Fast Beam Based Alignment Using AC Corrector Excitations* ⁑

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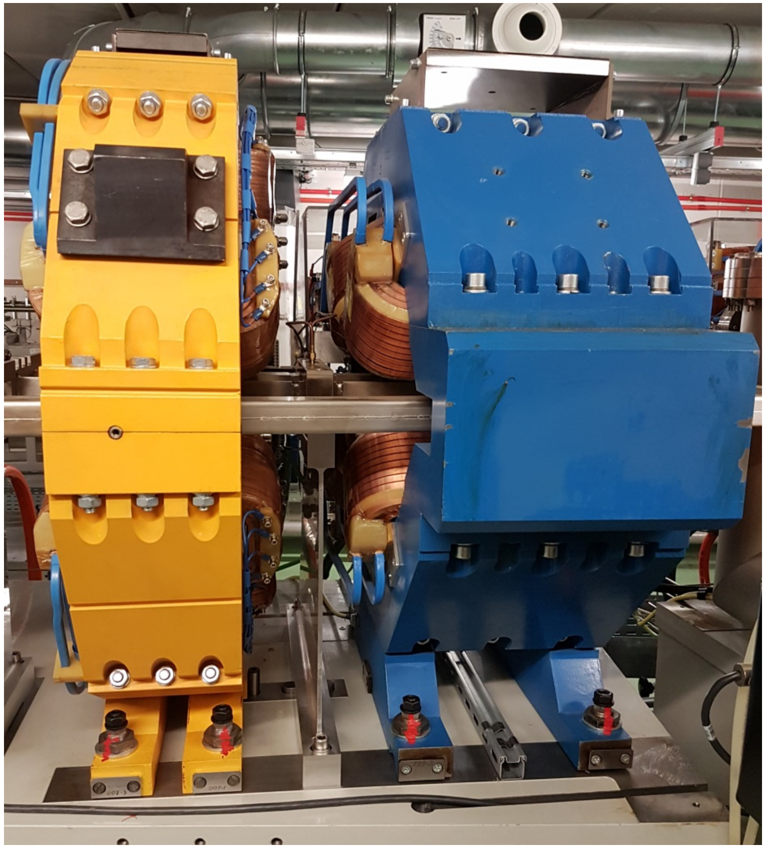

*paper: https://link.aps.org/doi/10.1103/PhysRevAccelBeams.23.012802
⁑ Python & Matlab implementations: https://gitlab.com/fbba
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Outline

BBA	FBBA
ALBA set up	Results

BBA

It is needed to:

- Minimize multipole feed down effect, minimizes the corrector strength needed:
  - Optic & coupling errors due to Sextupoles.
  - Orbit errors due to Quadrupoles.
- Bring the machine closer to the model in-between BPMs.

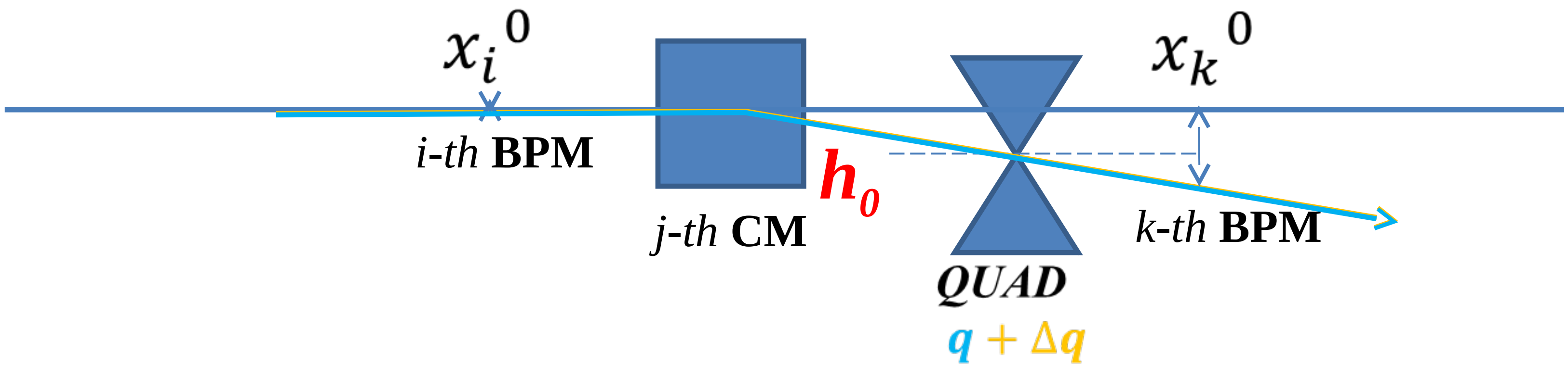
BBA

Misalignments come from:

- Real: mechanical
- Apparent: electronic

Several measurement methods:

- **Beam2quad**: Quad scan: Fast but Model dependent.
- **BPM2quad**: Quad&CM scan: Slow but Model independent.
  - There is a systematic error (orbit angle):



FBBA

Instead of scanning sequentially in DC the CM, it uses the FOFB hardware:

- 10kHz **Fast Acquisition Archiver**
- AC CM excitation (quads **could** also be AC)

The FBBA measurable quantities are the same as for the normal **bpm2quad** BBA, but:

- The two planes are done at the same time (h_0 and v_0)
- Optics coupling is taken into account -> skew magnets can also be aligned
- BPM gain and coupling, CM calibration and tilt are also considered

FBBA

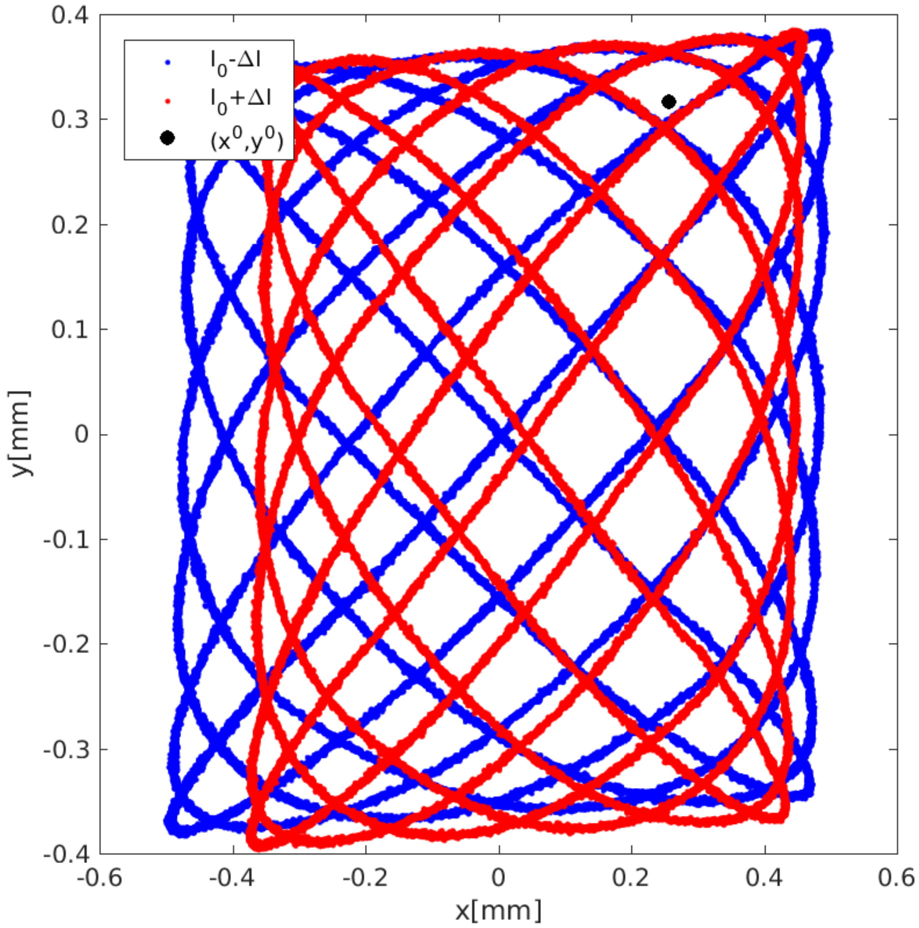
The method is valid for:

- *DC quad*
- *AC quad (additional factor 2 faster)*

And also:

- *Normal quad*
- ***Skew** quad (**sextupole** yoke)*

QUAD FBBA-DC BPM data example:



FBBA

The method is a factor 2 faster if two different frequencies are used in each plane.

$$h_j(t_n) = \hat{h}_j \cos(2\pi f_h t_n + \psi_h) = \Re\{(\hat{h}_j e^{i\psi_h}) e^{i2\pi f_h t_n}\}$$

$$v_j(t_n) = \hat{v}_j \cos(2\pi f_v t_n + \psi_v) = \Re\{(\hat{v}_j e^{i\psi_v}) e^{i2\pi f_v t_n}\}$$

The offset is obtained combining the Fourier components of each BPM signal.

$$h_j(t_n) = \Re\{(\hat{h}_j e^{i\psi_h}) e^{i2\pi f_h t_n}\} = \frac{1}{2}(\langle h_j | f_h \rangle e^{i2\pi f_h t_n} + \text{c.c.}),$$

$$v_j(t_n) = \Re\{(\hat{v}_j e^{i\psi_v}) e^{i2\pi f_v t_n}\} = \frac{1}{2}(\langle v_j | f_v \rangle e^{i2\pi f_v t_n} + \text{c.c.}).$$

FBBA

In the linear regime, the BPM readings as a function of CMs change with coupling are:

$$x_k(t) - x_k^0 = R_{kj}^{xx}\left(h_j(t) - h_0\right) + \boxed{R_{kp}^{xy}}\left(v_p(t) - v_0\right)$$
$$y_n(t) - y_n^0 = R_{np}^{yy}\left(v_p(t) - v_0\right) + \boxed{R_{nj}^{yx}}\left(h_j(t) - h_0\right)$$

DC quad:

$R_{kj}^{xx}\ R_{kp}^{xy}\ R_{np}^{yy}\ R_{nj}^{yx}$

have 2 values: two sets of data are acquired.

AC quad:

$R_{kj}^{xx}\ R_{kp}^{xy}\ R_{np}^{yy}\ R_{nj}^{yx}$

vary with time: only one set of data.

FBBA

Both for quads and skews the **solution** is:

$$\begin{cases} x_l^0 = \Re\left\{\langle x_l|0\rangle\right\} + \mathcal{S}\left\{\langle x_l|f_h\rangle\right\}\mathcal{M}_h + \mathcal{S}\left\{\langle x_l|f_v\rangle\right\}\mathcal{M}_v \\ y_l^0 = \Re\left\{\langle y_l|0\rangle\right\} + \mathcal{S}\left\{\langle y_l|f_v\rangle\right\}\mathcal{M}_v + \mathcal{S}\left\{\langle y_l|f_h\rangle\right\}\mathcal{M}_h \end{cases}$$

Where the observable (h_0 and v_0 *are not*) **relative corrector offsets** are:

$$\begin{cases} \mathcal{M}_h = \dfrac{h_{0j}}{\hat{h}_j} = -\dfrac{\mathcal{D}_x\mathcal{D}_{\mathrm{yv}} - \mathcal{D}_{\mathrm{xv}}\mathcal{D}_y}{\mathcal{D}_{\mathrm{xh}}\mathcal{D}_{\mathrm{yv}} - \mathcal{D}_{\mathrm{xv}}\mathcal{D}_{\mathrm{yh}}} = \dfrac{\mathcal{Y}_{hk}}{\mathcal{X}_{hk}} \\ \mathcal{M}_v = \dfrac{v_{0j}}{\hat{v}_j} = -\dfrac{\mathcal{D}_{\mathrm{xh}}\mathcal{D}_y - \mathcal{D}_x\mathcal{D}_{\mathrm{yh}}}{\mathcal{D}_{\mathrm{xh}}\mathcal{D}_{\mathrm{yv}} - \mathcal{D}_{\mathrm{xv}}\mathcal{D}_{\mathrm{yh}}} = \dfrac{\mathcal{Y}_{vk}}{\mathcal{X}_{vk}}. \end{cases}$$

BPM gain and coupling, CM calibration and tilt are taken into account.

FBBA

DC Quad/skew (1&2 measurements)

$$\begin{cases} \mathcal{D}_\mathrm{x} = \Re\{\langle x_{k2}|0\rangle\} - \Re\{\langle x_{k1}|0\rangle\} \\ \mathcal{D}_\mathrm{y} = \Re\{\langle y_{k2}|0\rangle\} - \Re\{\langle y_{k1}|0\rangle\} \\ \mathcal{D}_\mathrm{xh} = \mathcal{S}\{\langle x_{k2}|f_h\rangle\} - \mathcal{S}\{\langle x_{k1}|f_h\rangle\} \\ \mathcal{D}_\mathrm{yv} = \mathcal{S}\{\langle y_{k2}|f_v\rangle\} - \mathcal{S}\{\langle y_{k1}|f_v\rangle\} \\ \mathcal{D}_\mathrm{xv} = \mathcal{S}\{\langle x_{k2}|f_h\rangle\} - \mathcal{S}\{\langle x_{k1}|f_h\rangle\} \\ \mathcal{D}_\mathrm{yh} = \mathcal{S}\{\langle y_{k2}|f_h\rangle\} - \mathcal{S}\{\langle y_{k1}|f_h\rangle\} \end{cases}$$

AC Quad (at f_s: 1 measuremnt)

$$\begin{cases} \mathcal{D}_\mathrm{x} = \mathcal{S}\{\langle x_k|f_s\rangle\} \\ \mathcal{D}_\mathrm{y} = \mathcal{S}\{\langle y_k|f_s\rangle\} \\ \mathcal{D}_\mathrm{xh} = \mathcal{S}\{\langle x_k|f_h + f_s\rangle\} + \mathcal{S}\{\langle x_k|f_h - f_s\rangle\} \\ \mathcal{D}_\mathrm{yv} = \mathcal{S}\{\langle y_k|f_v + f_s\rangle\} + \mathcal{S}\{\langle y_k|f_v - f_s\rangle\} \\ \mathcal{D}_\mathrm{xv} = \mathcal{S}\{\langle x_k|f_v + f_s\rangle\} + \mathcal{S}\{\langle x_k|f_v - f_s\rangle\} \\ \mathcal{D}_\mathrm{yh} = \mathcal{S}\{\langle y_k|f_h + f_s\rangle\} + \mathcal{S}\{\langle y_k|f_h - f_s\rangle\} \end{cases}$$

Example: a 90° rotation (x ⇒ y & y ⇒-x) changes $\mathcal{D}_x \Rightarrow \mathcal{D}_y$, $\mathcal{D}_y \Rightarrow -\mathcal{D}_x$, $\mathcal{D}_{xh} \Rightarrow \mathcal{D}_{yh}$, $\mathcal{D}_{yh} \Rightarrow -\mathcal{D}_{xh}$, $\mathcal{D}_{xv} \Rightarrow \mathcal{D}_{yv}$ and $\mathcal{D}_{yv} \Rightarrow -\mathcal{D}_{xv}$ leaves $\mathcal{M}_h$ and $\mathcal{M}_v$ unchanged: Any linear coupling is automatically taken into account.

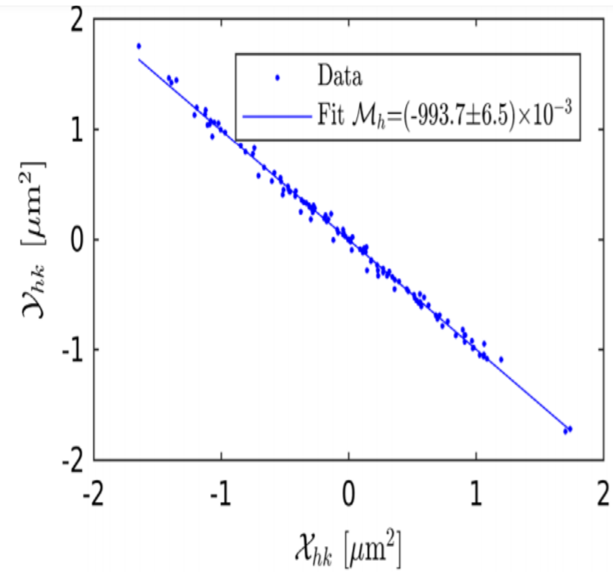
The signed amplitude of a signal x at a frequency f_z is defined as:

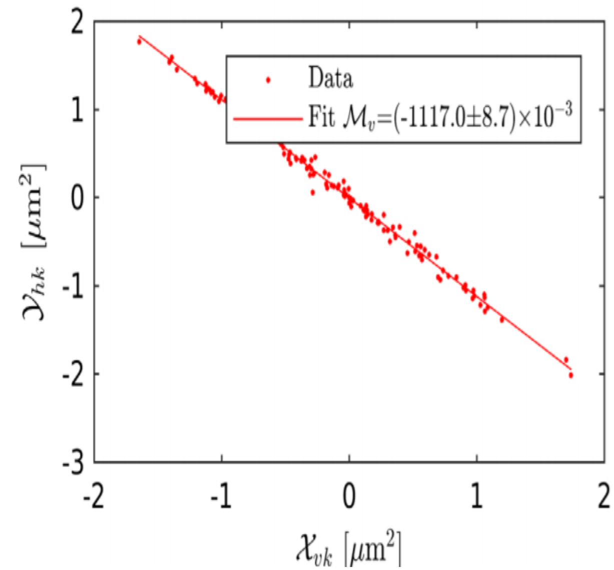
$$\mathcal{S}\{\langle x|f_z\rangle\} = |\langle x|f_z\rangle|\,\mathrm{sgn}\left\{\cos(\psi_x^{(z)} - \psi_z)\right\}$$

FBBA

Relative corrector offset fit: $\frac{h_{0j}}{\hat{h}_j}$

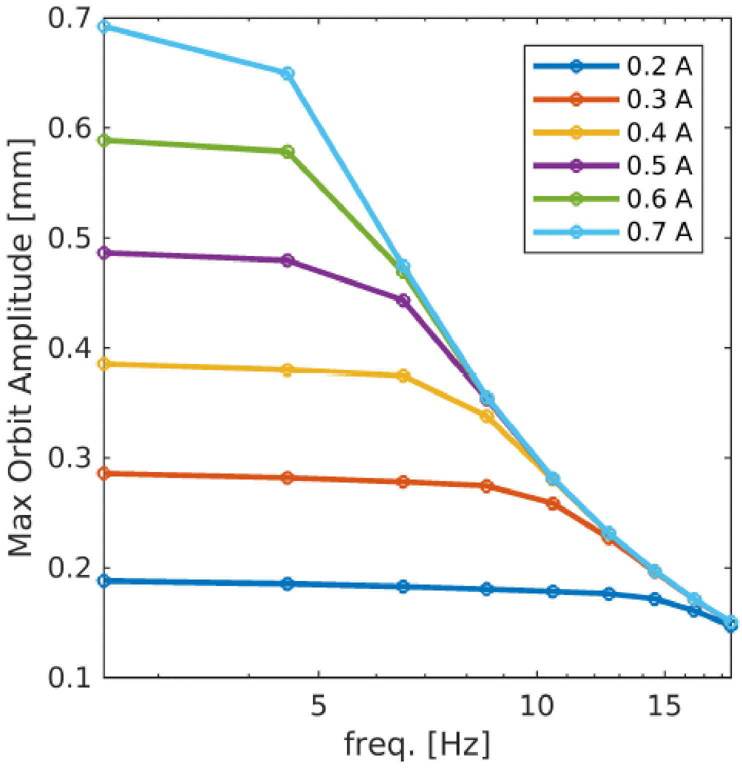
For every BPM, a point in the $\mathcal{X}_{hk}$ and $\mathcal{Y}_{hk}$ plane is calculated. Then, the fit result is used to calculate the offsets of a single BPM-l: x^0_l and y^0_l.





ALBA set up

Frequency choice: The CM waveforms have a limited effective kick as a function of the frequency:

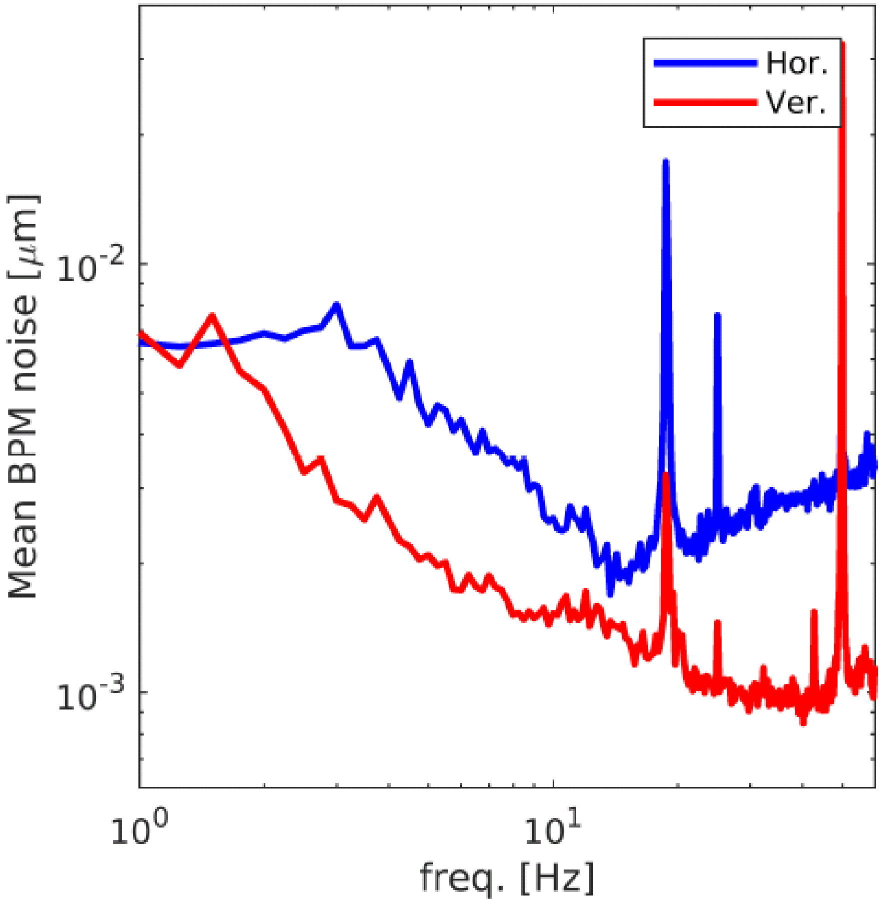


A minimum of **0.5 A** is needed to properly measure large offsets.

ALBA set up

Also, we study the BPM noise as a function of the frequency. It gets better the higher the frequency, in the 0 Hz-18 Hz range:

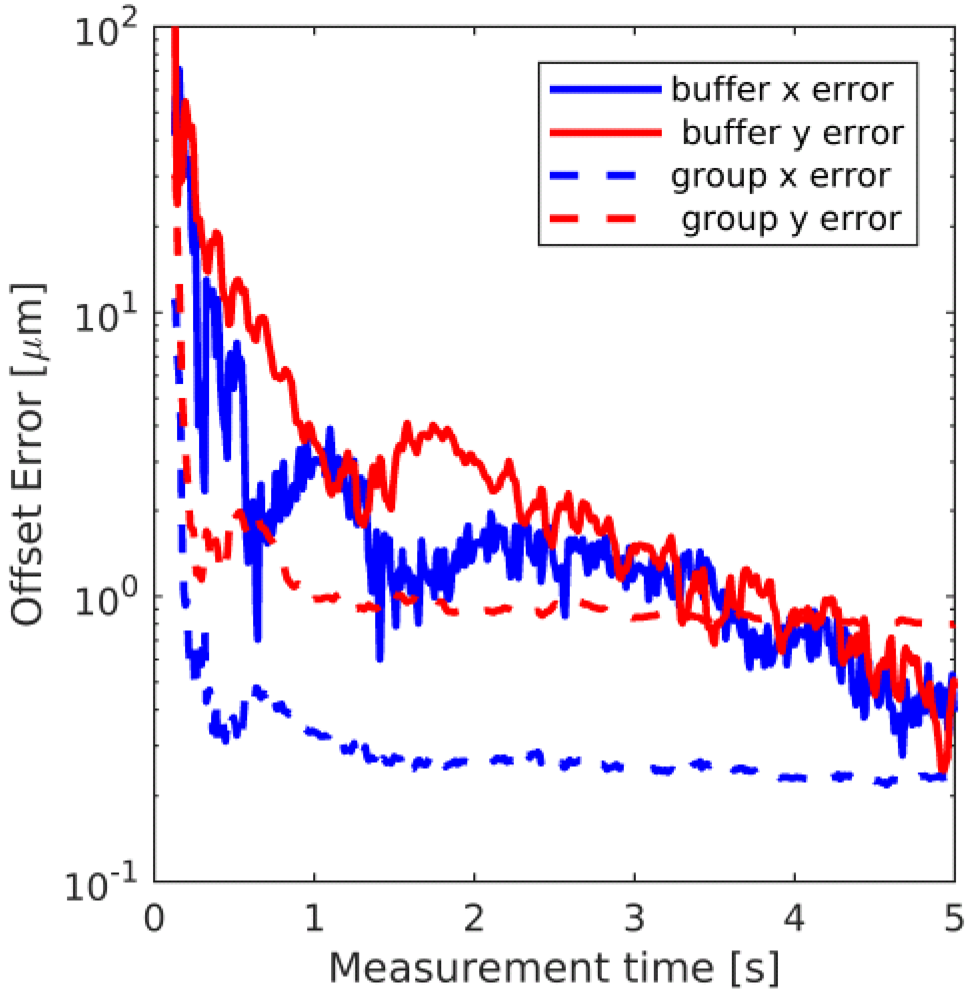
We decided to use **6 Hz** and **7 Hz** for the vertical and horizontal plane respectively (0.5mm).



ALBA set up

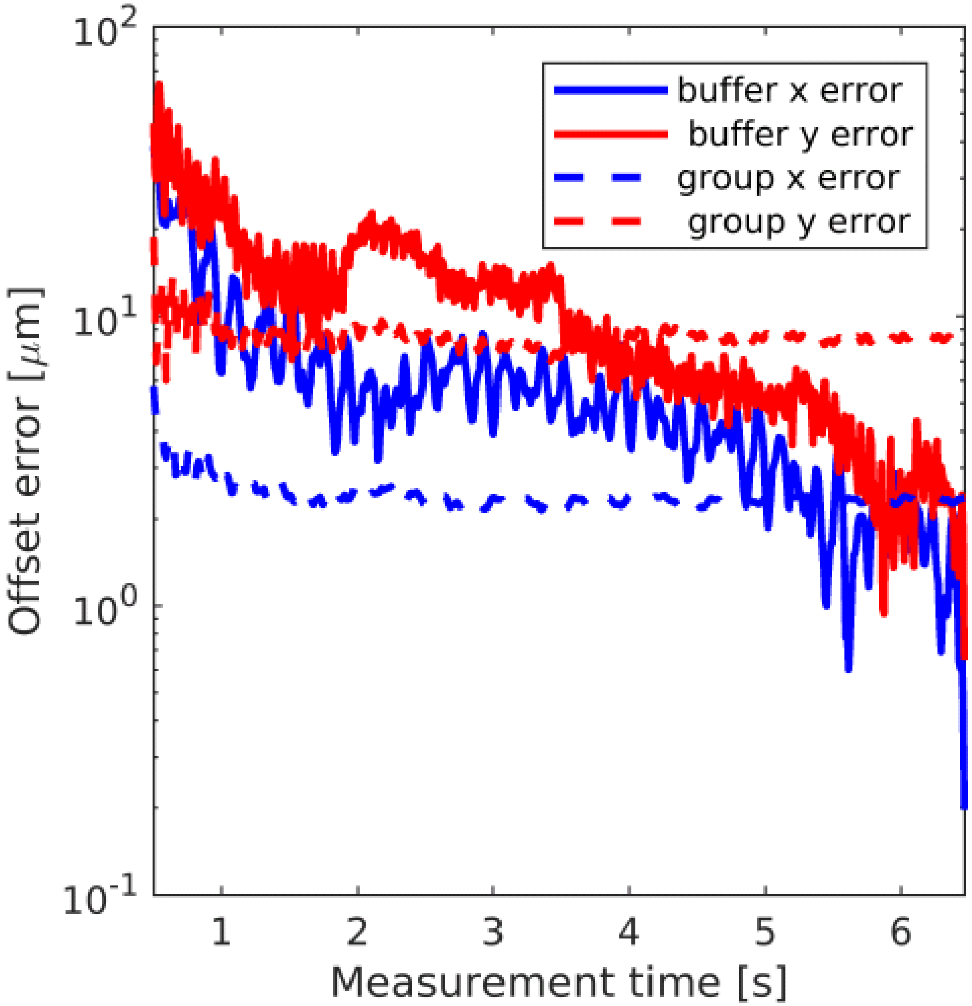
For a DC quad change of 2.5A, the **acquisition time** is optimized:

1.5 seconds (3 s/meas.)



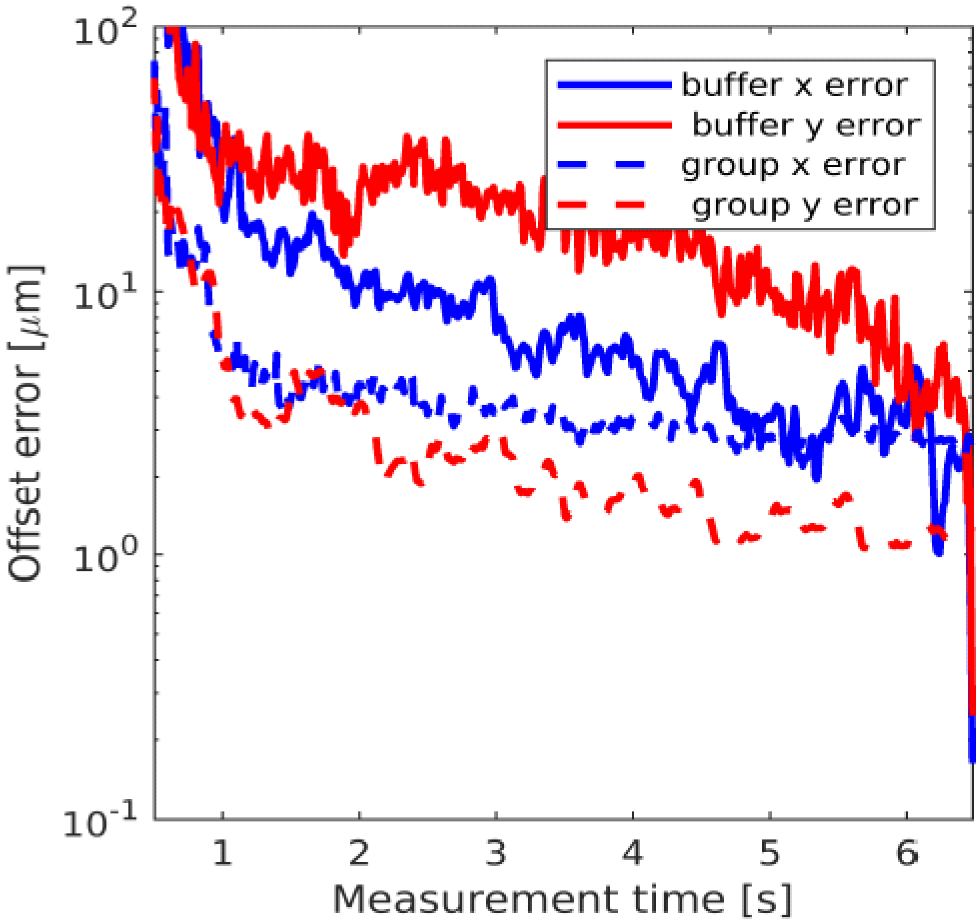
ALBA set up

For a DC skew change of 2.5A, the acquisition time is optimized: 6 sec (12s/meas)



ALBA set up

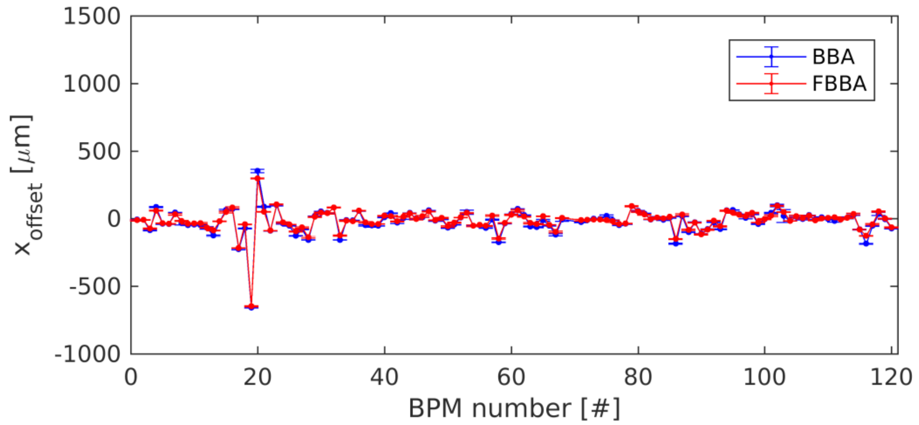
For an AC skew change of 2.5A at 1.6Hz, the acquisition time is optimized: 6 sec (6s/meas)

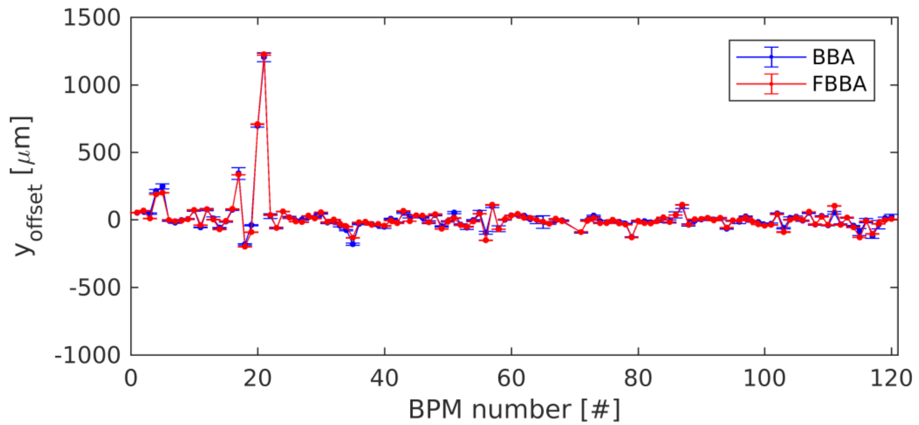


Results:Quads

BBA vs FBBA:

- The presented FBBA is ~30 times faster (10 min vs 5h) than the standard BBA.
- The level of precision is similar.

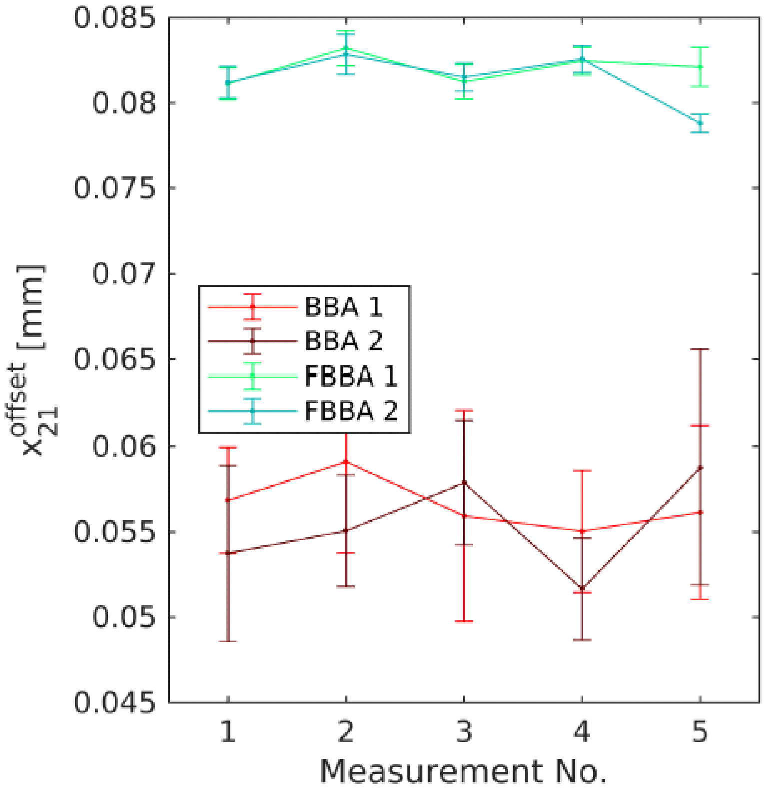




Results:Quads

For some BPMs, there are some systematic discrepancies effects **not** related to **quad hysteresis**…

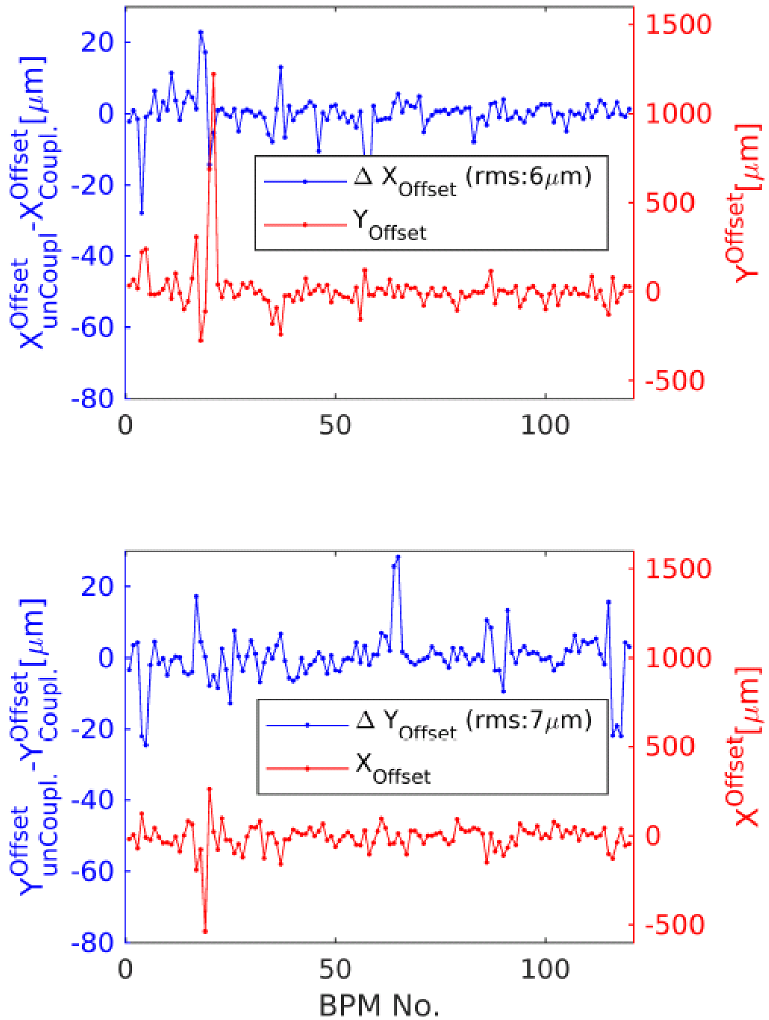
The measurements were performed with (1) and without (2) quad hysteresis cycles before the measurement.



Results:Quads

Regarding to **coupling** effects, they are of similar order.

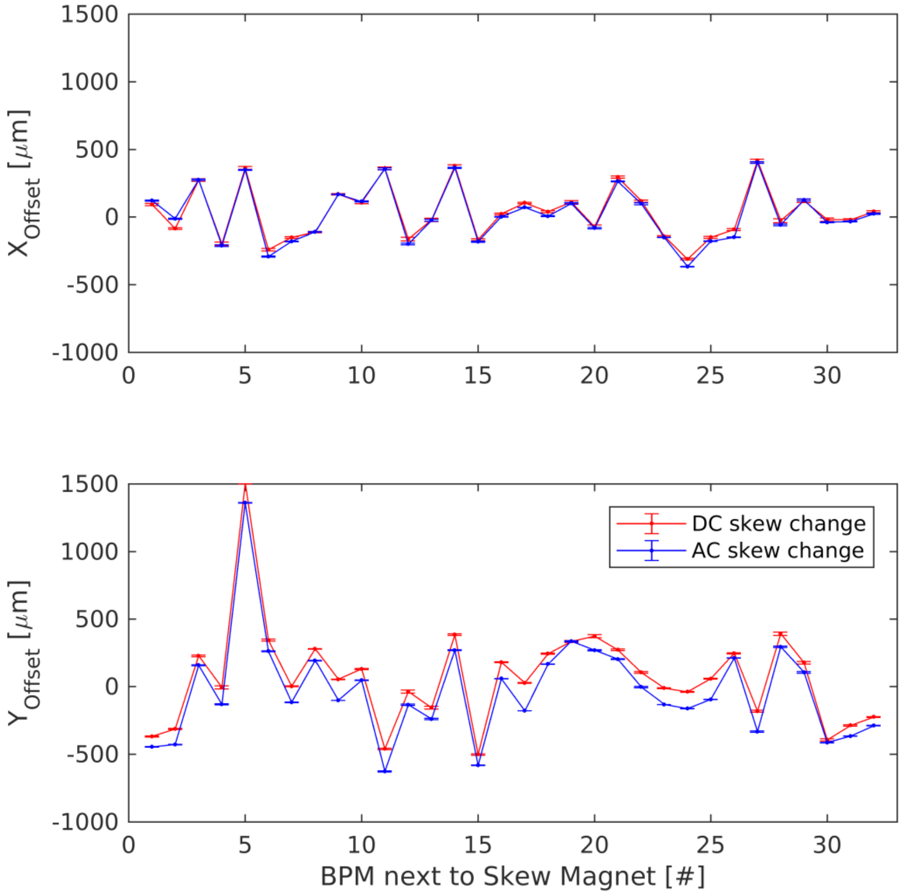
It seems not very relevant except in the case of large coupling or for skew quads…



Results: Skews

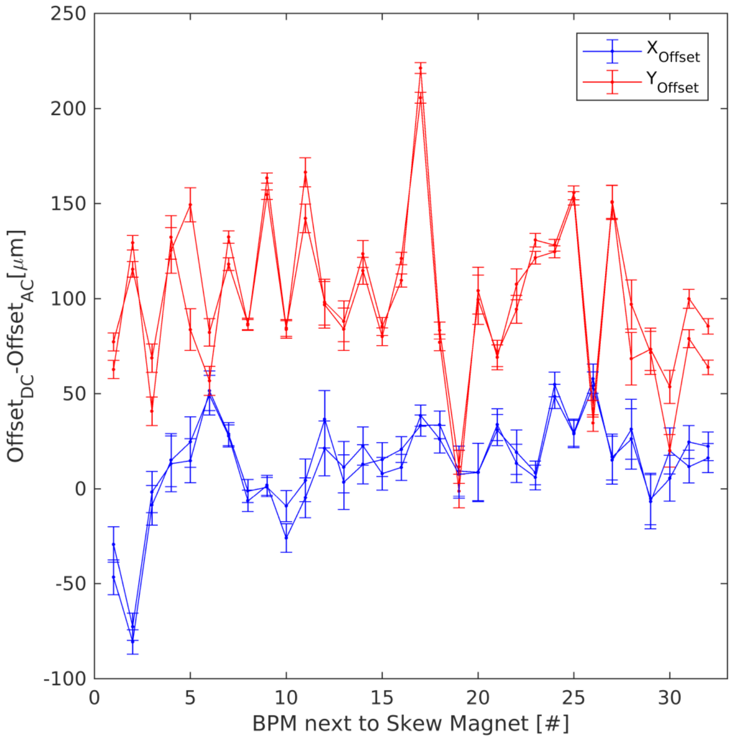
AC and DC magnet excitation give quite consistent results.

The AC is about 2 times faster, but there is a **systematic difference (unexplained)** of around 100um.



Results: Skews

We have performed random realistic simulations of FBBA at ALBA on skew quadrupoles and this effect is not expected.



	Horizontal	Vertical
Model rms quadrupole offset	150 μm	150 μm
Mean difference between offsets:		
(Normal quad.) BBA vs model	15 μm	12 μm
(Normal quad.) dc FBBA vs model	16 μm	12 μm
(Normal quad.) ac FBBA vs model	16 μm	13 μm
(Skew quad.) dc FBBA vs model	19 μm	9 μm
(Skew quad.) ac FBBA vs model	19 μm	6 μm
(Normal quad.) dc FBBA vs BBA	4 μm	2 μm
(Normal quad.) ac FBBA vs BBA	4 μm	3 μm
(Normal quad.) ac FBBA vs dc FBBA	0 μm	3 μm
(Skew quad.) ac FBBA vs dc FBBA	0 μm	5 μm

Conclusions

- Using the FOFB hardware, we have developed a method to perform quadrupole BBA which is **30times faster** than standard BBA and achieves even better precision (not sure about accuracy).
- The FBBA allows to perform simultaneous analysis of both planes, and accounts for any level of optics coupling, BPM roll and CM tilt.
- This novel approach allows also a skew quadrupole BBA (sextupole yoke).
- Some small differences between AC and DC modes remain unexplained (~30um for the quads case, and ~100um for the skews case).