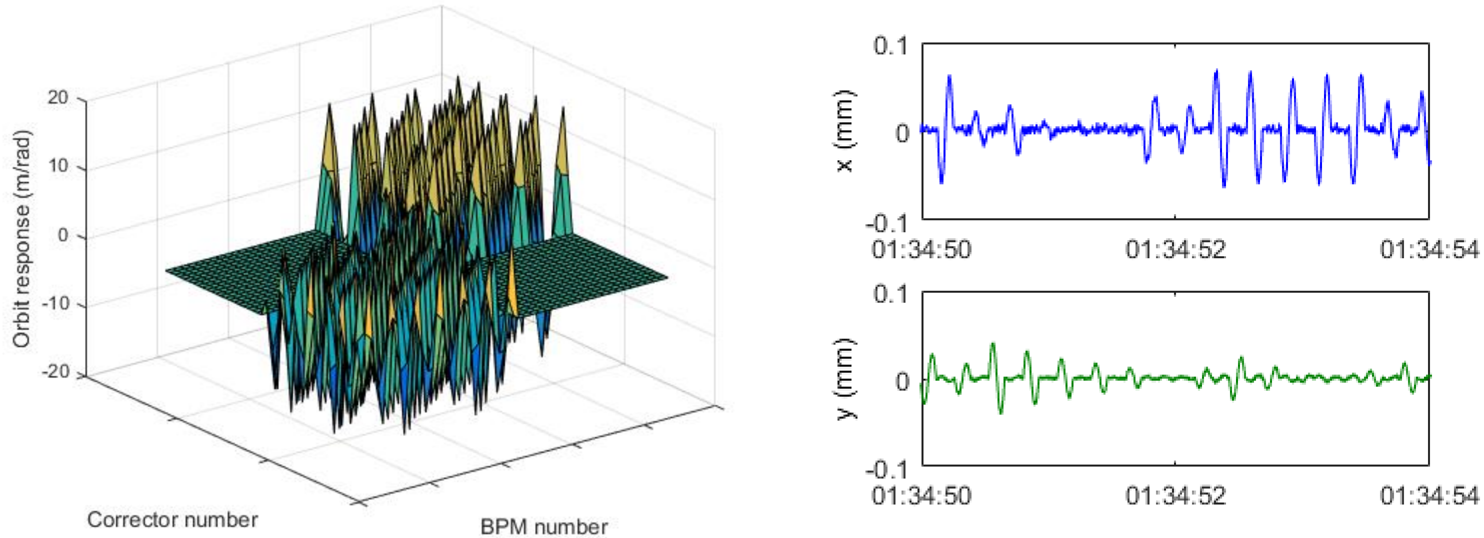
Optics Measurements using Fast Orbit Feedback Data



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Karlsruhe Institute of Technology
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diamond

Talk Outline

Introduction:

why use fast orbit data for LOCO?

Streamlined LOCO procedure:

fast orbit response matrix measurements
choice of excitation frequency
Python implementation
status at Diamond

Examples from other facilities:

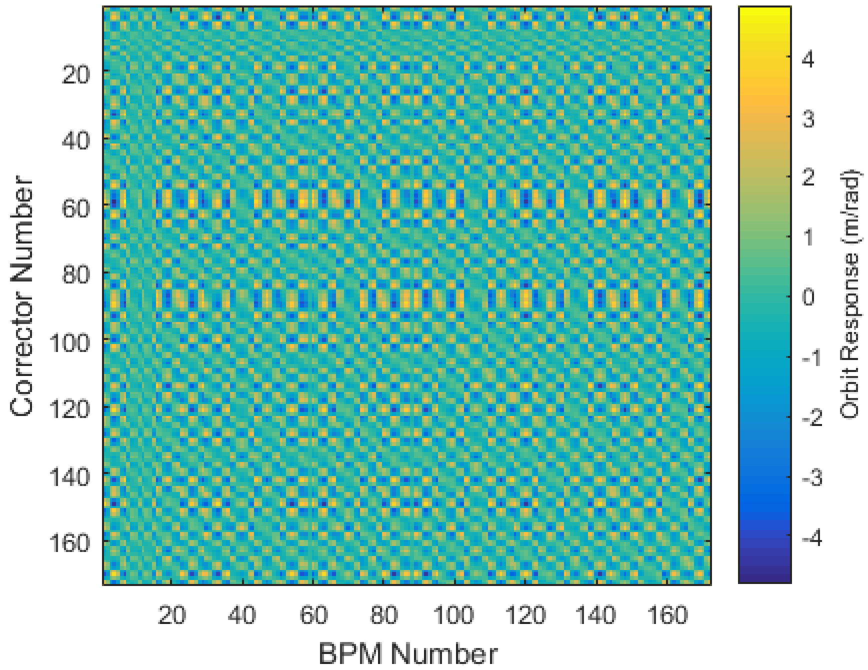
NSLS-II: algorithm comparisons; multi-corrector excitation
ALBA: off-energy measurements; non-linear lattice
ESRF: ID coupling compensation

Summary

Introduction

Excellent control of linear optics is mandatory for latest generation of light sources (source size, tune-stability, resonance control, coupling, vertical dispersion, lifetime, inj. efficiency, …).

Many techniques exist, however, LOCO[1]-style algorithms based on closed orbit response matrix (ORM) measurements are typically applied.



<u>The problem:</u>

- ORM large (Diamond-II: 252 BPMs x 252 CM x 2 planes); can take ~1h per correction cycle
- Significant drift can occur during measurement (particularly after fresh injection)
- Orbit stability can affect accuracy
- Invasive, so cannot be measured during user beam

Introduction

<u>Standard LOCO Method</u>

1) Measure ORM (+Dispersion, +BPM noise)
   - ➢ Correctors stepped up/down via matlab script over EPICS (MML)
   - ➢ Wait for magnet to reach set-point + fresh SA-BPM data (~1s)
   - ➢ Cycle through each HCM then VCM
2) Convert measured data to LOCO input file
3) Run LOCO analysis
4) Apply results

<u>Standard parameter fit for Diamond-I:</u>

- Individual quadrupole gradients (248)
- Individual skew-quadrupole gradients (98)
- BPM and CM gains / rolls

Typically takes ~20 minutes to acquire measured data, plus ~15-20 minutes to complete processing and to apply corrections.

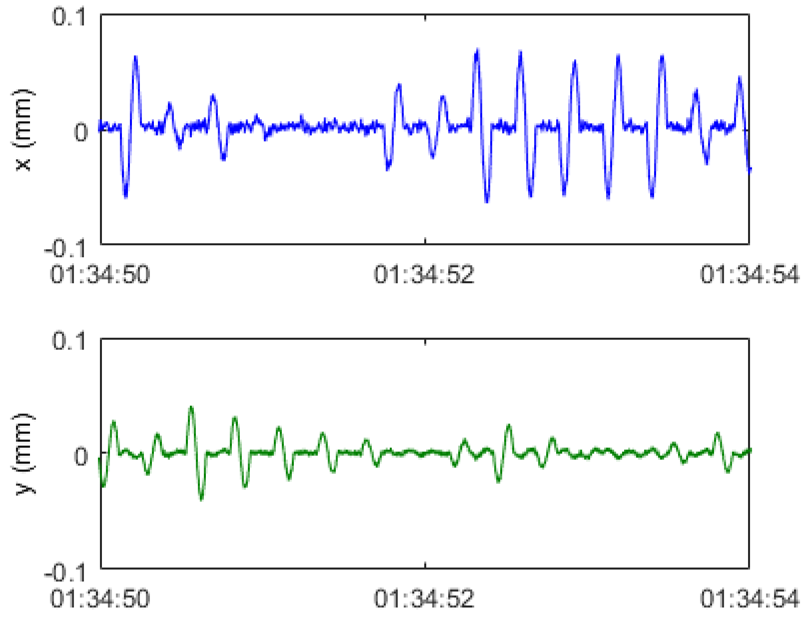
Orbit Response Matrix Measurement

Implementation

- Each feedback node can produce sine-wave excitation on each corrector with programmable amplitude, frequency, duration and synchronised start time
- Configured using Python script
- Orbit data extracted from 1 kHz FA data stream
- Amplitude extracted from measured orbit at BPM m and corrector n:

$$A_{m,n} = \langle 2 \times z_m(t) \times \sin(2\pi f t) \rangle$$

$$R_{m,n} = A_{m,n} / \theta_n$$



- Number of cycles, excitation frequency, choice of correctors, delay between corrector all configurable
- Particular choice depends on context (e.g. low alpha mode, fast coupling correction, …)

Introduction

Now

All stages automated via python interface, with Matlab stages launched in batch mode [2].

1) Measure ORM using fast orbit feedback network [3]
   - Programmed sine-wave excitation applied to each corrector in turn
   - Orbit data taken from fast acquisition (FA) BPM data and post-processed
   - Horizontal then vertical alternated
2) Convert measured data to LOCO input file
3) Run LOCO analysis (uses Matlab Parallel Computing Toolbox)
4) User queried if they would like to apply the results

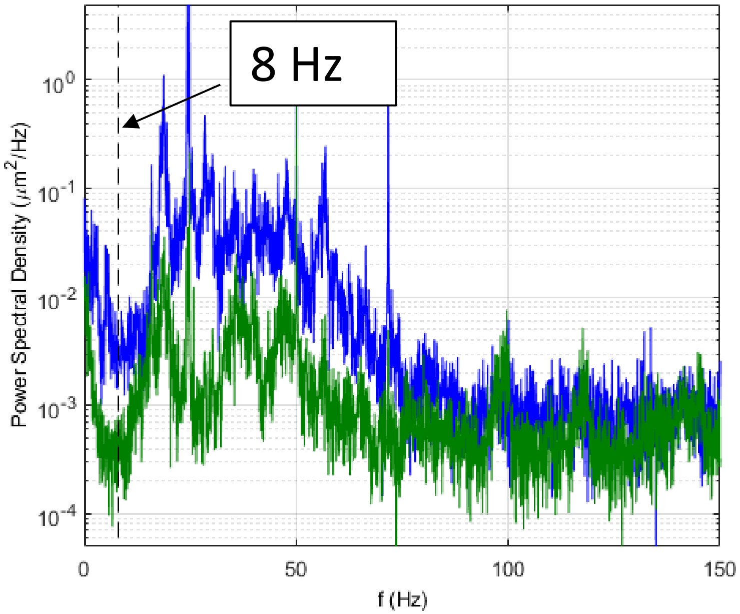
Keep the same parameter fits as previously

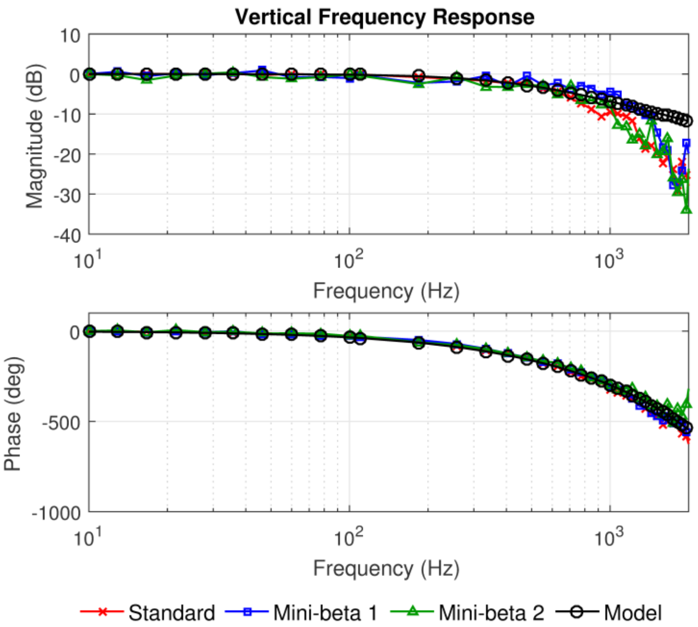
ORM measurement takes 52 seconds. Complete correction cycle ~5 minutes.

Choice of Excitation Frequency

Choice of excitation frequency is a trade off between reducing measurement time and improving accuracy

Noise spectrum at Diamond suggests 8 Hz is optimal



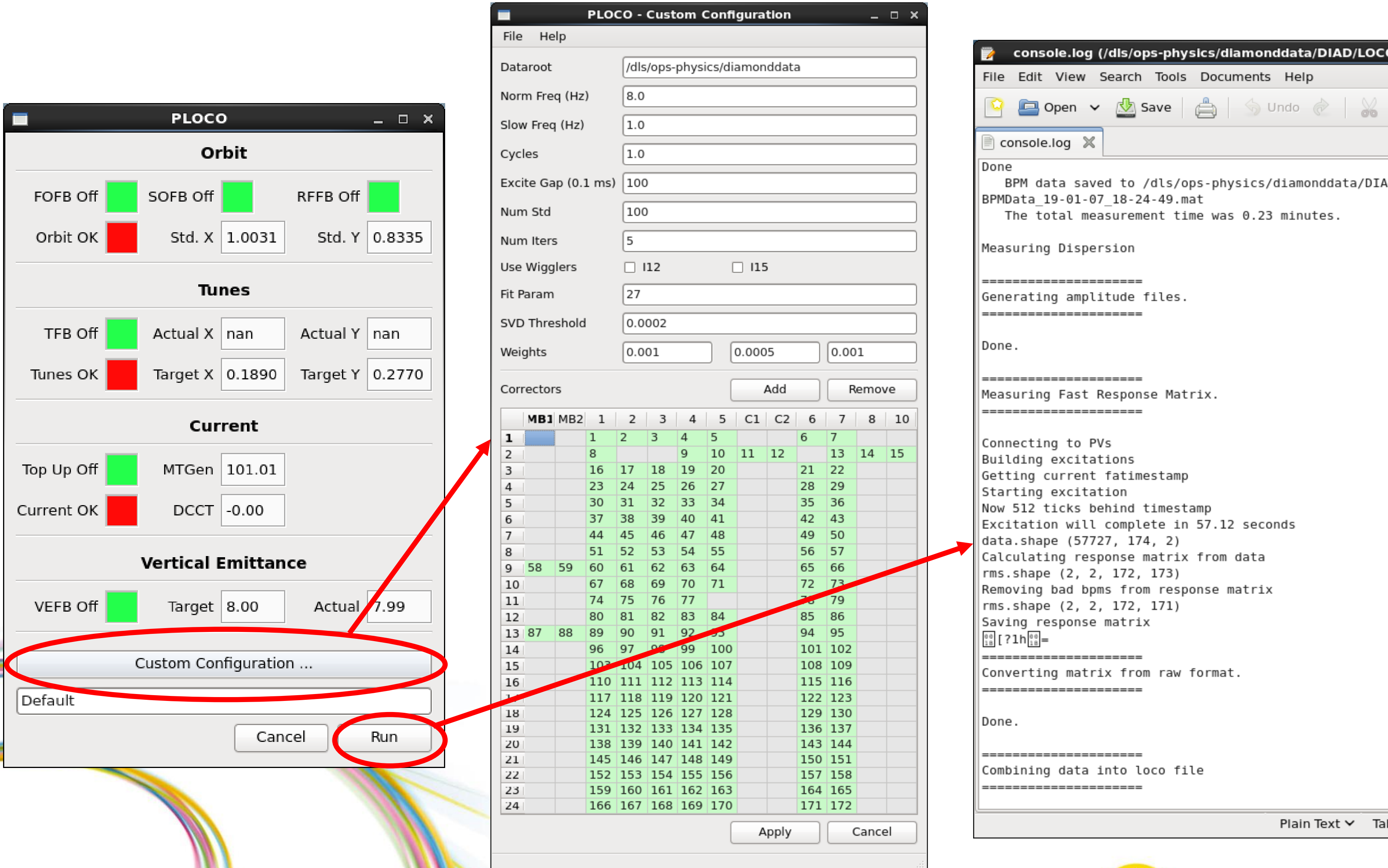


Freq. response of correctors affects measurement

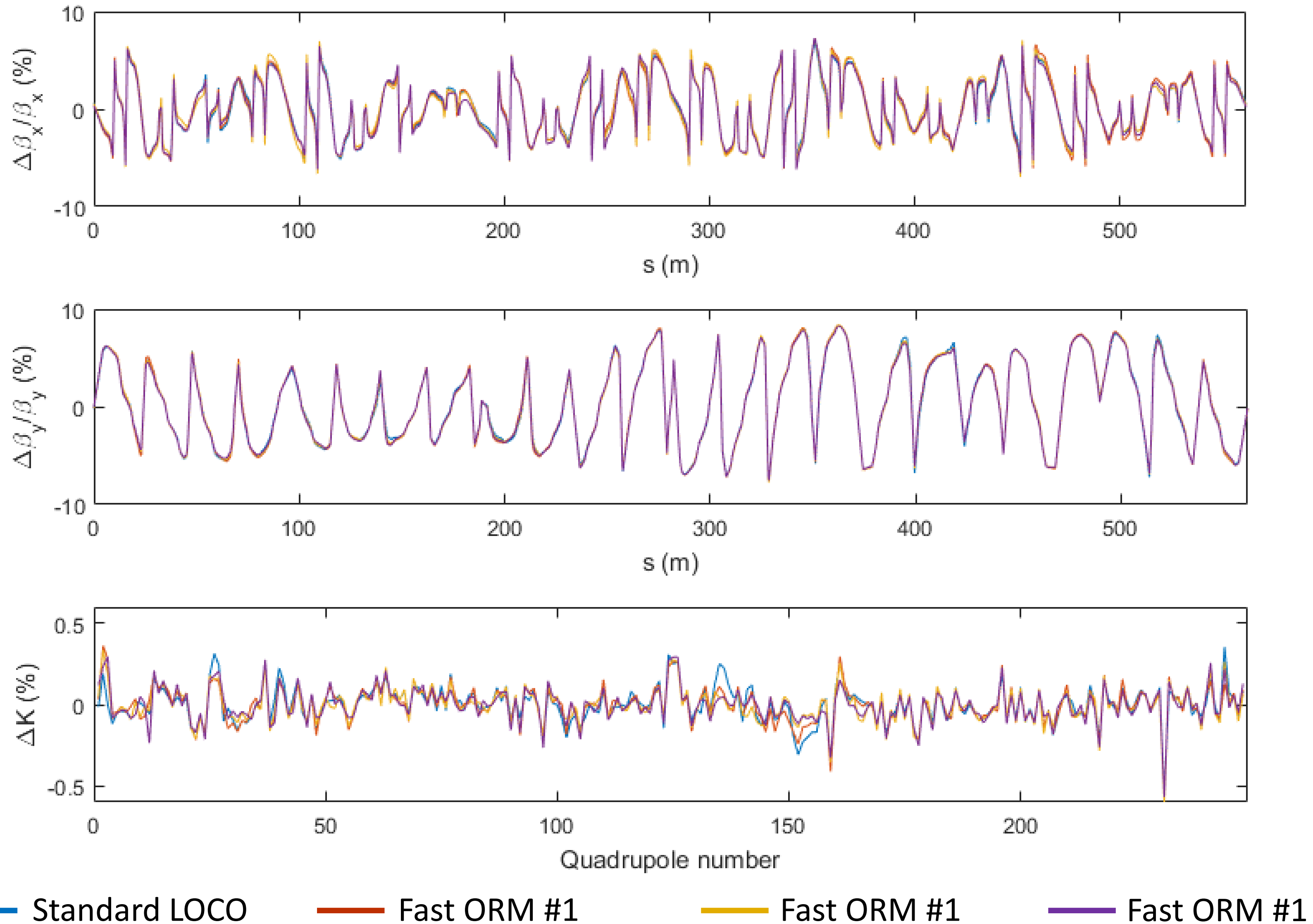
Depends on whole system (magnet, PS, vacuum chamber, …)

Currently using 8 Hz for embedded correctors on sextupoles, 1 Hz for discrete correctors in mini-beta straights

Python Interface



Results



Δβx/βx (%)
s (m)
Δβy/βy (%)
s (m)
ΔK (%)
Quadrupole number
Standard LOCO
Fast ORM #1
Fast ORM #1
Fast ORM #1

Status

- New LOCO application has been in routine operation since 2014
- Used by anyone (no specialist knowledge). Now applied for many situations:
  - Normal/skew quadrupoles for ID compensation
  - Re-correct the coupling (after beam trip)
  - Correct machine for MD studies (injection studies, resonant spin, pinhole calibration, ID studies, tune scans, ….)
- Different configurations in use for different operating modes:
  - User optics: single cycle, 100 samples for BPM sigma
  - Low alpha: 5 cycles, 200 samples for BPM sigma
- Parallelisation in Matlab allows increased number of iterations during LOCO fit to improve the convergence
- Tests with higher excitation frequencies show comparable results for optics; main impact is reduced fitted gain for correctors (attenuation / phase delay)
- Can further reduce acquisition and fit times by using fewer correctors; main impact is again on gain / roll values for correctors
- Using multiple excitations in parallel at different frequencies has been demonstrated. Can measure complete ORM in <10 s, however, it is the post-processing of the measured data that is limiting factor at present.

NSLS-II: Algorithms Cross-Check

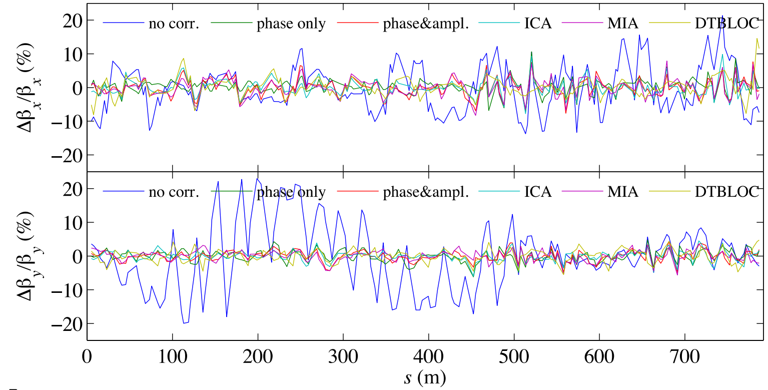
LOCO (DC and AC) results compared with various turn-by turn (TBT) schemes [4]:

4 TBT based algorithms:

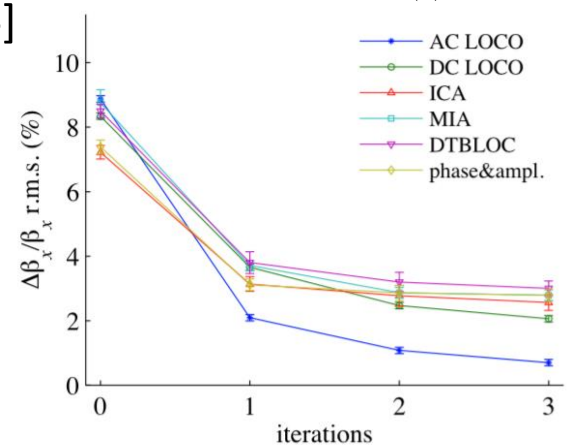
- weighted correction of betatron phase and amplitude [5]
- independent component analysis [6]
- model-independent analysis [7]
- driving-terms-based linear optics characterization [8]

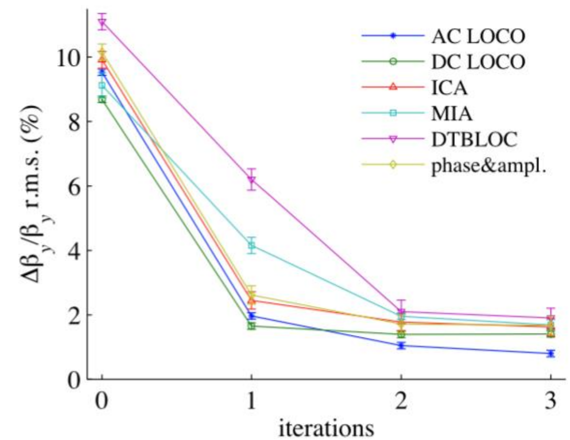
2 orbit-based algorithms:

- standard (DC) LOCO [1]
- AC LOCO [2, 9]



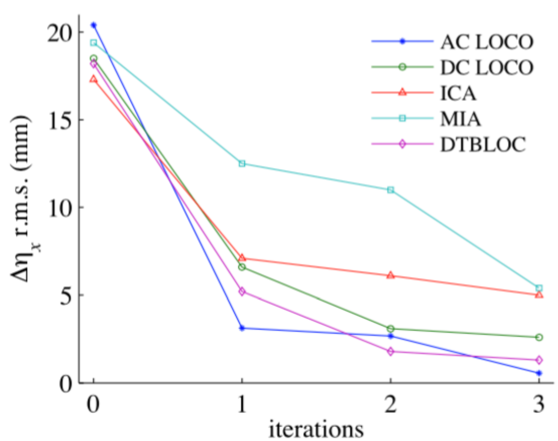
"Bad" lattice (random errors added to NSLS-II quadrupoles):
$\Delta\beta_x/\beta_x$ = 8% r.m.s.
$\Delta\beta_y/\beta_y$ = 10% r.m.s.
$\Delta\eta_x$ = 18 mm r.m.s.
$\Delta\eta_y$ = 8 mm r.m.s.

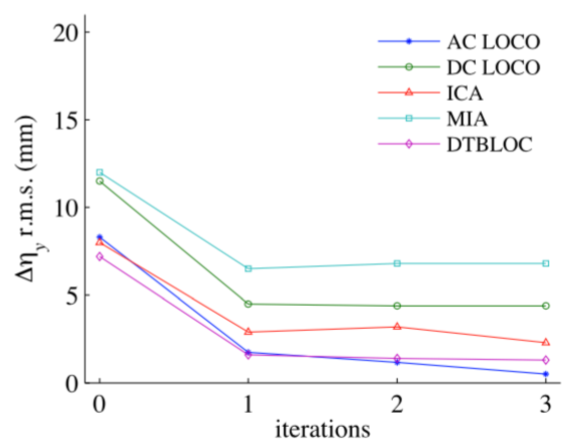




⇒ LOCO-based algorithms measurement precision higher

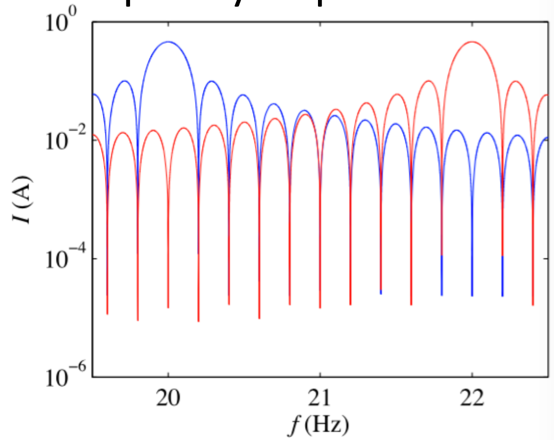
⇒ TBT-based algorithms less time-consuming



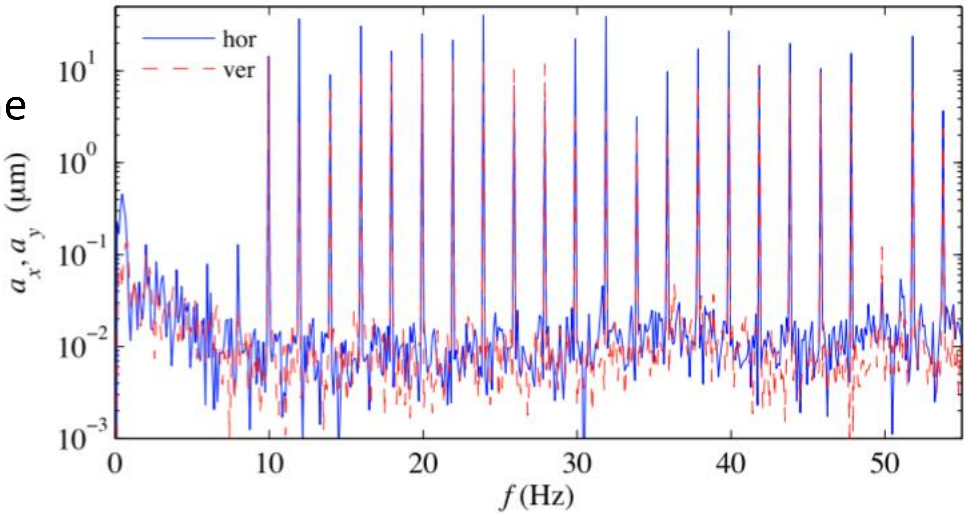


NSLS-II: Multi-Frequency Excitation

- Fast corrector signal bandwidth is small (0.2 Hz for a 5 sec measurement), it provides an opportunity of simultaneous excitation of beam oscillations via multiple fast correctors with different frequencies separated by an interval of Δf.
- Can potentially reduce the measurement time to be comparable with TBT-based methods
- Frequency range for the multiple excitations depends upon on the frequency-dependent signal-to-noise ratio of the system.

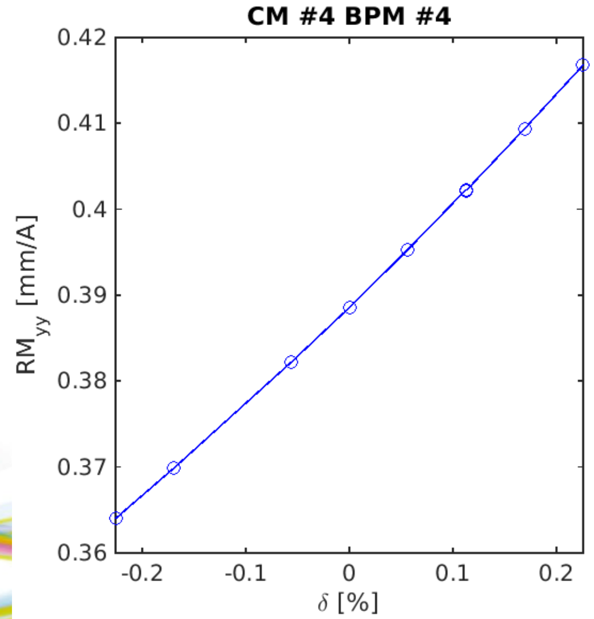


- Beam oscillation measured by BPMs is a finite-time sine wave, Fourier transform of which is proportional to:
$$\mathrm{sinc}(\pi T \Delta f) = \sin(\pi T \Delta f)\,/\pi T \Delta f$$
where $\Delta f = f - f_0$, and f_0 is the excitation frequency.
- This function has zero values at $\Delta f = k/T$, where k is an integer, so we can choose any of these frequencies.
NSLS-II: T = 5 s, k = 10 ⇒ Δf = 2 Hz
- 23 fast correctors, AC driving signals with the frequencies of 10 Hz; 12 Hz; ...; 54 Hz;
- Slow orbit feedback on to minimize drift
- 10 measurement sets for statistical errors
- Measured r.m.s. errors ~20 nm

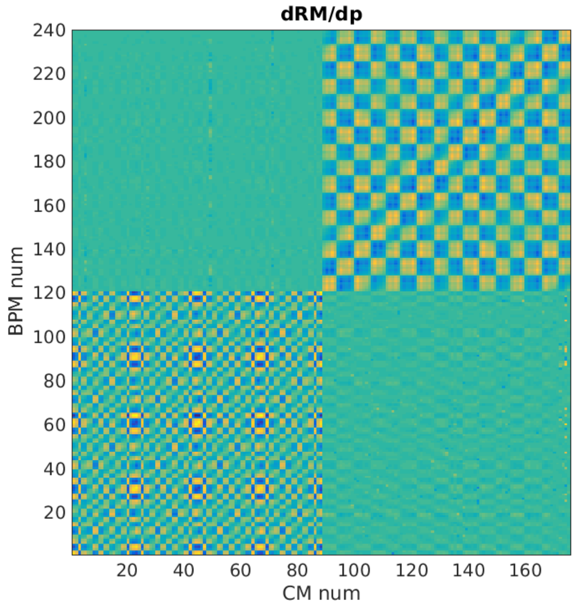


ALBA: Off-Energy Fast ORM

- Increased accuracy allows $\partial ORM/\partial\delta$ to be evaluated by measuring ORM at several values of RF frequency [10]
- Effective only for sextupoles at dispersive locations
- Discrepancies found to persist when fitting the sextupoles against the LOCO model



FORM element as a function of $\delta p/p$ induced by a RF frequency change.



FORM derivate with respect to $\delta p/p$. Could be used to fit non linear fields.

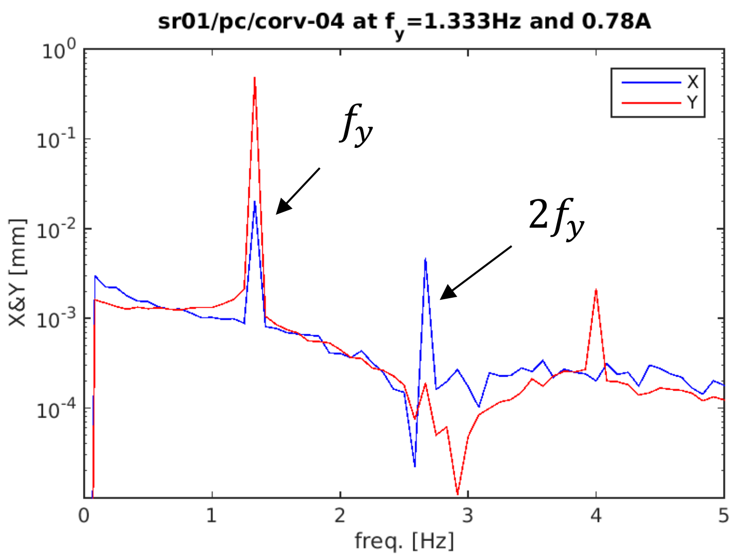
ALBA: Non-Linear Fast ORM

- Sextupolar fields induce harmonics of the CM waveform frequency (ORM^2)
- Excite the beam at f_x and f_y:

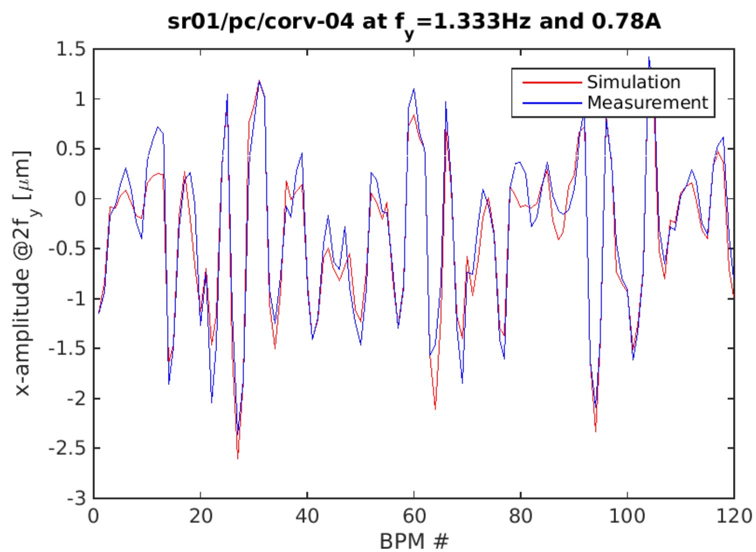
$$B_y = m(x^2 - y^2)$$ - horizontal orbit contains $2f_x$ and $2f_y$

$$B_x = 2mxy$$ - vertical orbit contains $f_x - f_y$ and $f_x + f_y$

- Requires large amplitude excitation to be visible
- Fit of the measured quantities against the model not yet attempted



Discrete FFT of the BPM signals for a particular single vertical CM.

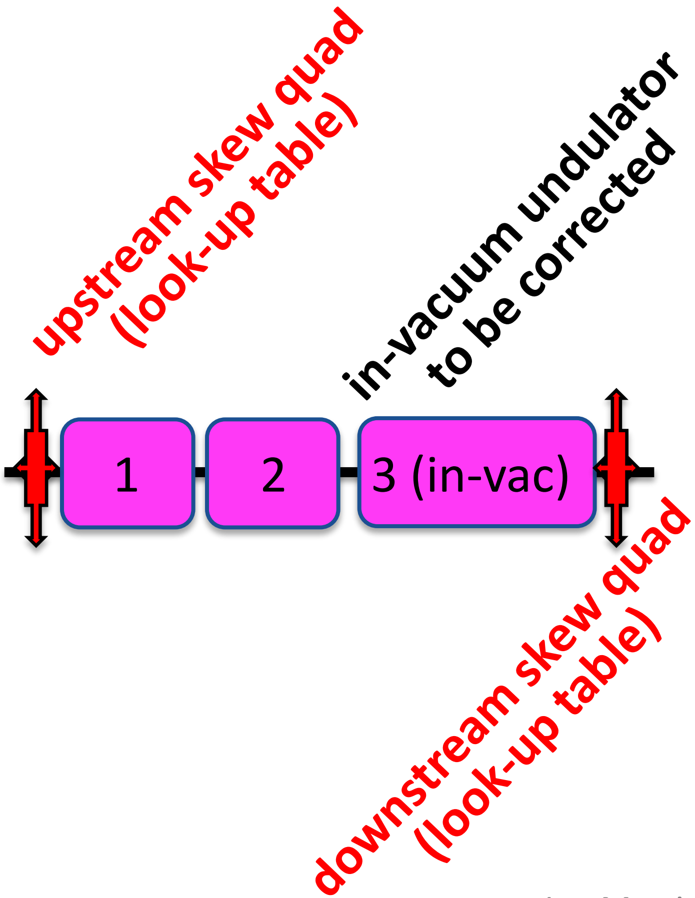


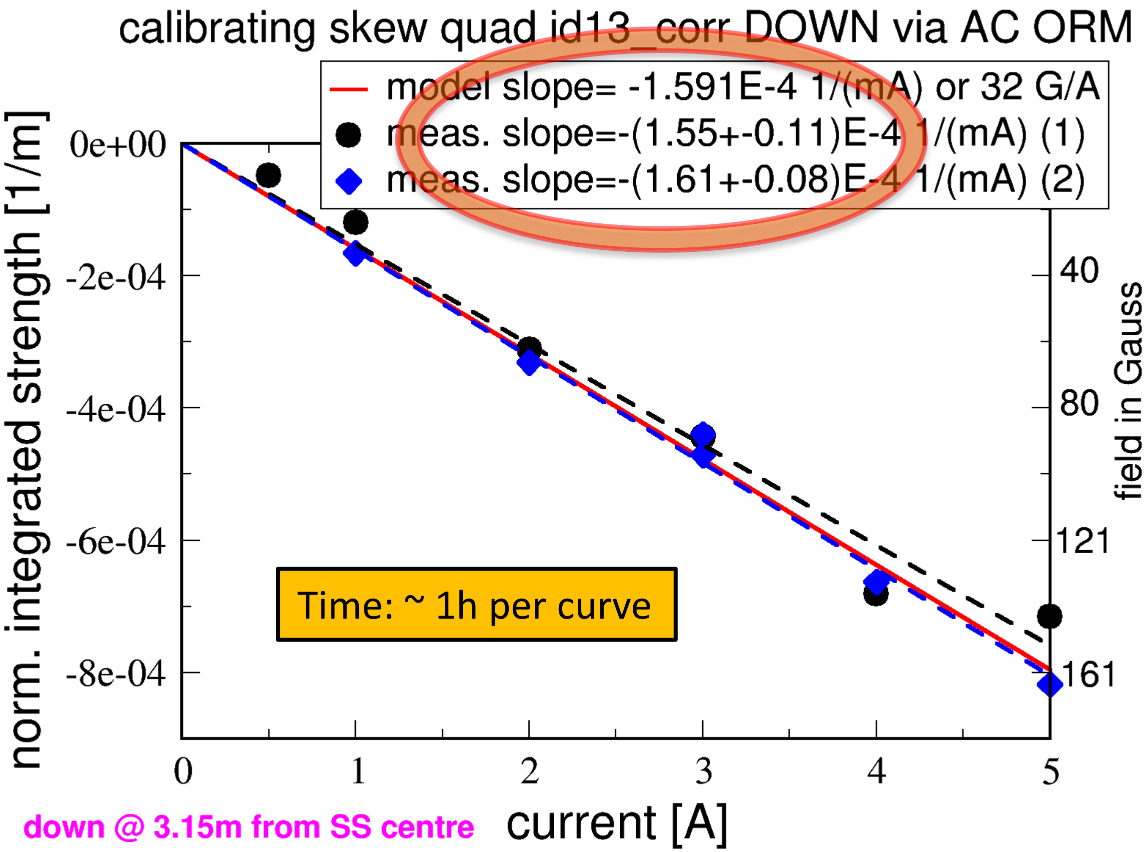
Amplitude of the $2f_y$ line for the horizontal BPMs.

ESRF: ID Compensation

Measure and fit AC ORM to infer ID gap-dependent skew quad field, calibrate corrector coils and check look-up tables

$\delta O_{xy} = O_{xy}^{(corr.\ coils)} - O_{xy}^{(corr.\ off)}$ → $\delta O_{xy} = M\,\delta J_1$ | δJ_1 skew quad field



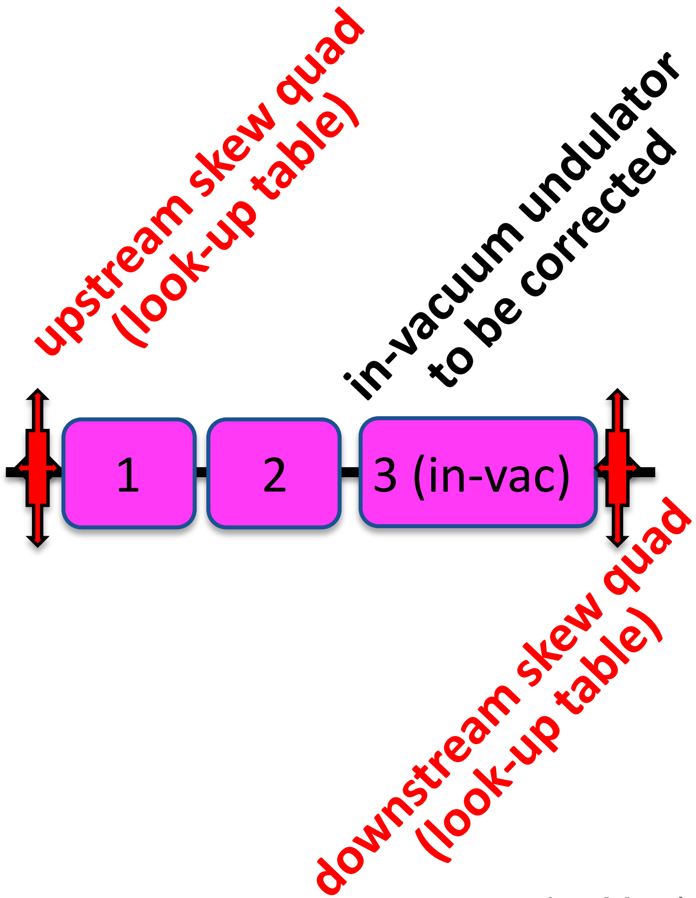


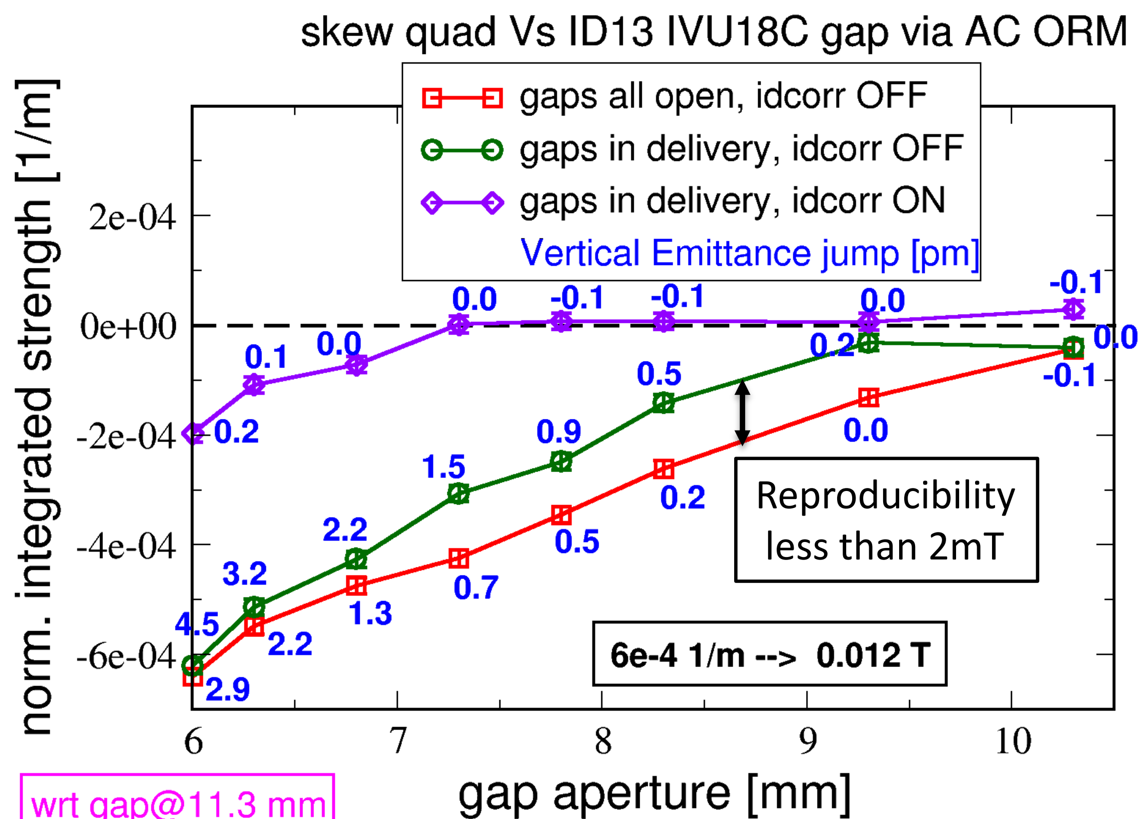
ESRF: ID Compensation

Measure and fit AC ORM to infer ID gap-dependent skew quad field, calibrate corrector coils and check look-up tables

$\delta O_{xy} = O_{xy}^{(ID\ gap\ closed)} - O_{xy}^{(ID\ gap\ open)}$ → $\delta O_{xy} = M\,\delta J_1$ | δJ_1 skew quad field

Time: ~ 1h per curve





Summary

Fast ORM measurements have many benefits:

- substantial reduction in measurement / correction times
- minimises impact from machine drift and / or hysteresis effects
- improved accuracy compared to DC LOCO or TBT-based algorithms
- enables frequent optics correction and use by non-experts
- enables new types of measurement (off-energy ORM, nonlinear ORM)

Potential future developments:

- Integrate measurement with fast orbit feedback
- Transfer existing Matlab code to Python to streamline data acquisition and processing
- Investigate small amplitude / long duration excitation to enable data acquisition during user time

References

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