PhD26:
Post-processing of ATF resolution measurements 2

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LabRF meeting, 11/02/26

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Introduction

I. Corrections
   A) Estimation of the beam position on the calibration
   B) Check resampling extremums for oscilloscope interpolation
   C) Acquisition times distribution

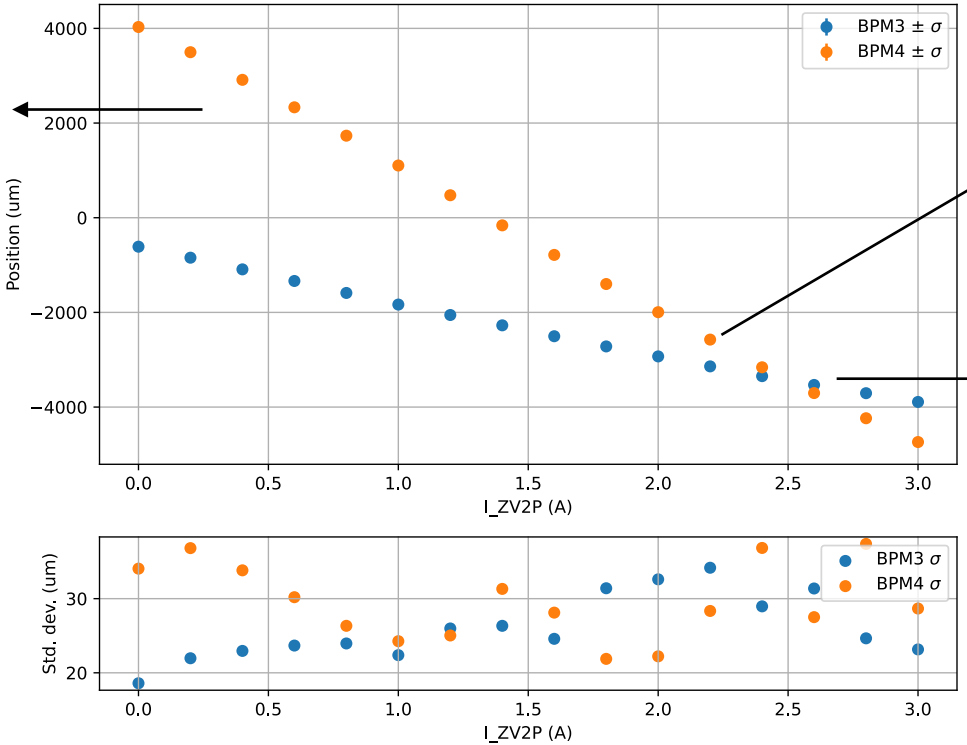
II. Overall results
   A) Without resolution algorithm improvements
   B) Specific cases
   C) With resolution algorithm improvement

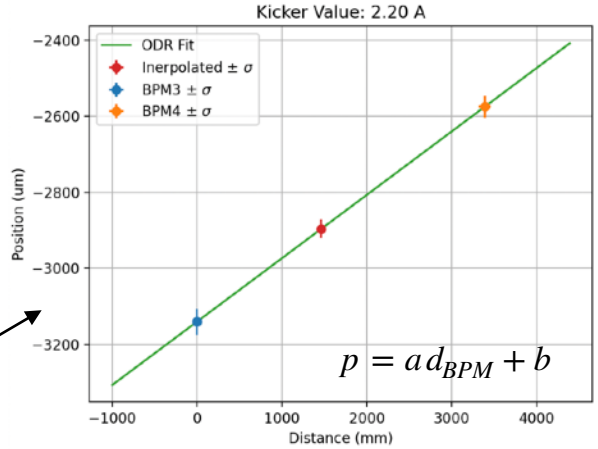
Conclusion

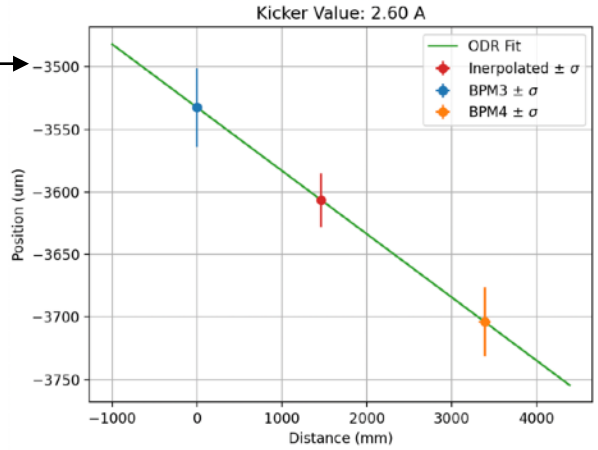
I. Corrections

A) Estimation of beam position on calibration

For each steering magnet magnitude, from the 100 bunches taken, the data is cleaned with criterion $< 5\sigma$ and then the mean value and standard deviation is computed for BPMs 3 and 4 (surrounding the cBPM)



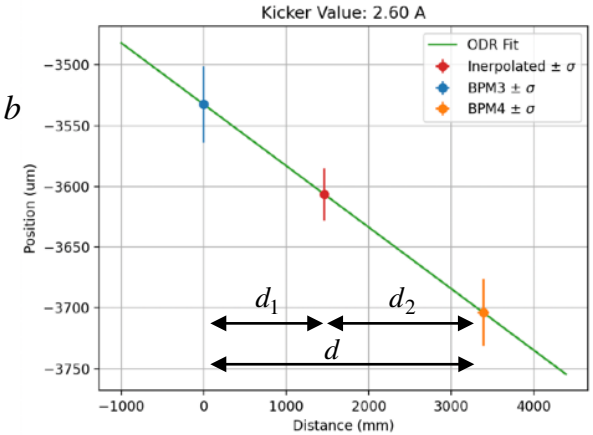




I. Corrections

A) Estimation of beam position on calibration

$$p = a\,d_{BPM} + b$$



Estimation of errors for each kick value:

- We consider a error measure distance of 5 cm on d_1 and d_2 $\Rightarrow \sigma_d = \sqrt{\sigma_{d_1}^2 + \sigma_{d_2}^2}$
- Taking into account σ_{BPM_3} , σ_{BPM_4} and σ_d , the **ODR linear fit** gives an estimation of the errors on the slope a and the intercept b : σ_a and σ_b ; and the covariance between a and b : $cov(a,b)$
- The interpolated position is calculated simply as: $p_{int} = a\,d_1 + b$
- The error on the interpolation is computed with the propagation of errors as:

$$\sigma_{int} = \left(\frac{\partial p}{\partial a}\sigma_a\right)^2 + \left(\frac{\partial p}{\partial d_1}\sigma_{d_1}\right)^2 + \left(\frac{\partial p}{\partial b}\sigma_b\right)^2 + 2\frac{\partial p}{\partial a}\frac{\partial p}{\partial b}cov(a,b) = (d_1\sigma_a)^2 + (a\sigma_{d_1})^2 + \sigma_b^2 + 2d_1 cov(a,b)$$

I. Corrections

A) Estimation of beam position on calibration

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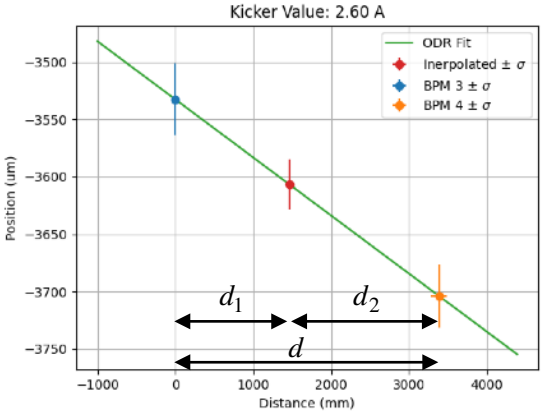
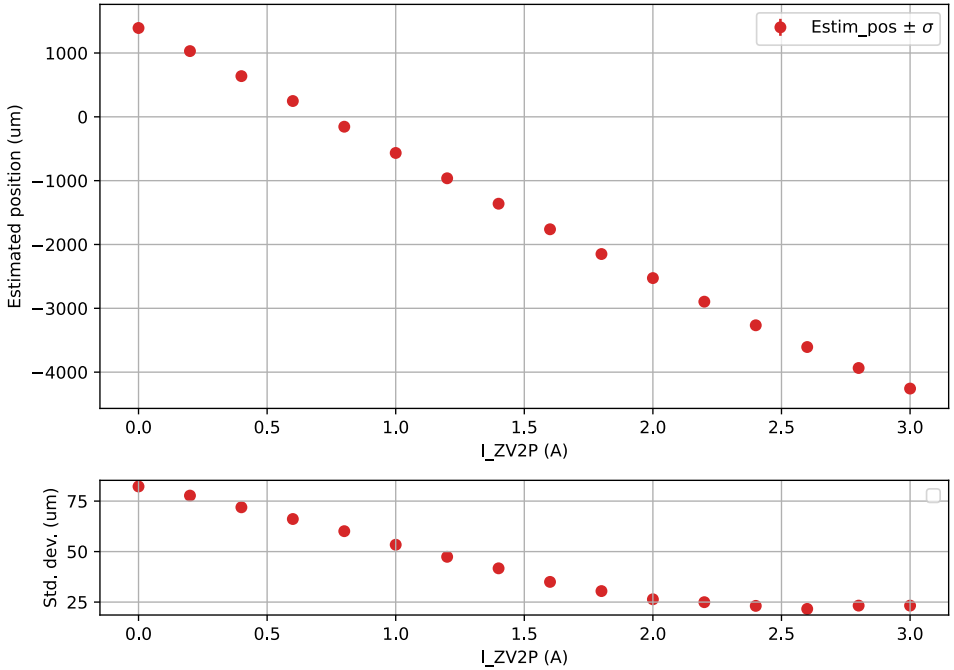
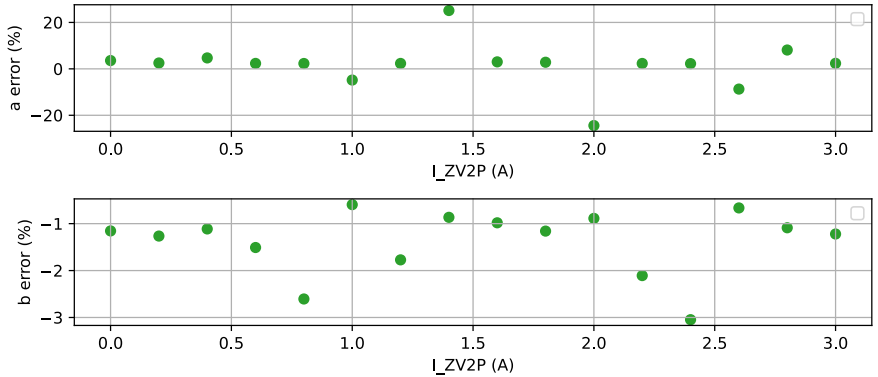


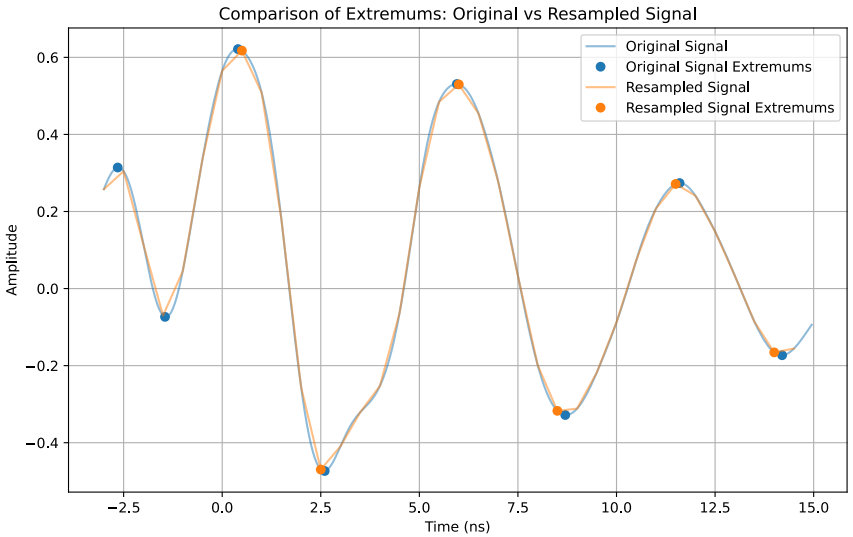




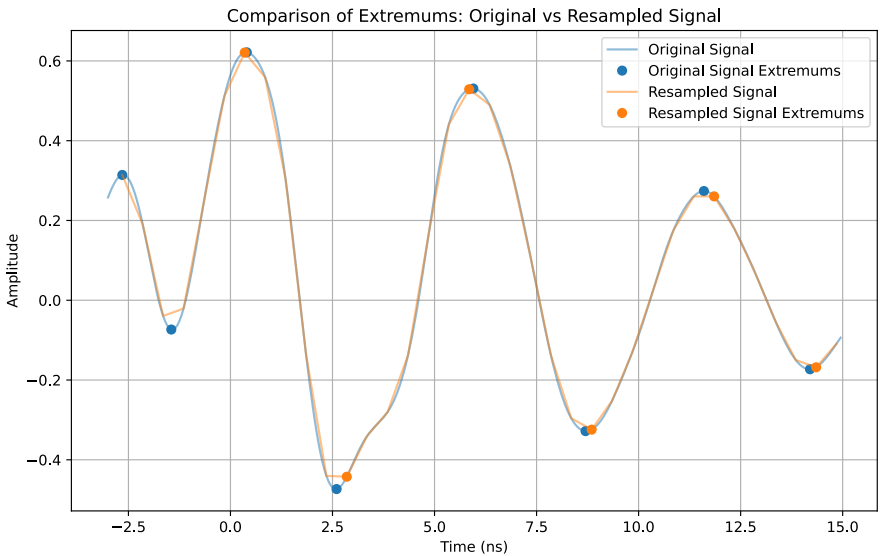
I. Corrections

B) Check resampling extremums for oscilloscope interpolation

offset = 0



offset = 7

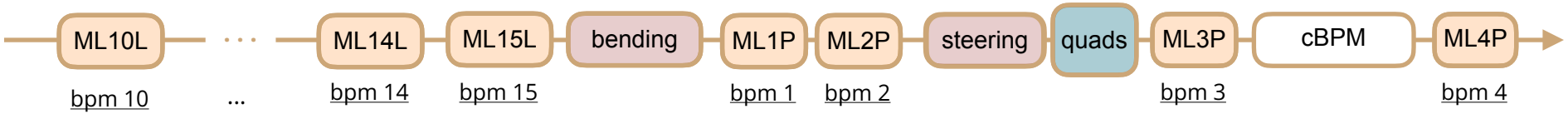


(Result that gave the best resolution)

None of the offsets give a result where all the extremums are the same than the extremums of the “original” interpolated data. The oscilloscope is not performing a linear interpolation.

I. Corrections

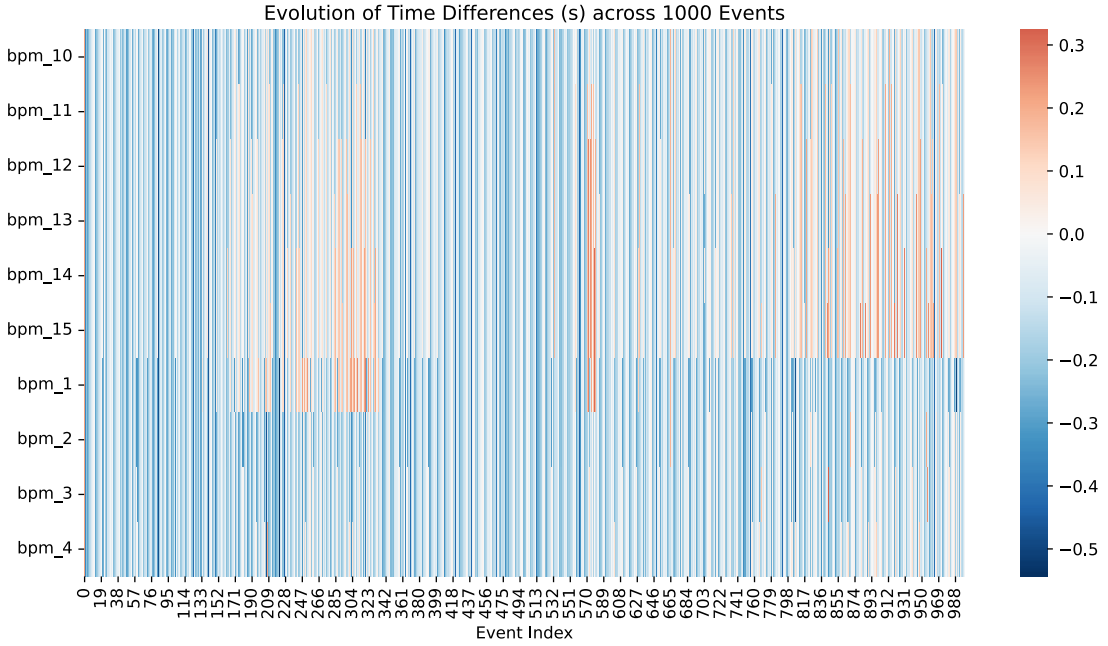
C) Acquisition times distribution



Observing all BPMs time-stamps differences with the oscilloscope acquisition.

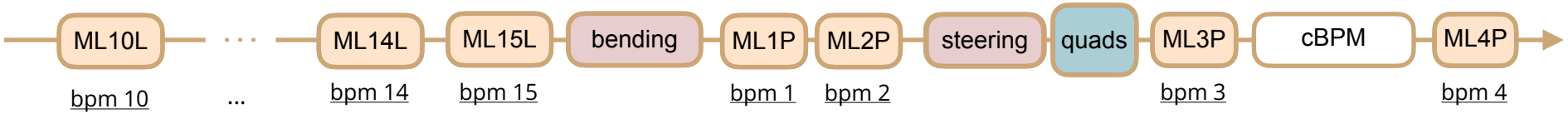
$$t_{diff,BPMx} = ts_{cBPM} - ts_{BPMx}$$

This time difference is observed for all BPMs and all bunches in the Heat-map:



I. Corrections

C) Acquisition times distribution



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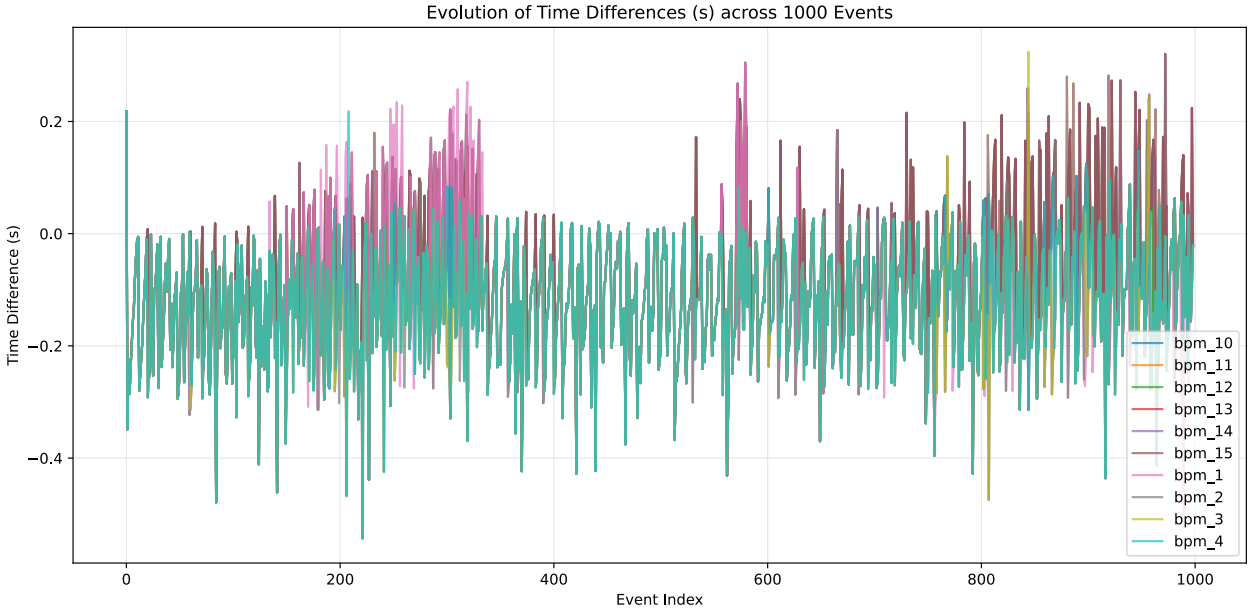
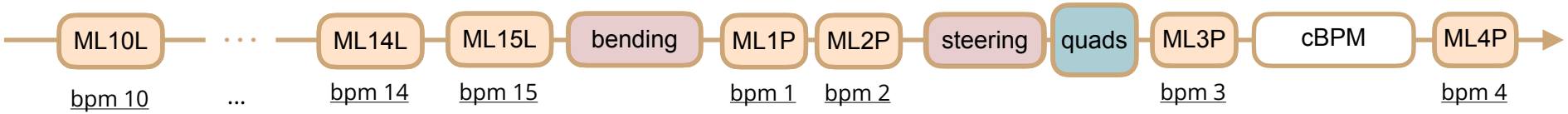


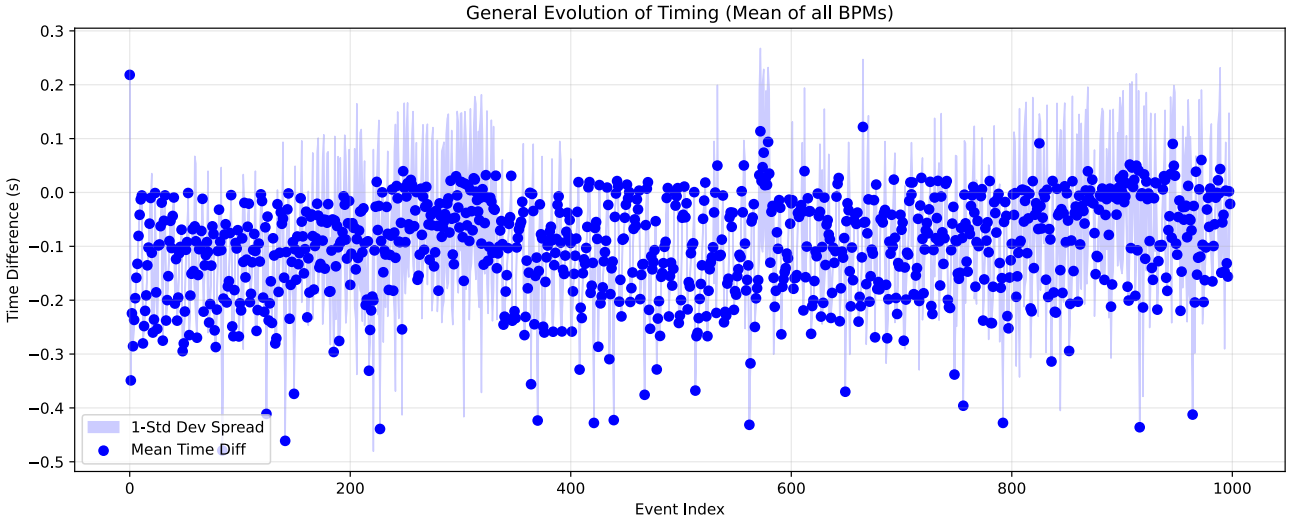
I. Corrections

C) Acquisition times distribution



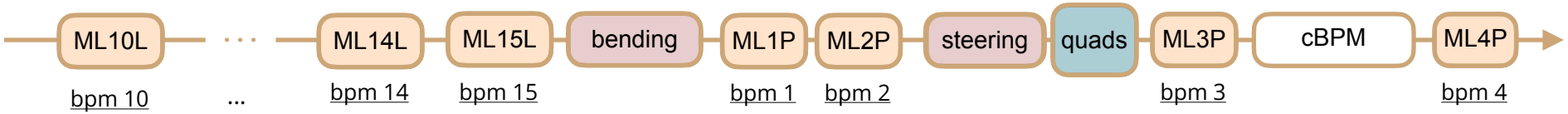
Averaging for each bunch all the stripline BPMs time-differences and calculating the standard deviation:

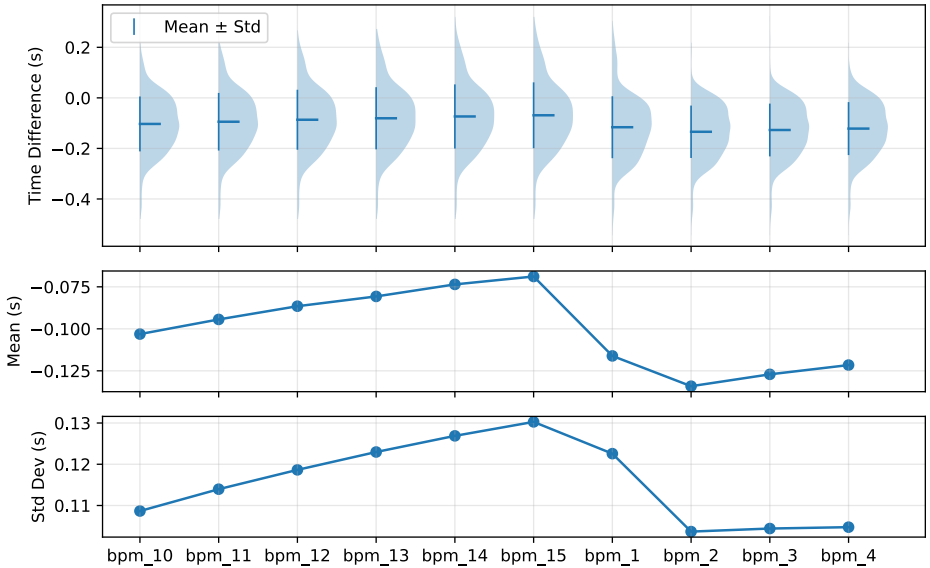
$$\overline{ts} = \frac{\sum ts_{diff,BPMx}}{\#BPMs}$$



I. Corrections

C) Acquisition times distribution





Distribution of time differences for each BPM:

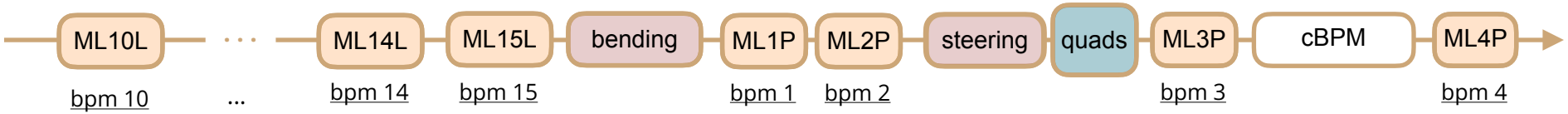
$$t_{diff,BPMx} = ts_{cBPM} - ts_{BPMx}$$

Mean value of the time difference for each BPM

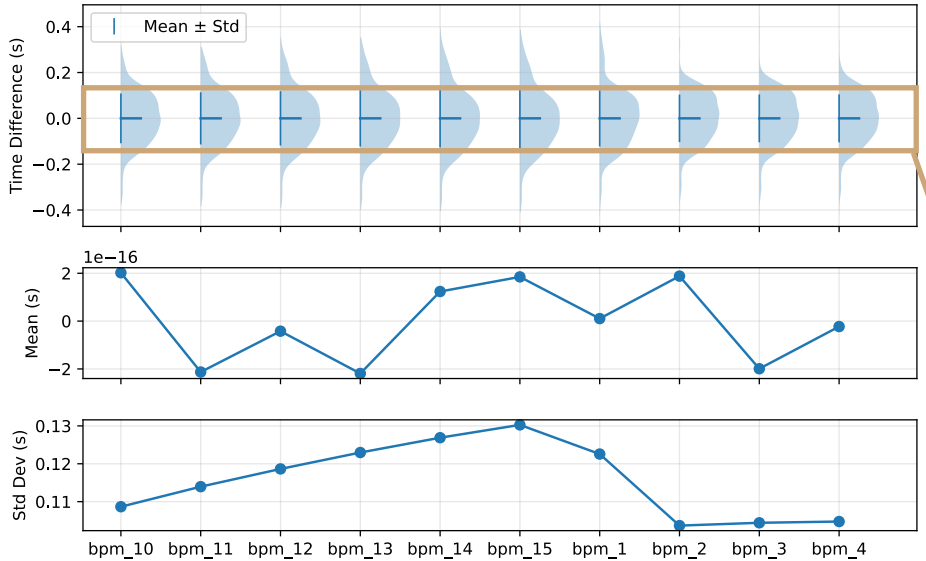
Stdv of the time difference for each BPM

I. Corrections

C) Acquisition times distribution



After removing the mean value to each BPM time-stamp



Distribution of time differences for each BPM:

$$t_{diff,BPMx} = ts_{cBPM} - ts_{BPMx} - \bar{ts}_{BPM_x}$$

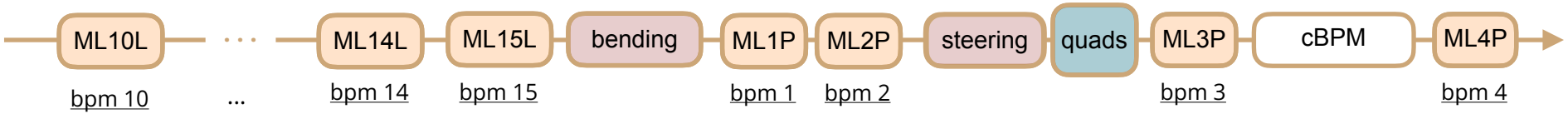
Mean value of the time difference for each BPM (should be close to 0)

Stdv of the time difference for each BPM

I select only the values present in a **time window**

I. Corrections

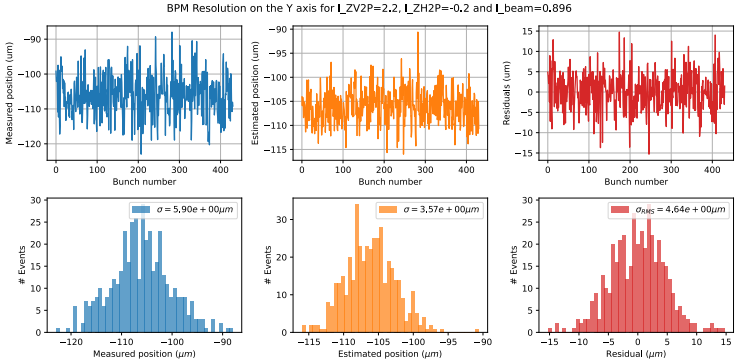
C) Acquisition times distribution



For time_window = 0.25 s

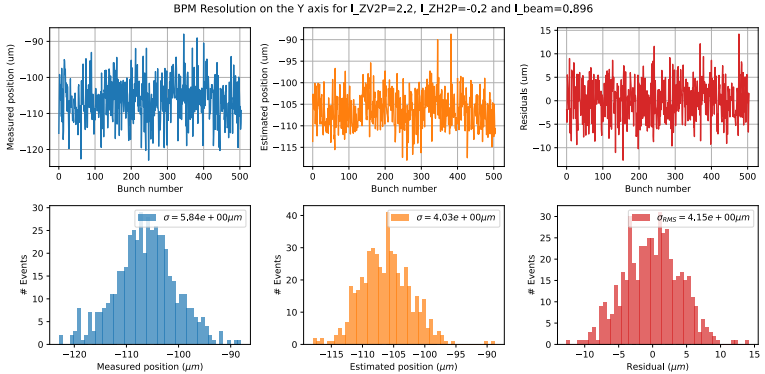
Subtracting the mean time difference per BPM to the time-stamps comparison:

```
No synchronization found for 511 bunches at BPM bpm_1
No synchronization found for 515 bunches at BPM bpm_2
No synchronization found for 494 bunches at BPM bpm_3
No synchronization found for 475 bunches at BPM bpm_4
No synchronization found for 433 bunches at BPM bpm_10
No synchronization found for 424 bunches at BPM bpm_11
No synchronization found for 421 bunches at BPM bpm_12
No synchronization found for 422 bunches at BPM bpm_13
No synchronization found for 419 bunches at BPM bpm_14
No synchronization found for 422 bunches at BPM bpm_15
```



4.64 μm

```
No synchronization found for 272 bunches at BPM bpm_1
No synchronization found for 240 bunches at BPM bpm_2
No synchronization found for 233 bunches at BPM bpm_3
No synchronization found for 228 bunches at BPM bpm_4
No synchronization found for 247 bunches at BPM bpm_10
No synchronization found for 267 bunches at BPM bpm_11
No synchronization found for 279 bunches at BPM bpm_12
No synchronization found for 289 bunches at BPM bpm_13
No synchronization found for 302 bunches at BPM bpm_14
No synchronization found for 321 bunches at BPM bpm_15
```



4.15 μm

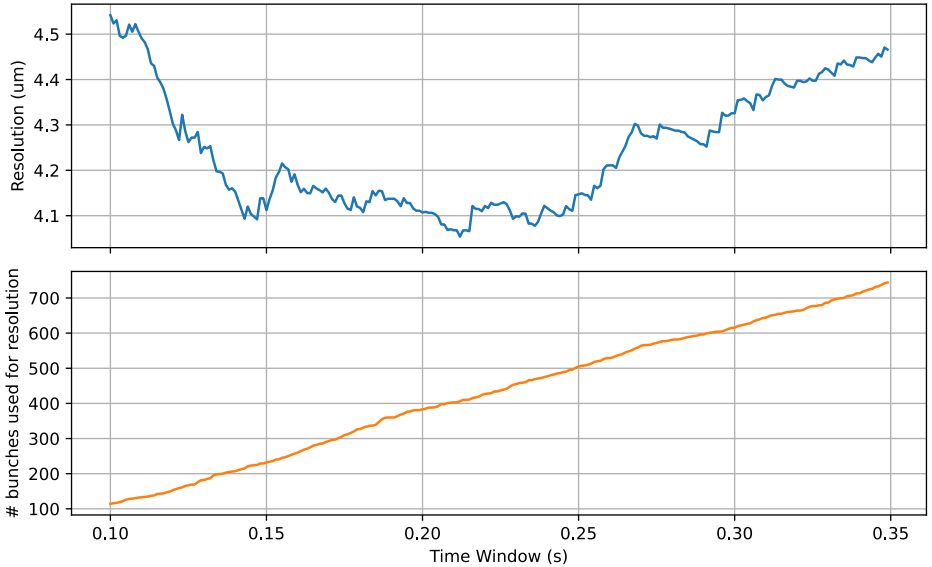
I. Corrections

D) Evaluating the resolution as a function of the time window

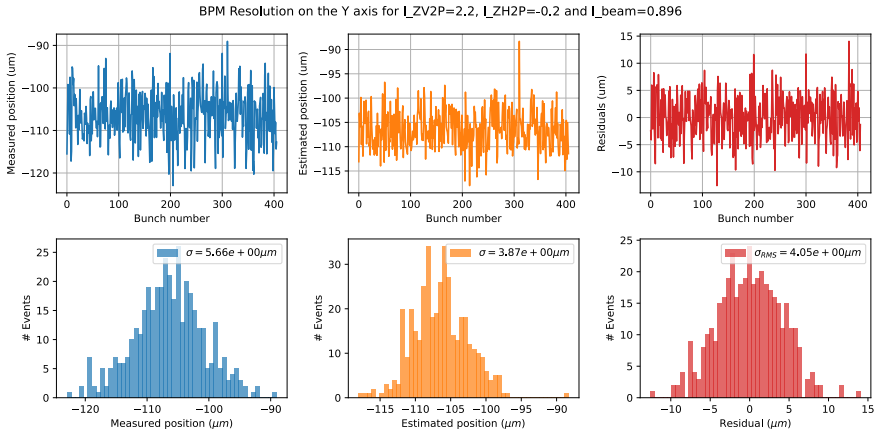
Best results for Setup A: Lower IF

Evaluating the resolution as a function of the time window:

(Before: 4.64 μm)



Optimal time window: 0.212 s with resolution: 4.05 um using 406 bunches



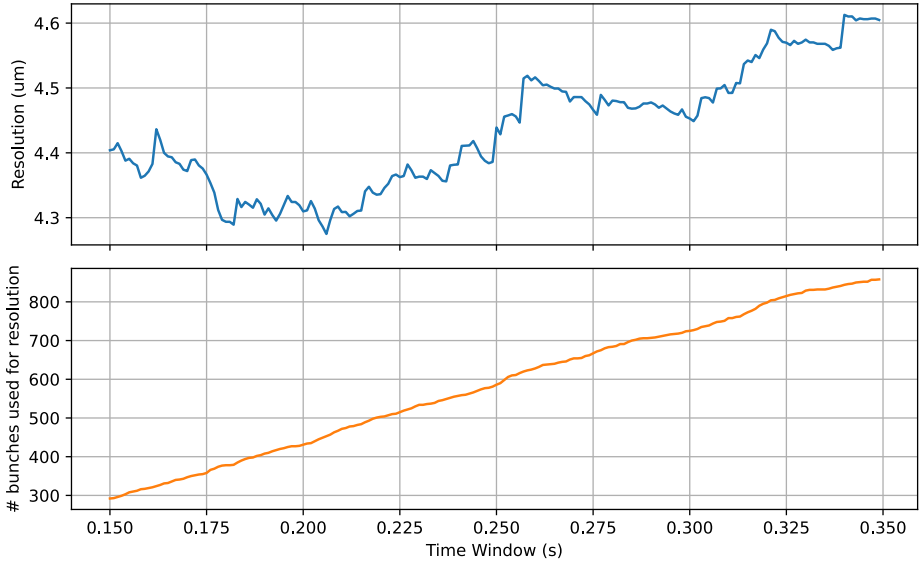
I. Corrections

D) Evaluating the resolution as a function of the time window

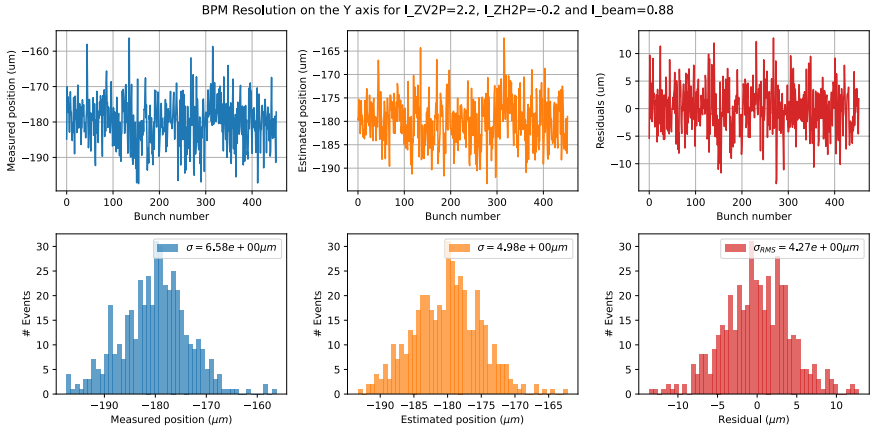
Best results for Setup B: Phase shifter

Evaluating the resolution as a function of the time window:

(Before: 4.63 μm)



Optimal time window: 0.206 s with resolution: 4.27 um using 453 bunches

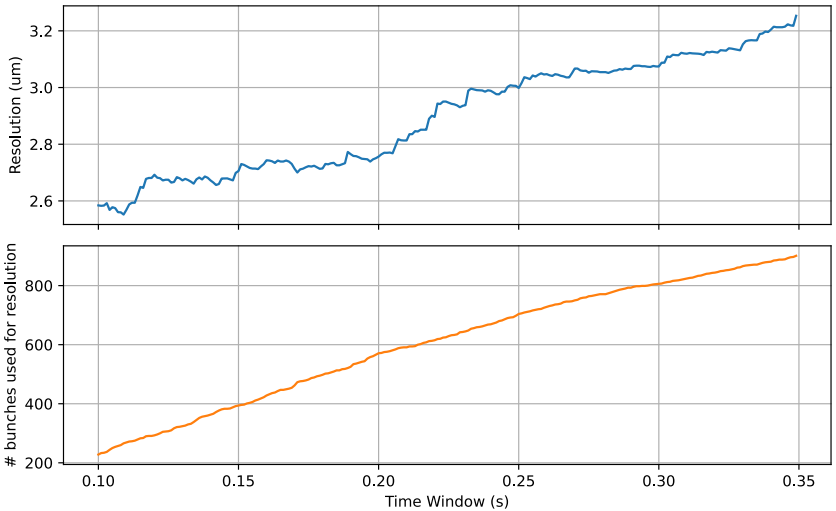


I. Corrections

D) Evaluating the resolution as a function of the time window

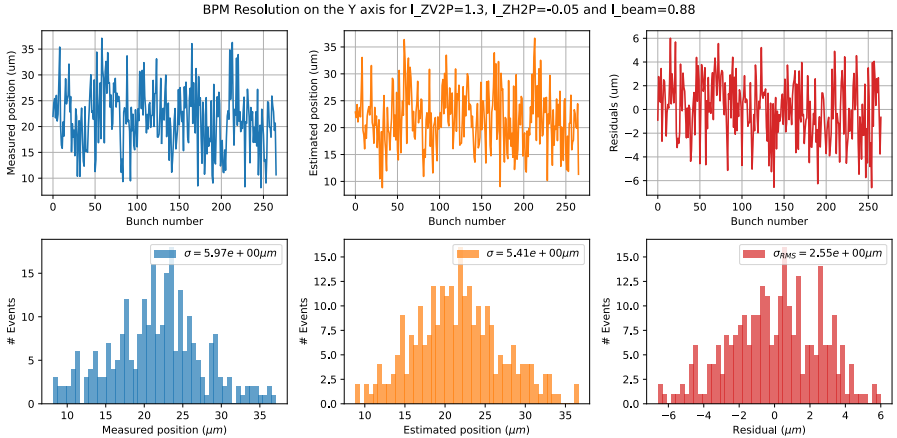
Best results for Setup C: double DC

Evaluating the resolution as a function of the time window:



(Before: 3.16 μm)

Optimal time window: 0.109 s with resolution: 2.55 um using 266 bunches



The number of bunches is very low....

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   C) Acquisition times distribution

II. Overall results
   A) Without resolution algorithm improvements
   B) Specific cases
   C) With resolution algorithm improvement

Conclusion

II. Overall results

A) Without resolution algorithm improvement

[1]: IQ plot split in two
[2]: external trigger
[3]: the beam is centred

RESOLUTION RESULTS ON THE X PLANE								
May - June 2025						December 2025		
LO phase-unlocked			LO phase-locked			Lower IF freq (A)		
I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (mm)	**res (um)**
(23/05)			(17/06)			(08/12)		
0.68	~ 1	**228** [2]	0.32	0 [3]	**40.4**	0.96	0	**12.4**
	~ 1.5	**178**		2	**45.4**		1	**21.9**
			0.8	0	**111**	1.36	0.4	**20.8**
				2	**121**	1.49	0.8	**22.9**
			(23/06)					
			0.44	0	**93.2** [1]			
				1.3	**57.9**			
			0.85	0	**83.2** [1]			
				1	**37.9**			

II. Overall results

A) Without resolution algorithm improvement

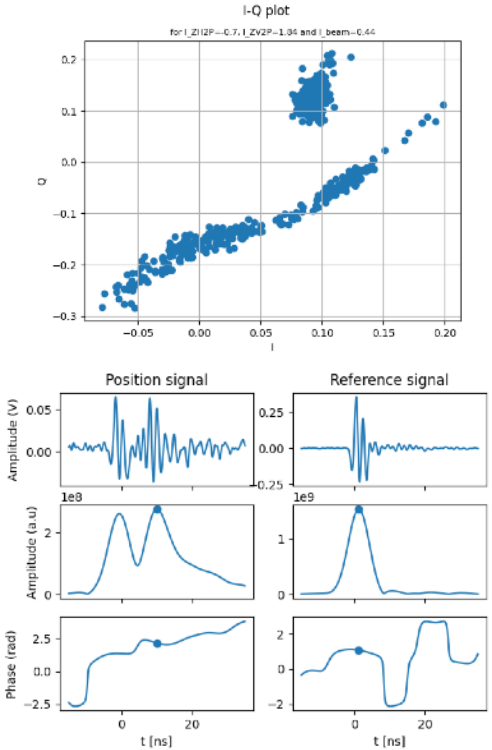
[1]: IQ plot split in two
[2]: the beam is centred
[3]: the beam jumped in the middle of the meas.

RESOLUTION MEASUREMENTS ON THE Y PLANE												
May - June 2025			**December 2025**									
LO phase-locked			**Lower IF freq (A)**			**Phase shifter (B)**			**Double DC (C)**			
I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (mm)	**res (um)**	
(17/06)			(05/12)			(08/12)			(08/12)			
0.32	0 [2]	**19.2**	0.35	1	**11.1**	0.56	0.4	**12.3**	0.69	0.1	**6.88**	
			(08/12)									
	2.5	**33.7**	0.46	0.4	**41.5**	0.88	0	**6.82**	0.89	0	**6.32**	
0.8	0	**23.7**	0.72	0.3	**8.37**	1.33	0.1	**7.83**	1.04	-0.1	**6.71**	
	2.5	**57.1**							(15/12)			
(23/06)			0.89	0	**8.5**				0.54	0.9	**6.03**	
0.44	0	**13.5**							0.66	0.8	**13.8** [3]	
	1	**24.8**							0.72	0.7	**4.89**	
0.85	0	**27.1** [1]							0.80	0.1	**4.60**	
	2	**28.4**							0.88	0.6	**12.4** [1]	

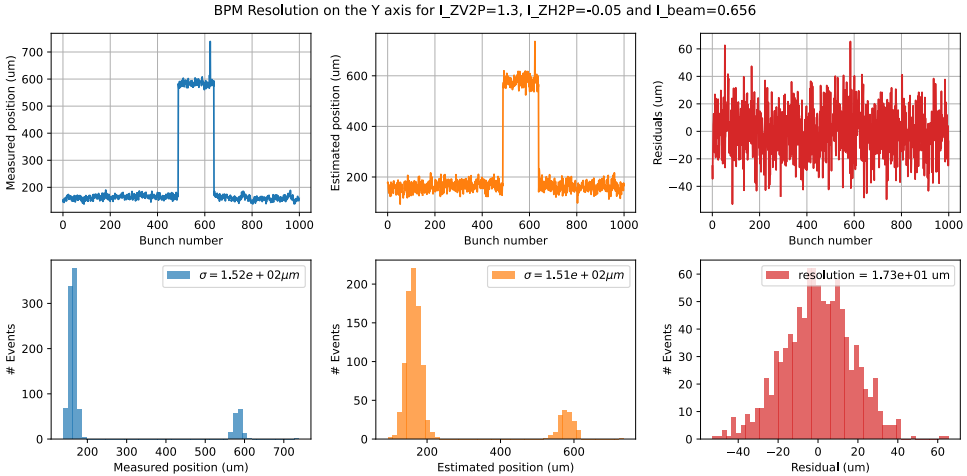
II. Overall results

B) Specific cases:

[1]: IQ plot split in two
(23/06 for centered beam)



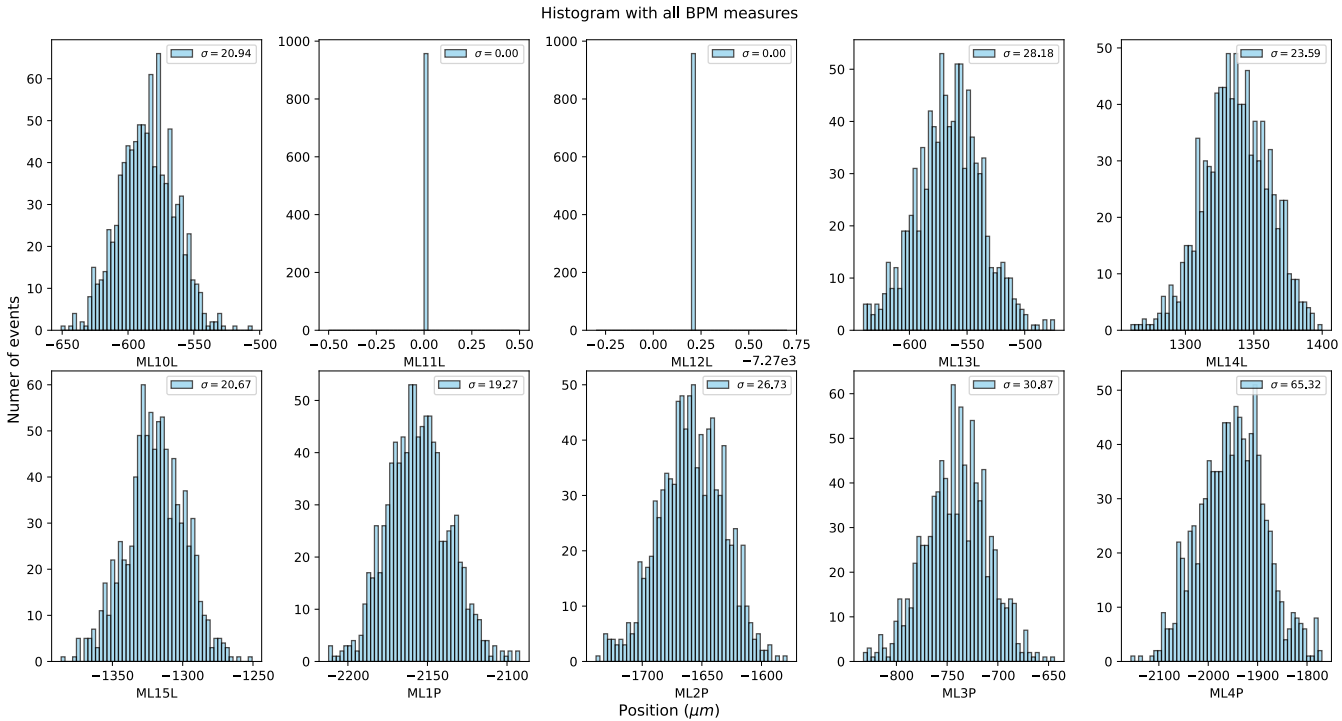
[3]: the beam jumped in the middle of the meas.



II. Overall results

B) Specific cases:

Lower IF for Y, Ibeam = 0.46

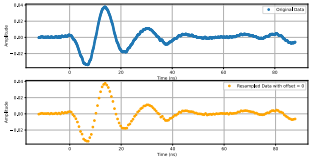


II. Overall results

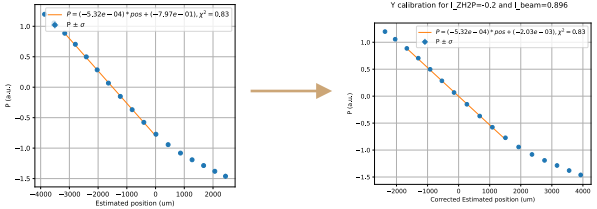
C) With resolution algorithm improvement

Changes that were implemented on the DDC, calibration and resolution algorithms:

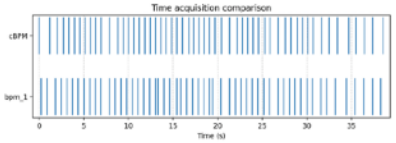
- **Re-sampling:**
  removes interpolated points added by the oscilloscope



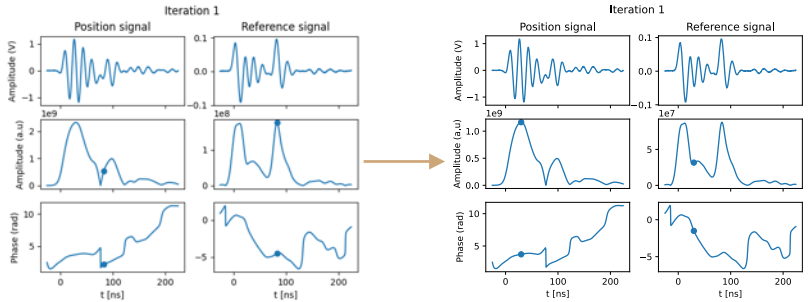
- **Calibration:**
  fixing the statical offset → provides more accurate cBPM measurements



- **Time-stamps comparison:**
  selecting only measurements that correspond to the same bunch for all BPMs and correcting the systematic time error in the acquisition (window = 0.21 s)



- **Fixed sampling point:**
  unifies the way the waveform is processed and avoids different position result when there is a reflection of the waveform



- **Removing frozen stripline BPMs**

II. Overall results

C) With resolution algorithm improvement

With window = 0.21 s
Not all have the same # bunches!

[1]: the beam moved heavily

RESOLUTION RESULTS ON THE X PLANE								
May - June 2025						December 2025		
LO phase-unlocked			LO phase-locked			Lower IF freq (A)		
I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (mm)	**res (um)**	I_b (nC)	δx (um)	**res (um)**
(23/05)			(17/06)			(08/12)		
0.68	~ 1	228 [2]	0.32	0 [3]	40.4	0.96	80	~~12.4~~ **7.57**
	~ 1.5	178		2	45.4		1200	~~21.9~~ **22.5** [1]
			0.8	0	111	1.36	350	~~20.8~~ **8.78**
				2	121	1.49	700	~~22.9~~ **10.9**
			(23/06)					
			0.44	0	93.2 [1]			
				1.3	57.9			
			0.85	0	83.2 [1]			
				1	37.9			

II. Overall results

C) With resolution algorithm improvement

With window = 0.21 s
Not all have the same # bunches!

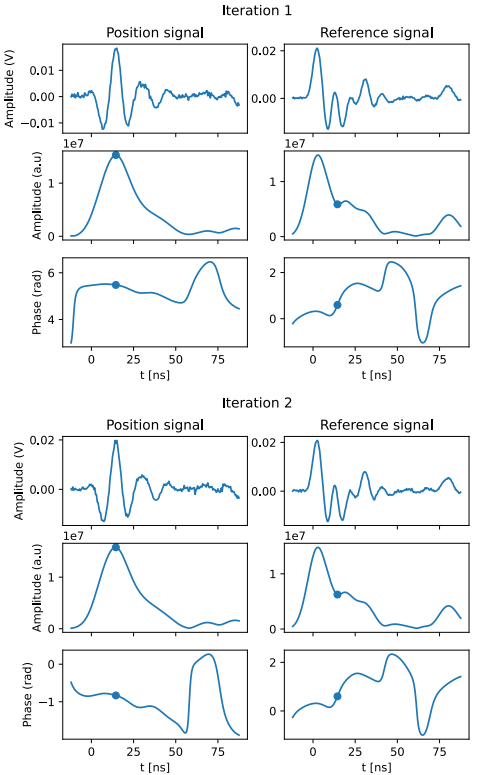
[1]: some BPMs were removed
[2]: IQ plot split
[3]: a set of measures was deleted

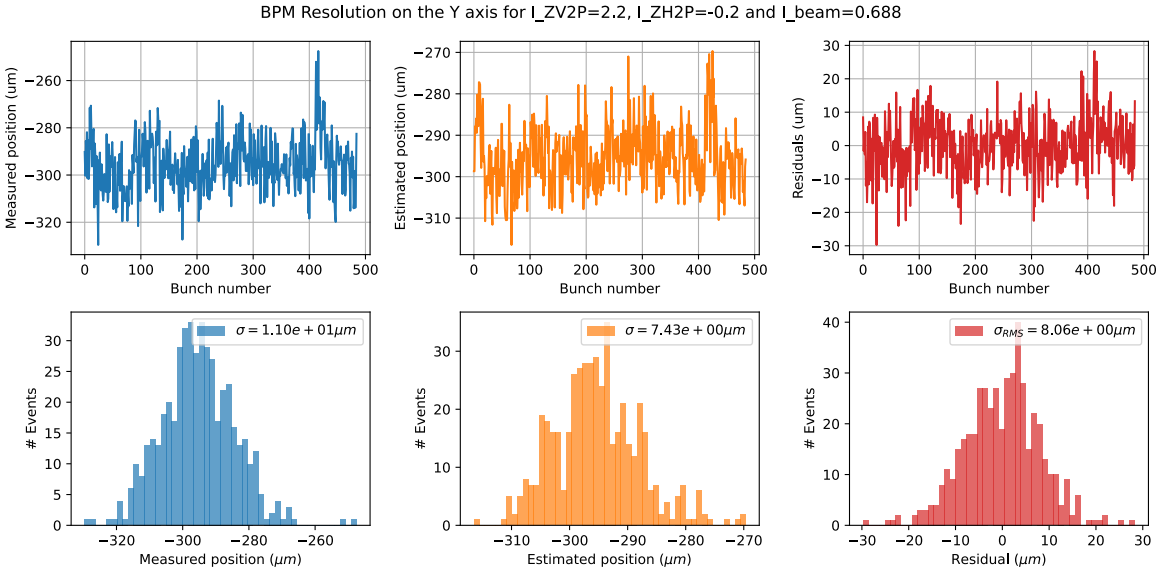
RESOLUTION MEASUREMENTS ON THE Y PLANE												
May - June 2025			**December 2025**									
LO phase-locked			**Lower IF freq (A)**			**Phase shifter (B)**			**Double DC (C)**			
I_b (nC)	δx (um)	**res (um)**	I_b (nC)	δx (um)	**res (um)**	I_b (nC)	δx (um)	**res (um)**	I_b (nC)	δx (um)	**res (um)**	
(17/06)			(05/12)			(08/12)			(08/12)			
0.32	0	19.2	0.35	1000	11.1	0.56	115	~~12.3~~ **7.04** [1]	0.69	300	~~6.88~~ **8.23**	
			(08/12)									
	2500	33.7	0.46	30	~~41.5~~ **7.08** [1]	0.88	180	~~6.82~~ **4.31**	0.89	330	~~6.32~~ **4.38**	
0.8	0	23.7	0.72	80	~~8.37~~ **4.63**	1.33	390	~~7.83~~ **5.00**	1.04	380	~~6.71~~ **14.8** [2]	
	2500	57.1							(15/12)			
(23/06)			0.89	110	~~8.5~~ **4.07**				0.54	100	~~6.03~~ **8.84**	
0.44	0	13.5							0.66	80	~~13.8~~ **10.5** [3]	
	1000	24.8							0.72	55	~~4.89~~ **3.81**	
0.85	0	27.1							0.80	50	~~4.60~~ **3.29**	
	2000	28.4							0.88	20	~~12.4~~ **2.81**	

II. Overall results

C) With resolution algorithm improvement

2DC for Y, Ibeam = 0.69

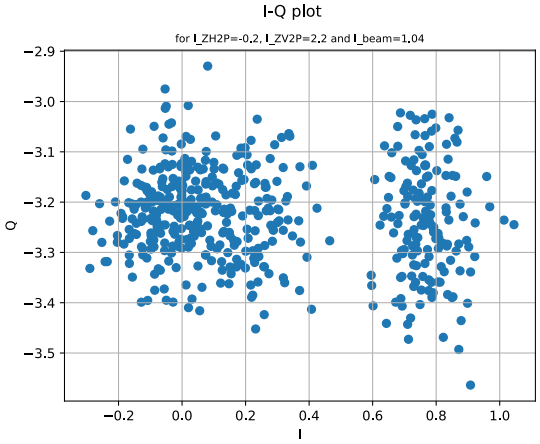


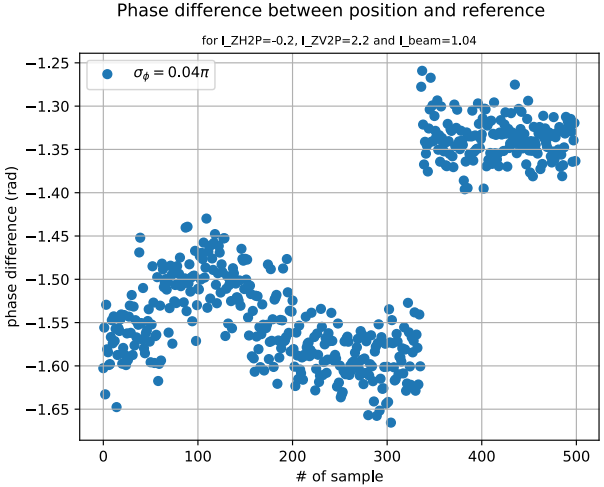


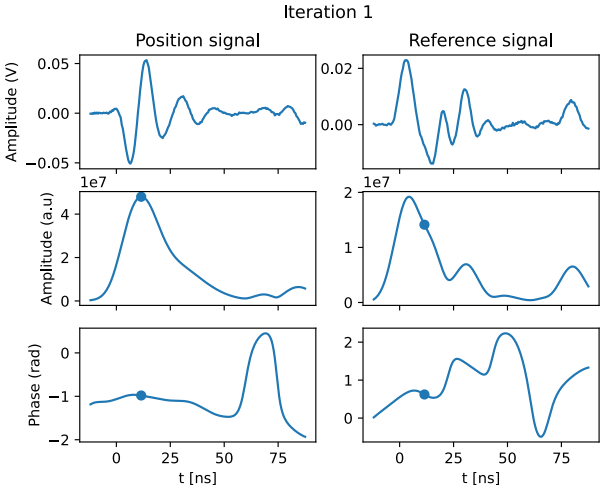
II. Overall results

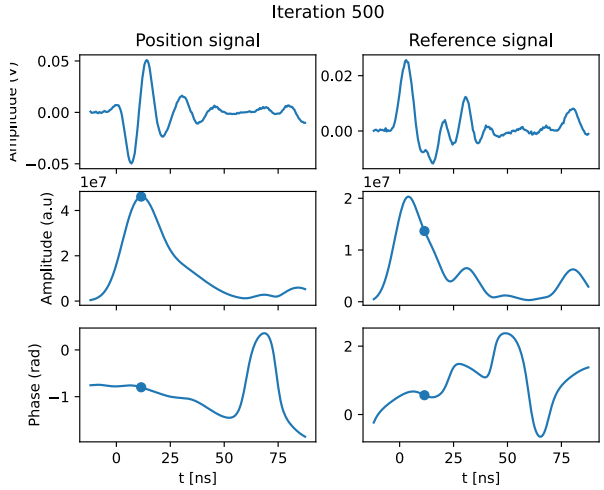
C) With resolution algorithm improvement

2DC for Y, Ibeam = 1.04









II. Overall results

D) With lower sampling rate

~~2GS/s~~ 1GS/s

[1]: some BPMs were removed
[2]: IQ plot split
[3]: a set of measures was deleted

RESOLUTION MEASUREMENTS ON THE Y PLANE								
December 2025								
Lower IF freq (A)			**Phase shifter (B)**			**Double DC (C)**		
I_b (nC)	δx (um)	**res (um)**	I_b (nC)	δx (um)	**res (um)**	I_b (nC)	δx (um)	**res (um)**
(05/12)			(08/12)			(08/12)		
0.35	1000	11.1	0.56	115	~~7.04~~ **11.2**	0.69	300	~~8.23~~ **8.39**
(08/12)								
0.46	30	~~7.08~~ **10.7**	0.88	180	~~4.31~~ **6.00**	0.89	330	~~4.38~~ **4.99**
0.72	80	~~4.63~~ **6.45**	1.33	390	~~5.00~~ **6.20**	1.04	380	~~14.8~~ **15.6** [2]
						(15/12)		
0.89	110	~~4.07~~ **5.71**				0.54	100	~~8.84~~ **9.12**
						0.66	80	~~10.5~~ **11.2** [3]
						0.72	55	~~3.81~~ **3.99**
						0.80	50	~~3.29~~ **3.45**
						0.88	20	~~2.81~~ **3.03**

There is a higher degradation of the resolution for worst resolutions.

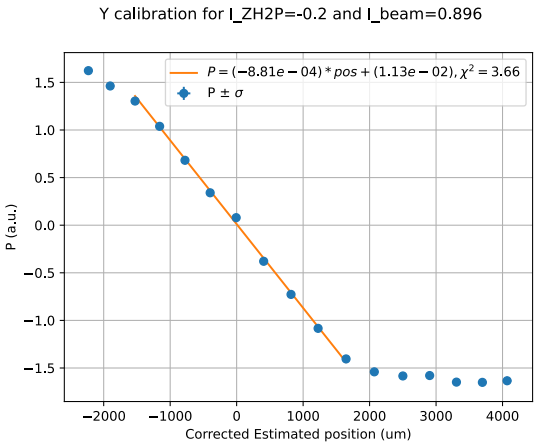
Conclusion

There seams to be an optimal beam intensity, around 0.8 nC/bunch to perform resolution measurements.

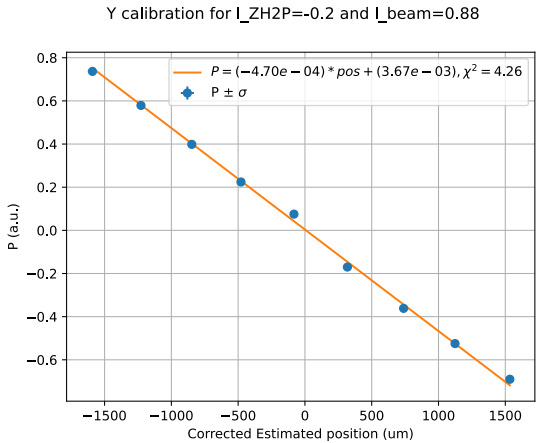
The closer the beam to the center of the cBPM the better the resolution measurement.

Not only the resolution is worth looking at. The linearity and dynamic range play an important role in the cBPM performance.

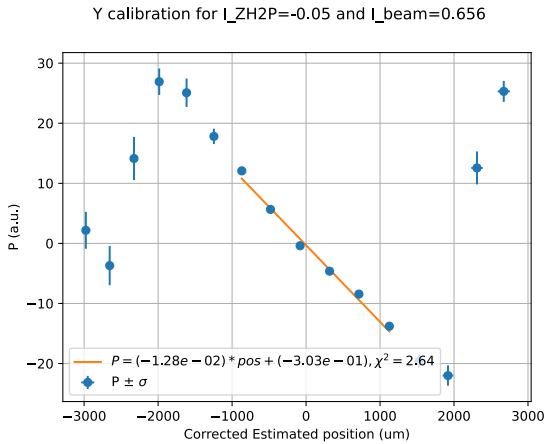
Lower IF (A)



Phase shifter for LO (B)



2DC (C)



Next: - SVD analysis
- DDC alternative: mean value on amplitude and phase over the whole waveform

Thank you for your attention

We gratefully acknowledge the ATF staff for their assistance during the installation and BPM measurements. Special thanks to Toshiyuki Okugi, Alex Aryshev, and Konstantin Popov for their support. We also thank Toshihiro Matsumoto and Hiroshi Kaji for providing the necessary equipment for the measurements.

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Back-up slides

I. Resolution measurement and calculation

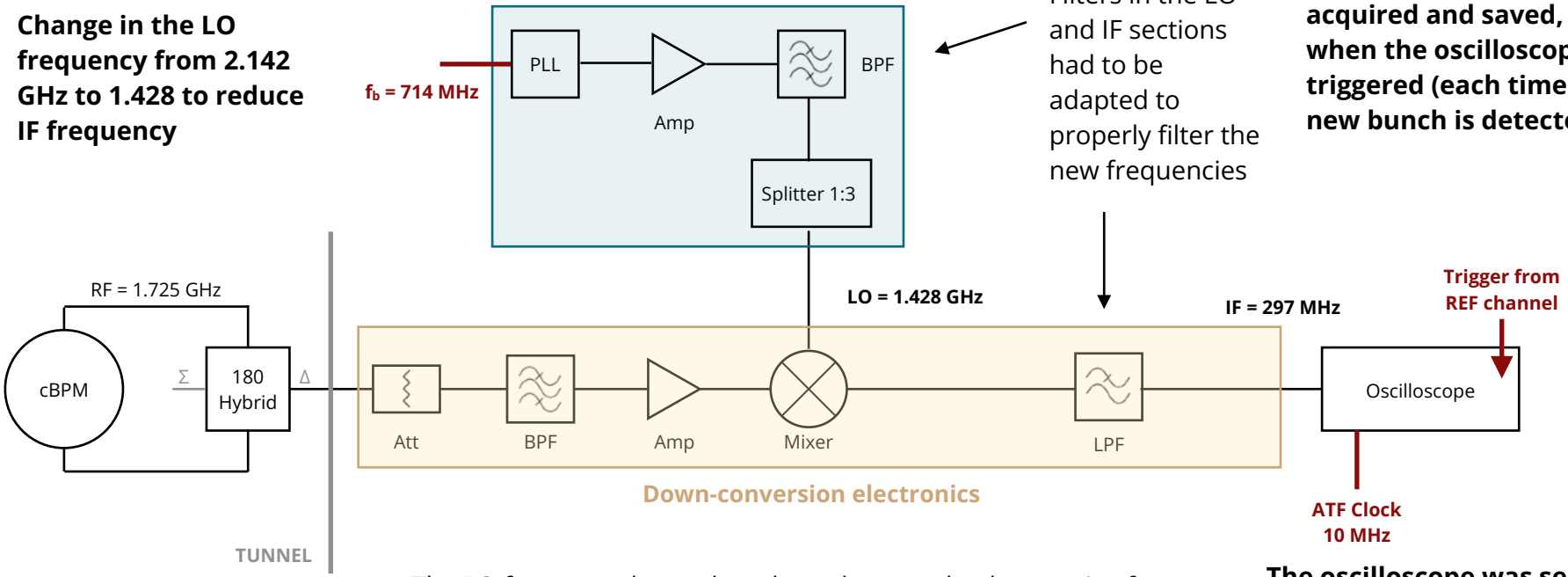
A) Setups employed for measurements

The bunch data (from cBPM and from striplines) is taken every time the data from the previous bunch has been properly acquired and saved, and when the oscilloscope is triggered (each time a new bunch is detected)

Setup A - basic electronics changes

Change in the LO frequency from 2.142 GHz to 1.428 to reduce IF frequency

Filters in the LO and IF sections had to be adapted to properly filter the new frequencies



The LO frequency has to be adapted to match a harmonic of the bunch repetition signal from ATF: 714 MHz

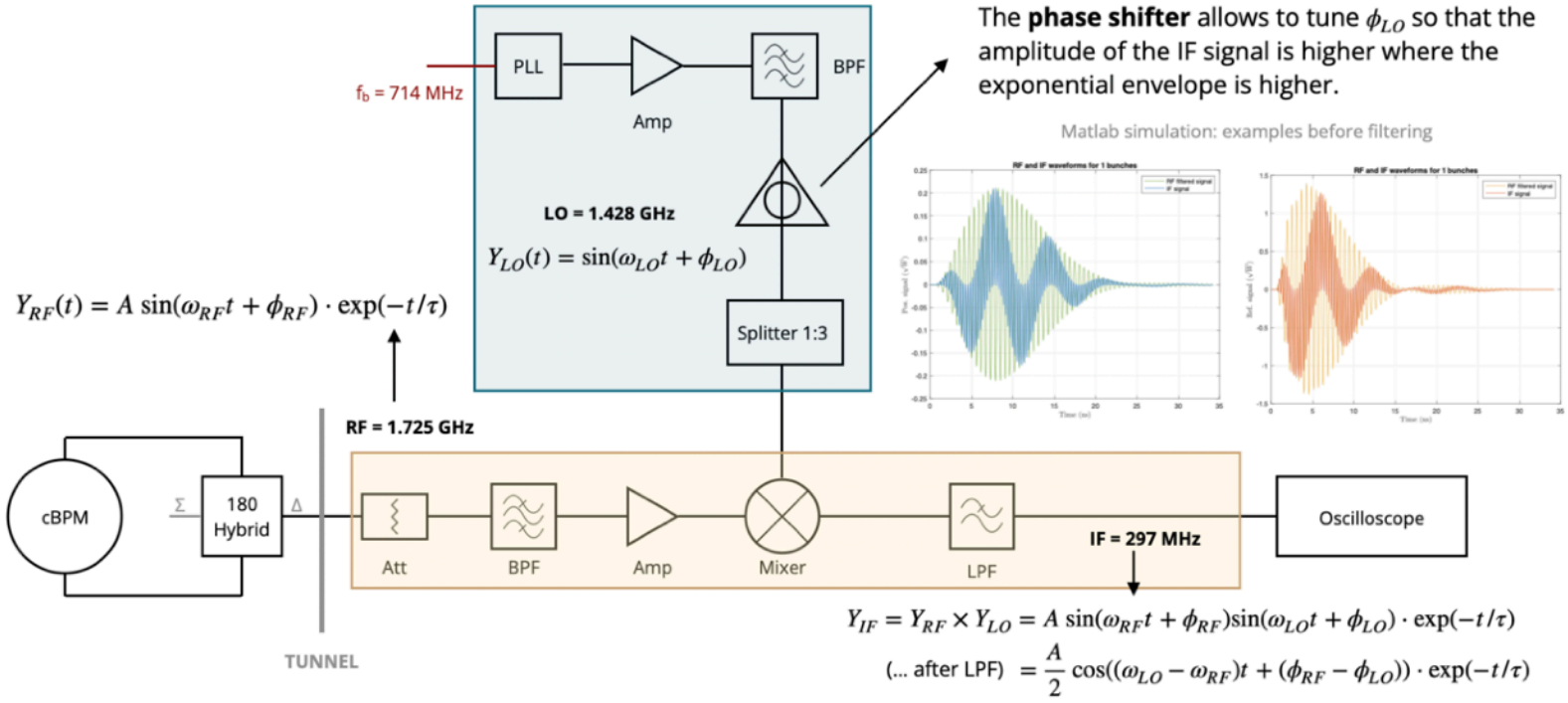
The oscilloscope was self-triggered using the reference channel

I. Resolution measurement and calculation

A) Setups employed for measurements

Setup B - Phase shifter

Phase shifter for LO to maximise sensitivity



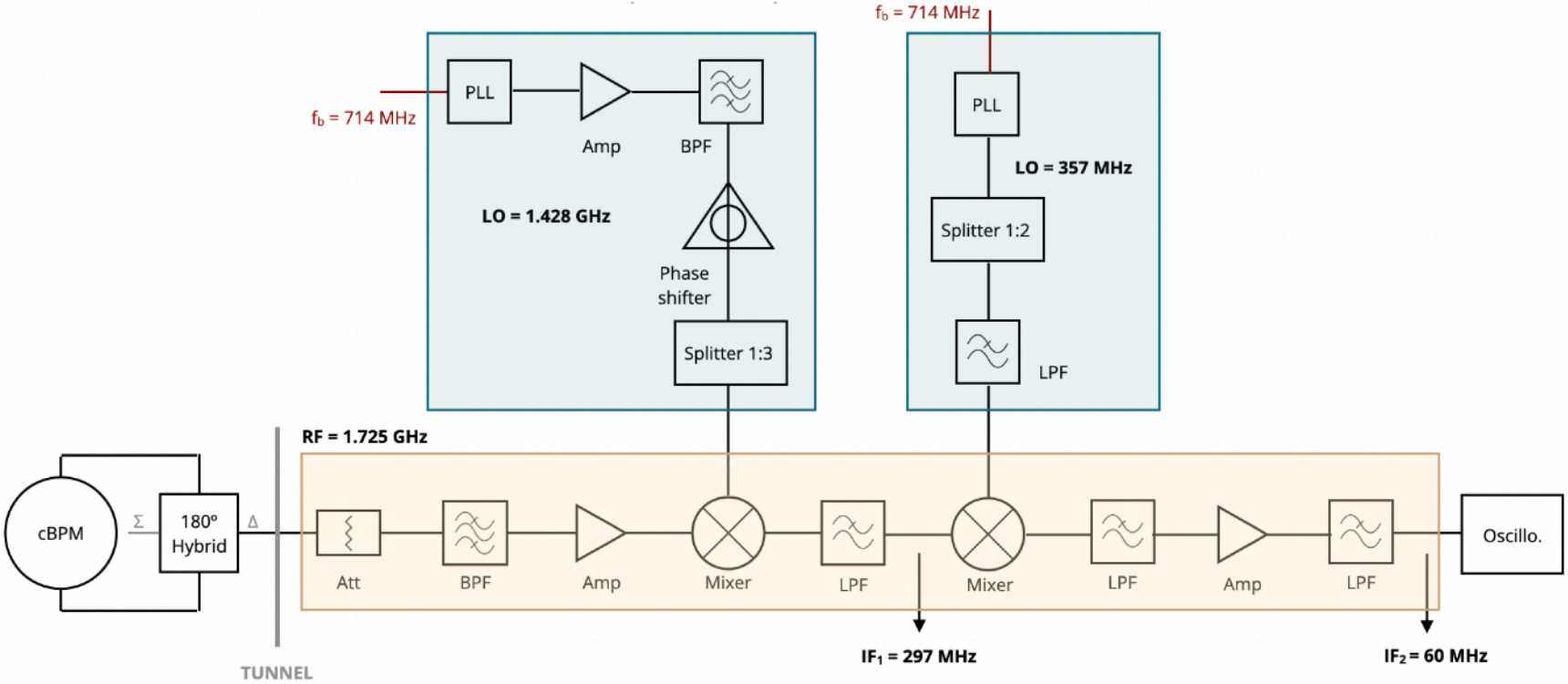
The **phase shifter** allows to tune ϕ_{LO} so that the amplitude of the IF signal is higher where the exponential envelope is higher.

Matlab simulation: examples before filtering

I. Resolution measurement and calculation

A) Setups employed for measurements

Setup C - double down conversion



I. Resolution measurement and calculation

B) Resolution calculation

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

$M = 1000$ is the number of measured waveforms

$N = 10$ is the number of BPMs used

Resolution measurements: Model Independent Analysis

cBPM measured values → $\begin{pmatrix} d_{k0} \\ d_{k1} \\ d_{k2} \\ \vdots \\ d_{kM} \end{pmatrix} = \begin{pmatrix} d_{00} & d_{10} & d_{20} & \cdots & d_{i\neq k,0} & \cdots & d_{N0} \\ d_{01} & d_{11} & d_{21} & \cdots & d_{i\neq k,1} & \cdots & d_{N1} \\ d_{02} & d_{12} & d_{22} & \cdots & d_{i\neq k,2} & \cdots & d_{N2} \\ \vdots & \vdots & \vdots & & \vdots & & \vdots \\ d_{0M} & d_{1M} & d_{2M} & \cdots & d_{i\neq k,M} & \cdots & d_{NM} \end{pmatrix} \cdot \begin{pmatrix} v_0 \\ v_1 \\ v_2 \\ \vdots \\ v_N \end{pmatrix}$ ← correlation coefficients

stripline BPM measured values

To find the correlation coefficients: $\mathbf{v} = \mathbf{D_k}^{-1}\mathbf{d}_k$. where the inverse of D_k is calculated using the SVD method: $SVD(\mathbf{D}_k) = \mathbf{USV^T}$,

The residuals between measured position and estimated position are calculated as $\mathbf{R_k} = \mathbf{d_k} - \mathbf{D_k} \cdot \mathbf{v}$.

And the resolution is estimated do be the rms of the residuals:

$$\sigma_k = \sqrt{\frac{\sum_i^M R_{ki}^2}{M}}.$$

BPMs taken: up-stream: ML10L, ML11L, ML12L, ML13L, ML14L, ML15L, ML1P, ML2P, ML3P ; down-stream: ML4P

I. Resolution measurement and calculation