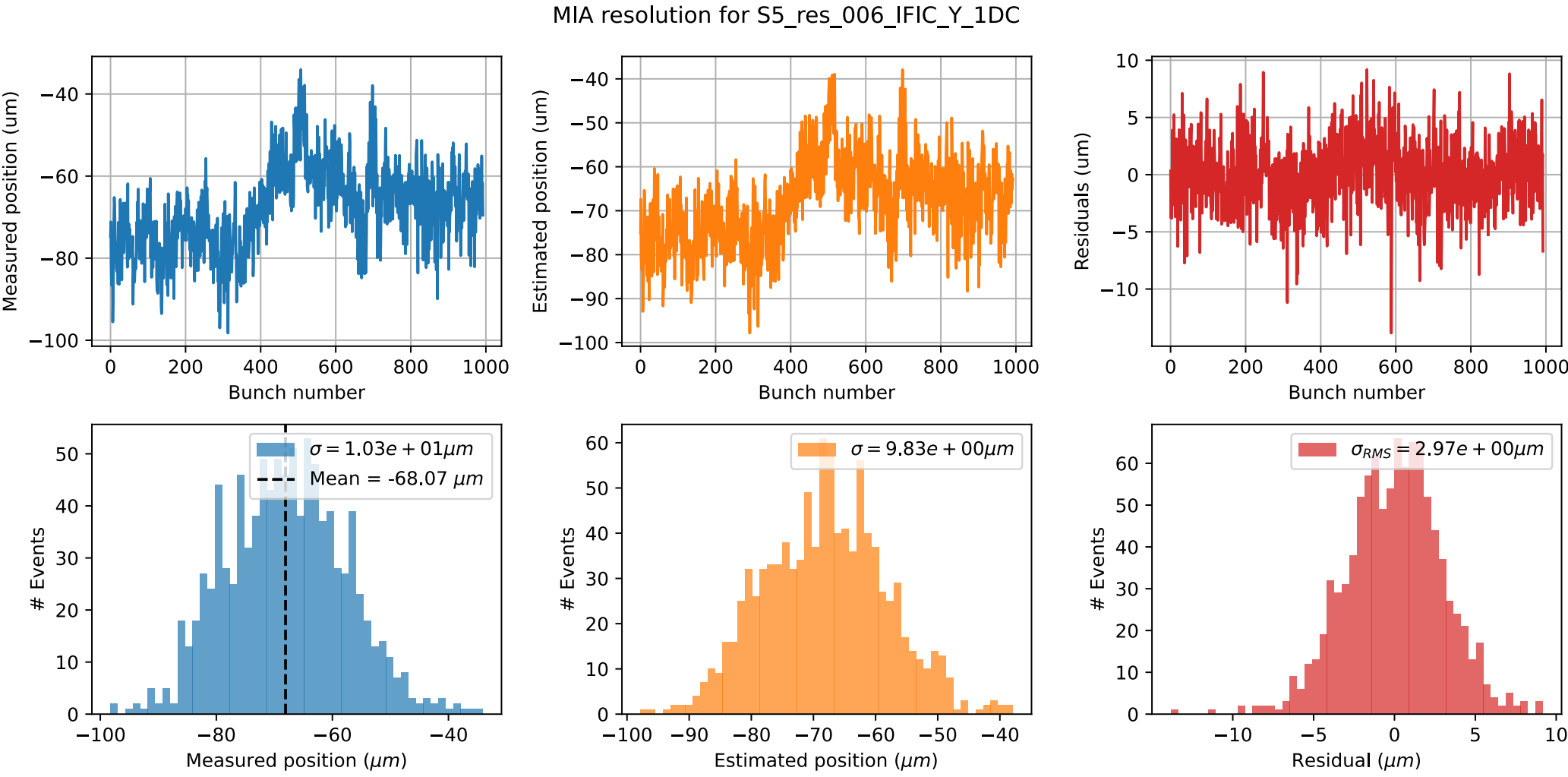
$$\begin{aligned} \mathbf{D}^{-1} &= \mathbf{V}^T \mathbf{S}^{-1} \mathbf{U}^T \\ &= \mathbf{V} \begin{pmatrix} 1/\sigma_1 & & \\ & \ddots & \\ & & 1/\sigma_M \end{pmatrix} \mathbf{U}^T \end{aligned}$$

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

I. Resolution estimation results

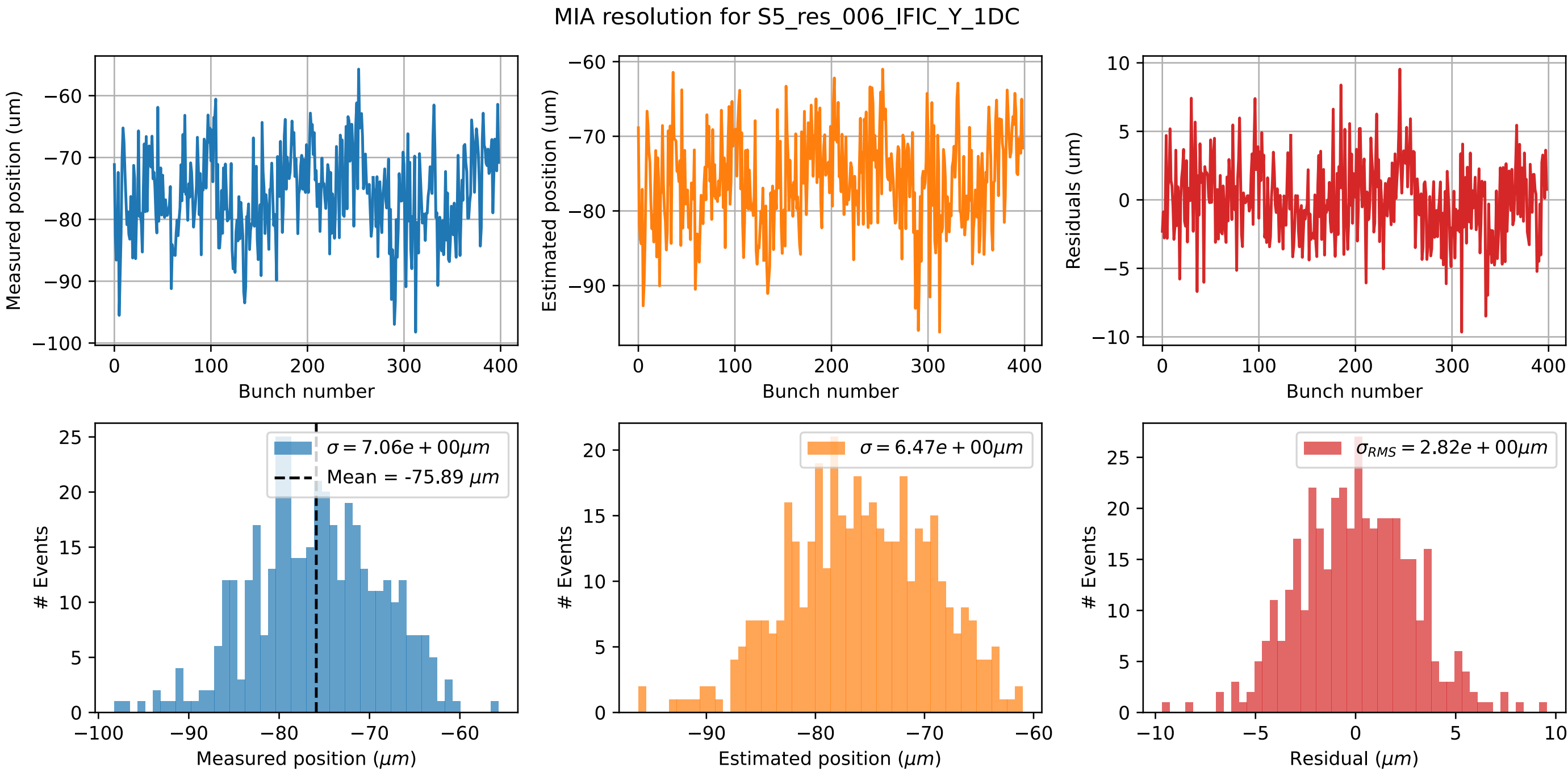
B) Selecting a specific part of the data

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

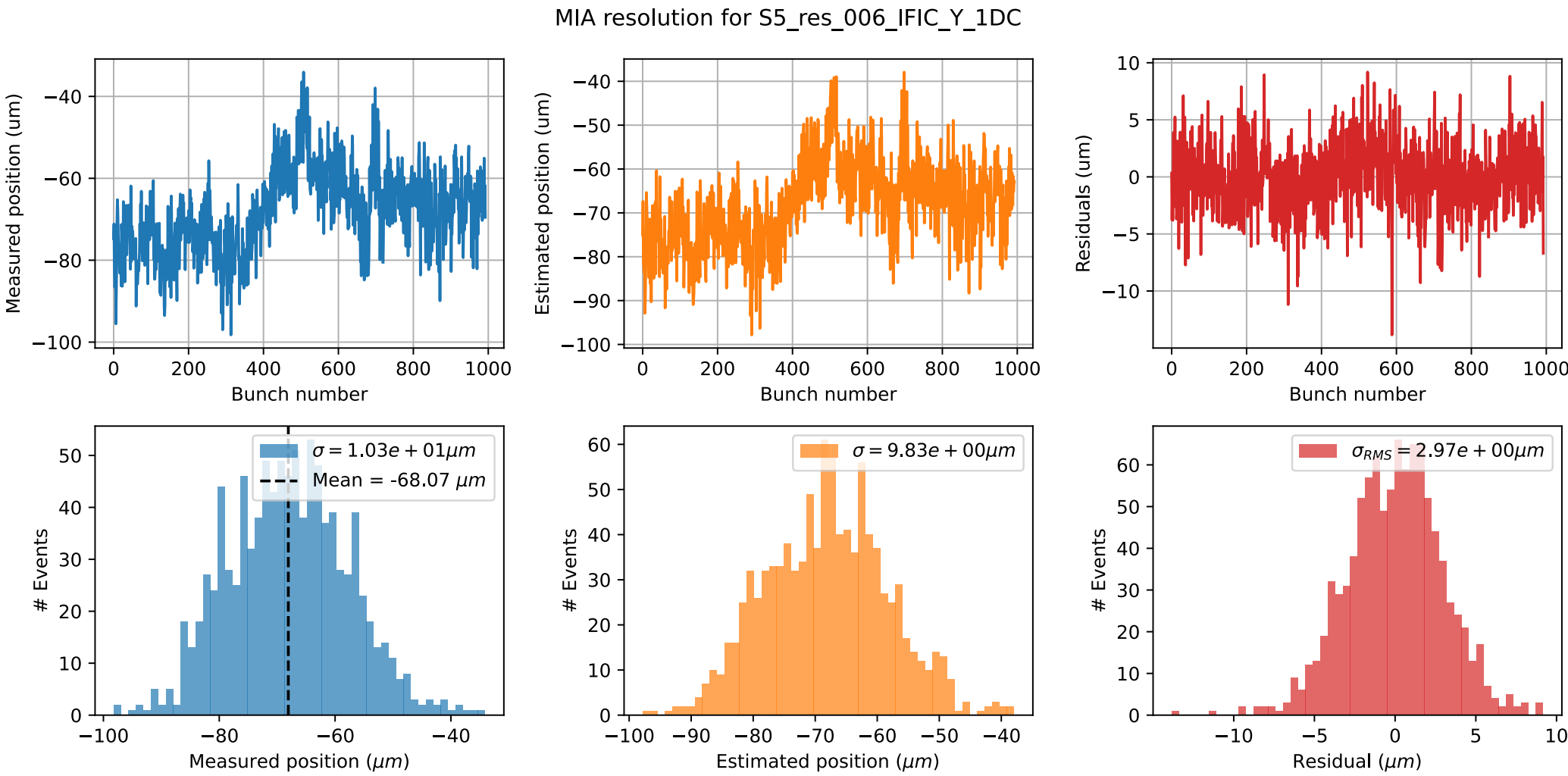


RESOLUTION with other cBPM			
resolution	res_err_n	res_err_c	res_err_2
(um)	(um)	(um)	(um)
2.82	2.20	0.82	2.46

I. Resolution estimation results

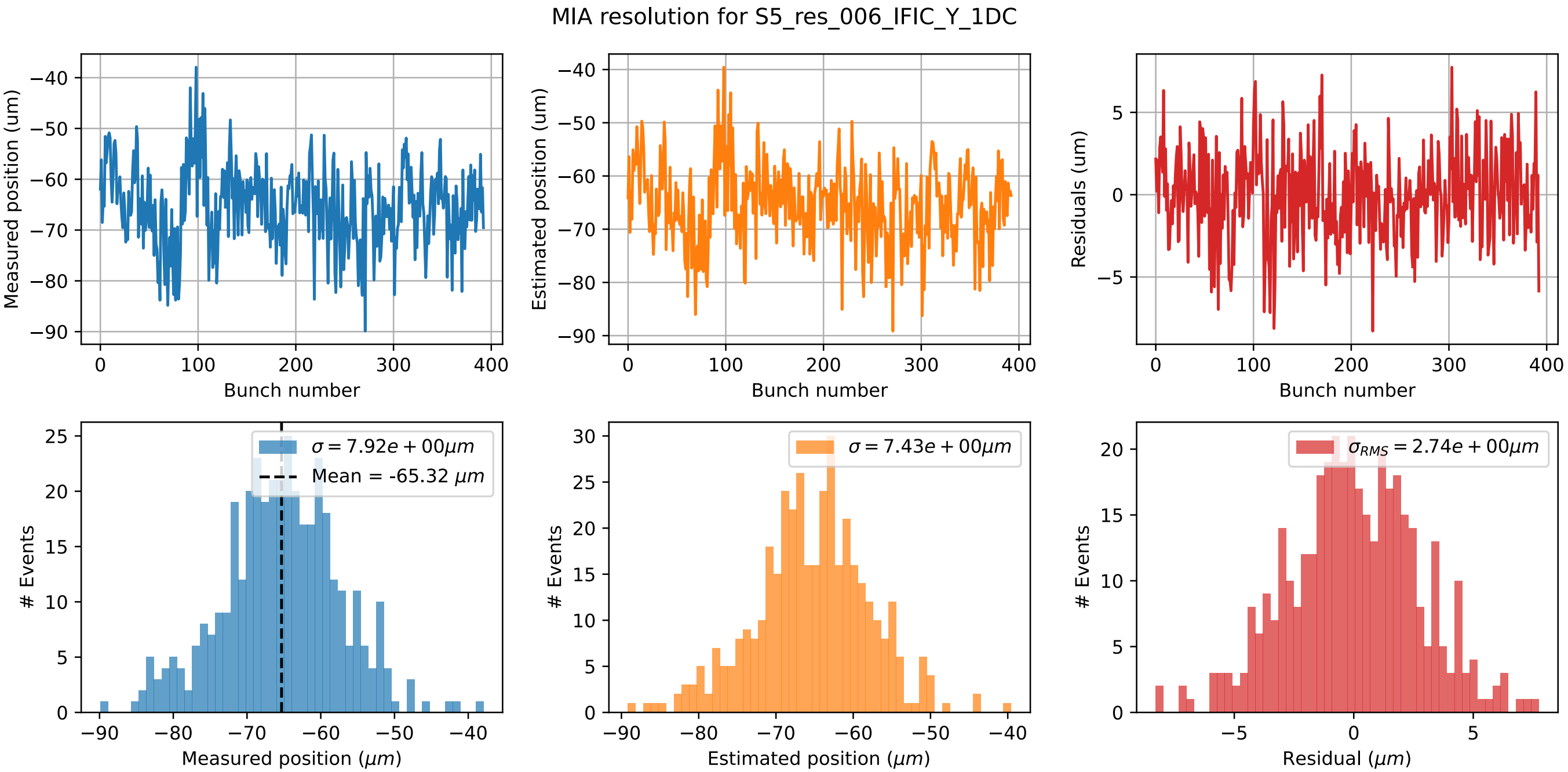
B) Selecting a specific part of the data

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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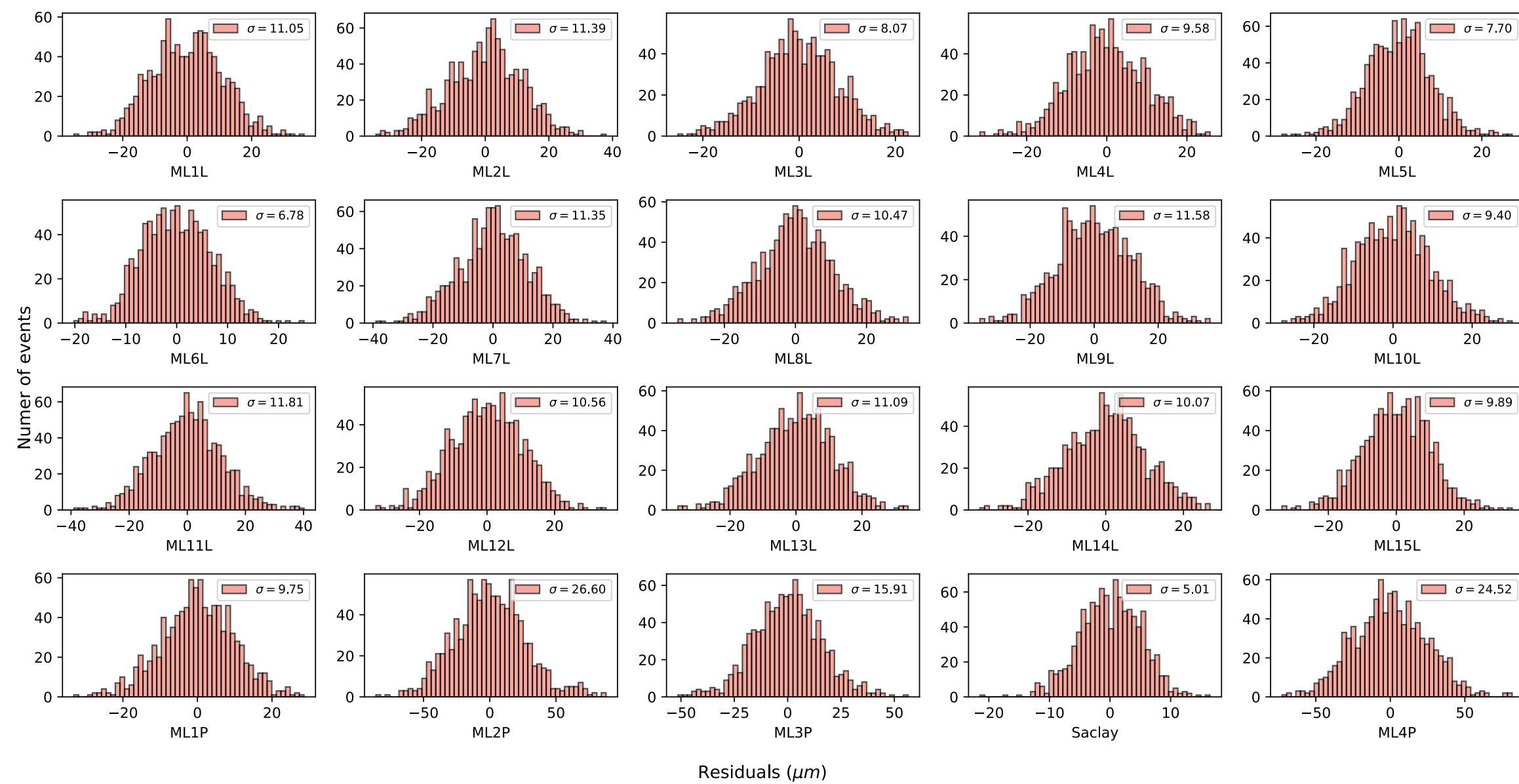
Conclusion

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:**

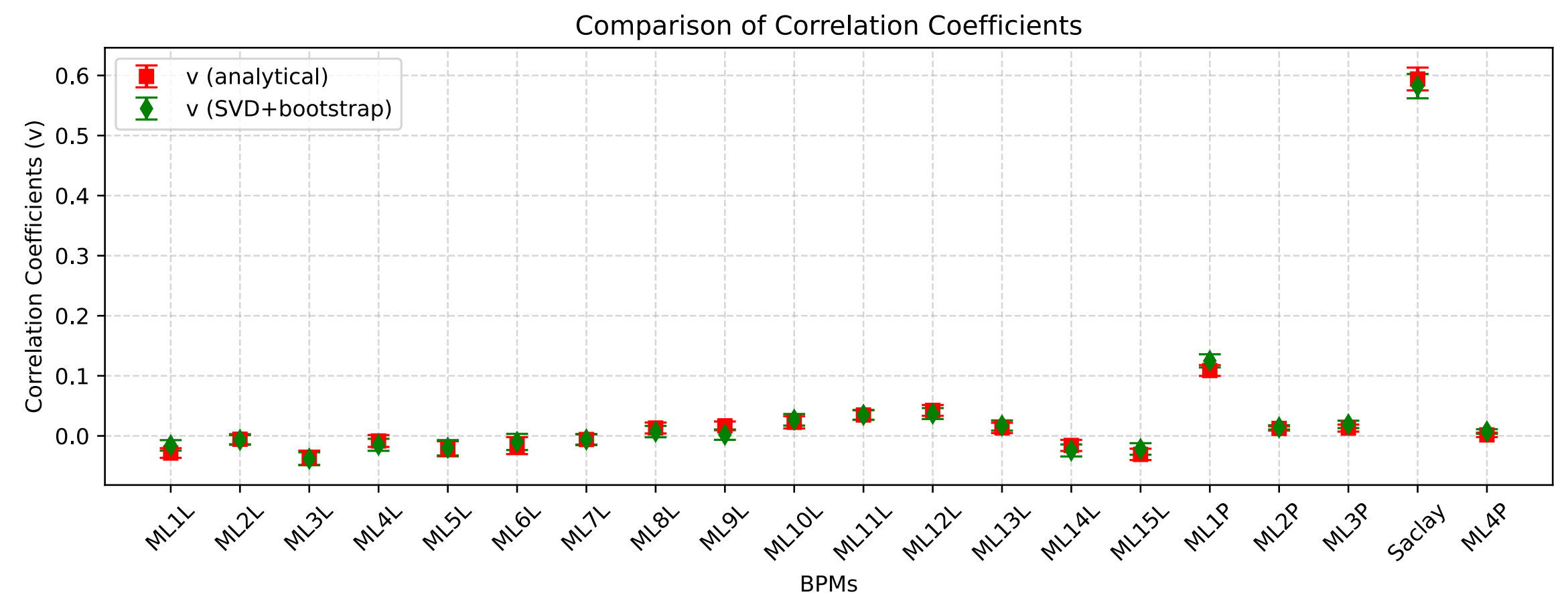
from the square root of the diagonal elements of the covariance matrix $Cov(\mathbf{v})$, where

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

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

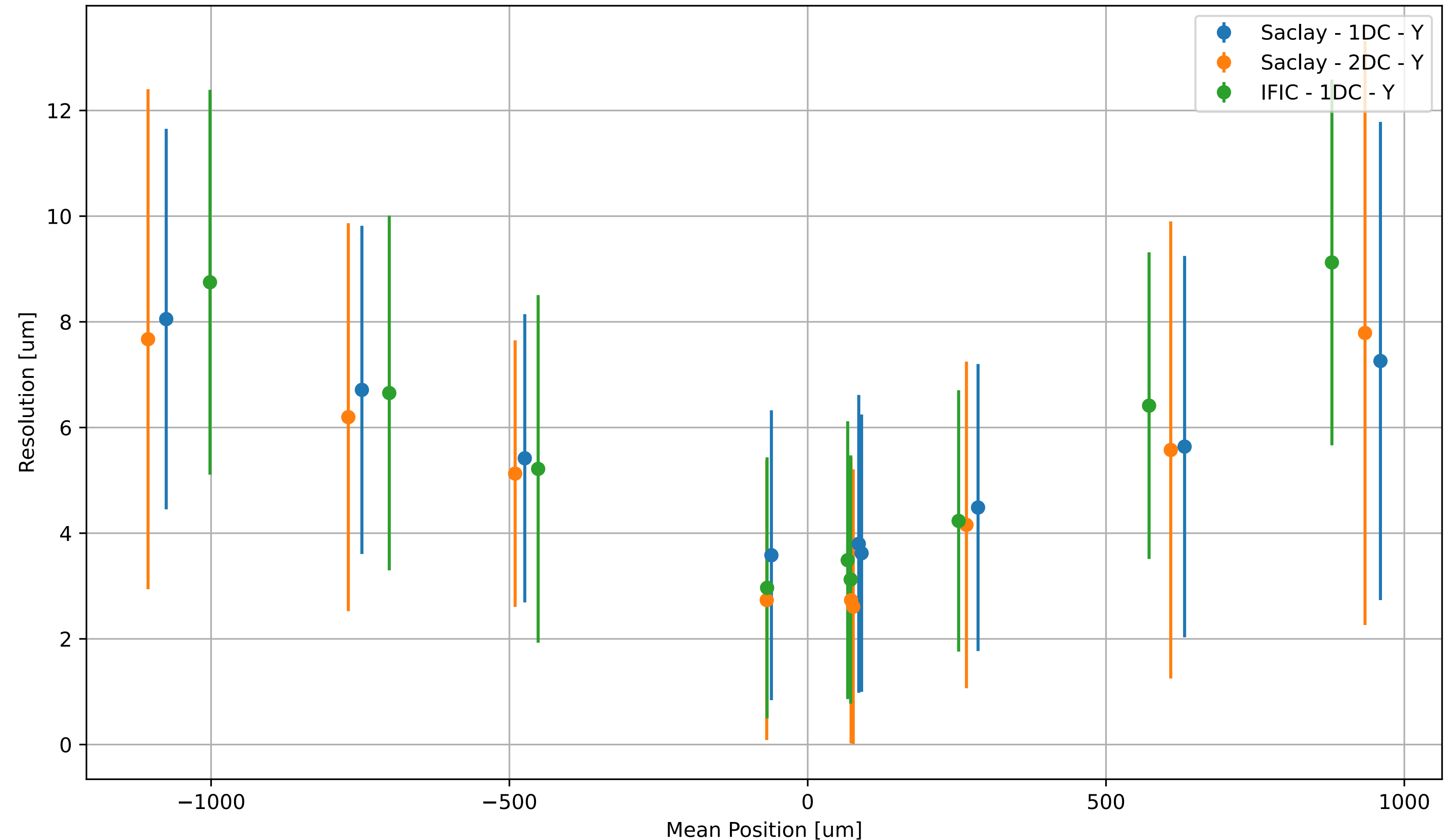
II. Pseudo-inverse method limitations

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?

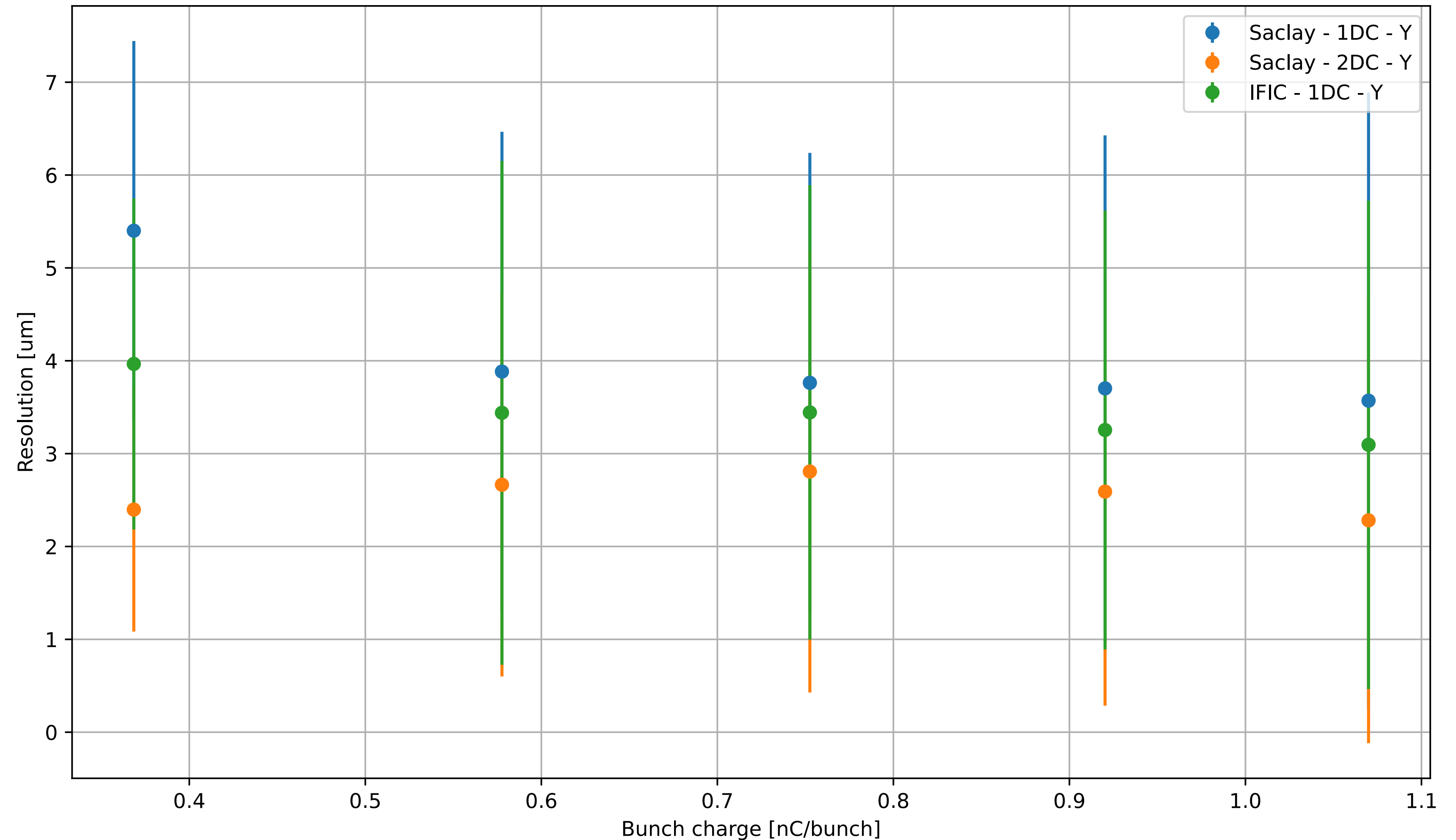


II. Pseudo-inverse method limitations

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

D) Resolution as a function of the time window

Work in progress...

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Backup-slides

I. Resolution estimation results

A) Resolution calculation with Pseudo-inverse