Optics measurements & correction in the old ESRF storage ring (2010-2018)

Andrea Franchi (ESRF, Grenoble)

mini-workshop on FCC-ee optics tuning and alignment, 11-12 May 2022

Outlines

- Understanding & correcting linear coupling (2009-2010)
- Nonlinear optics & magnet calibration via turn-by-turn (TbT) BPM data (2010-2013)
- Error analysis of linear optics measurements via orbit & TbT analysis (2016-2017)
- Applications of AC Orbit data (2016-2019)
- Experience of AC dipole & TbT BPM data (2016-2018)

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Understanding & correcting linear coupling

- Misconception #1: In the presence of coupling we deal with vertical emittances (plural is not a typo)
- Misconception #2: Coupling correction is a linear problem not needing CPU-intense random/genetic/non-linear optimizers
- Misconception #3: Guignard formulas don't apply to modern synchrotron light sources & damping rings (**integer part** of tunes $Q_x >> Q_y$)
- Misconception #4: "indirect measurements" of vertical emittance should be avoided

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Vertical emittance in the absence of coupling

- Eigen-emittance $\mathcal{E}$: constant along the ring, with $\mathcal{E}v$≅0
- Non measurable RMS emittance:

$$\epsilon_y = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}$$

- Measurable emittance from RMS beam size:

$$\mathbb{E}_y = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > -(\delta D_y(s))^2}{\beta_y(s)}$$

$\mathcal{E}v$=Ɛy=E*y*=const.

With zero vertical dispersion, $\mathcal{E}v$=Ɛy=E*y*≅0

Vertical emittances in the presence of coupling

- Eigen-emittance $\mathcal{E}$: **constant** along the ring, but $\mathcal{E}v \neq 0$
- Non measurable projected **s-dependent** RMS emittance:

$$\epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}$$

- Measurable apparent **s-dependent** emittance from RMS beam size:

$$\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > -(\delta D_y(s))^2}{\beta_y(s)}$$

$\mathcal{E}v$=const ≠ Ɛy(s) ≠ E*y*(s)

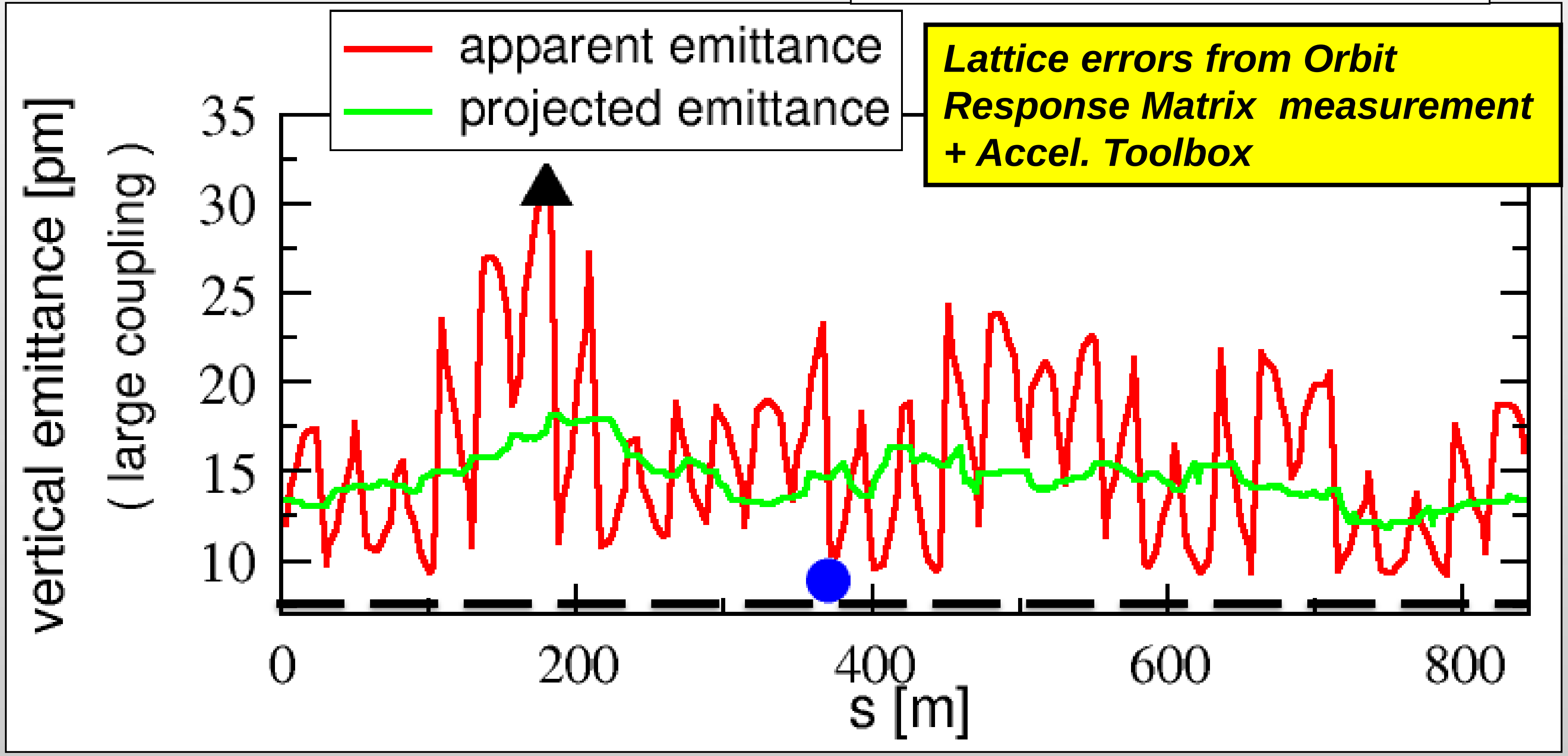
Vertical emittances in the presence of coupling

Measurable apparent emittance:

$$\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > -(\delta D_y(s))^2}{\beta_y(s)}$$

Non measurable projected emittance:

$$\epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}$$



Lattice errors from Orbit Response Matrix measurement + Accel. Toolbox

eigen-emittance $\mathcal{E}_v$= 9 pm

Vertical emittances in the presence of coupling

Measurable apparent emittance: $\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > -(\delta D_y(s))^2}{\beta_y(s)}$

Non measurable projected emittance: $\epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}$

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25**, 044001 (2022)

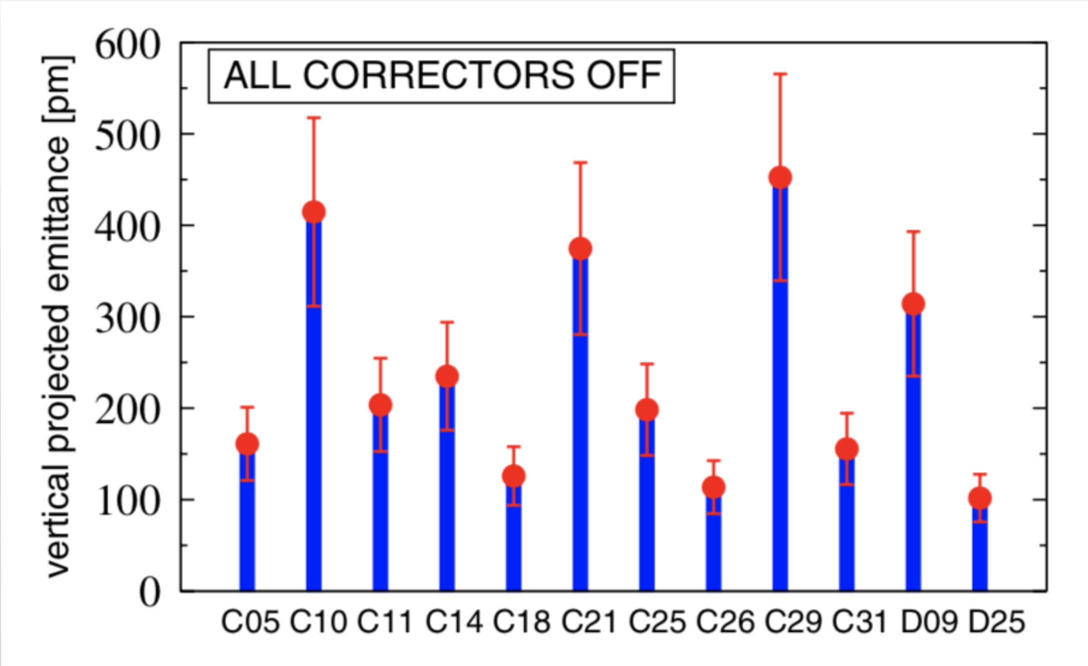
Demonstration of eigen-to-projected emittance mapping for an ellipsoidal electron bunch

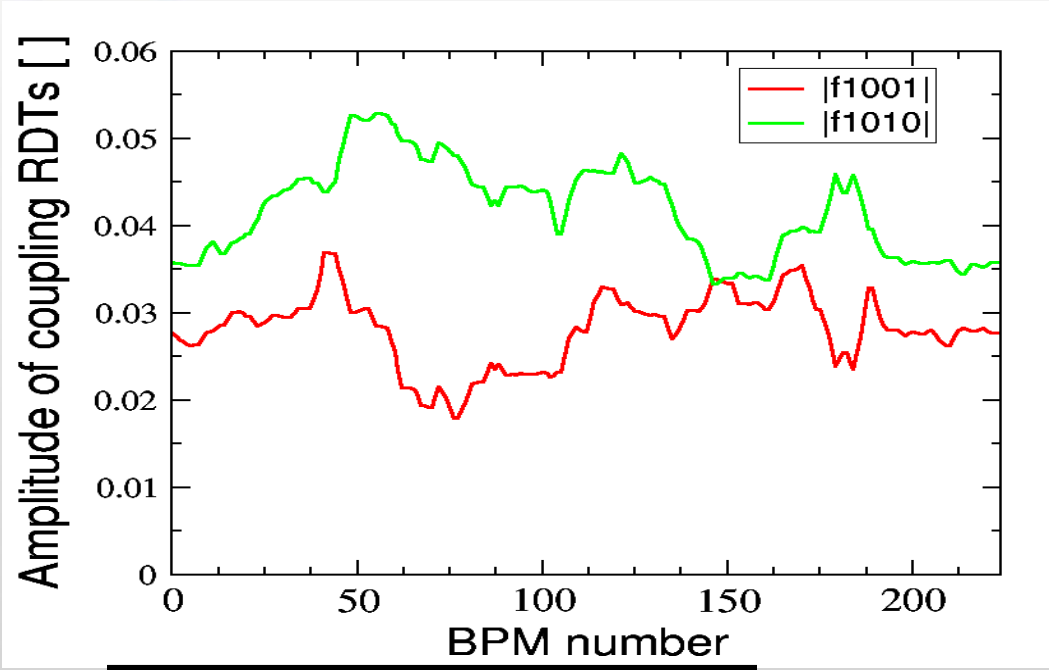
consider the position-conjugate momentum pair (q_ℓ, p_ℓ), with $\ell = x, y, z$, associated with d.o.f., the moment invariant $\varepsilon_\ell \equiv [\langle q_\ell^2 \rangle \langle p_\ell^2 \rangle - \langle q_\ell p_\ell \rangle^2]^{1/2}$ is often introduced

In beam physics, the eigenemittances are a generalization of the projected emittances to the case of beams with coupled d.o.f. [8].

Coupling correction is a linear problem not needing CPU-intense random/genetic/non-linear optimizers

all skew quad correctors OFF $\varepsilon_y/\varepsilon_x \sim 5\%$



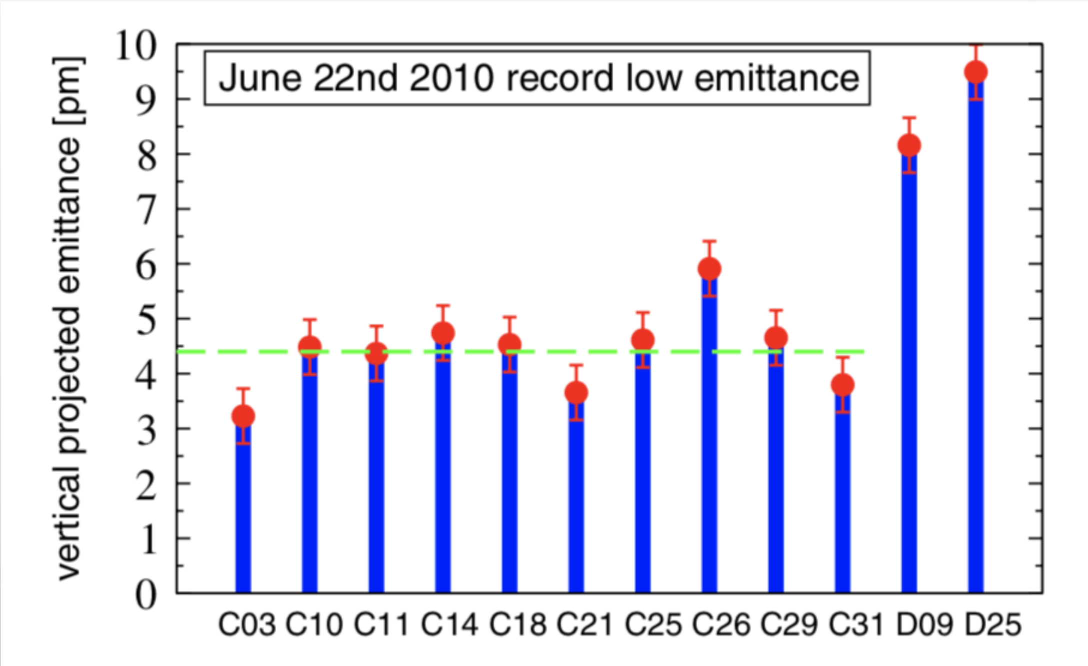


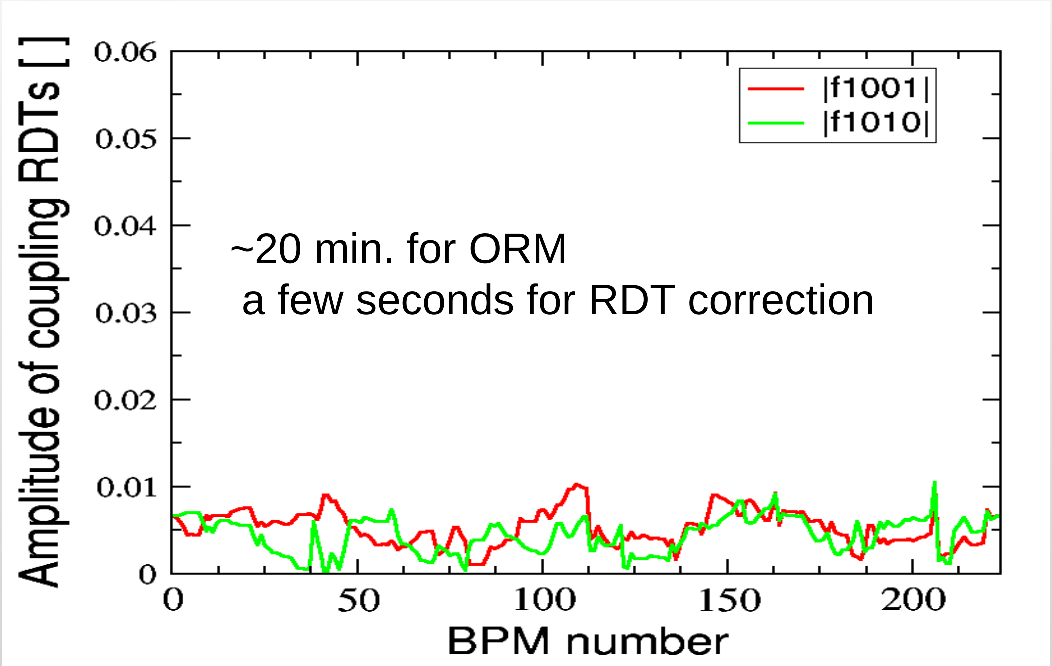
C*, D*: emittance monitors

$$\begin{pmatrix} a_1\vec{f}_{1001} \\ a_1\vec{f}_{1010} \\ a_2\vec{D}_y \end{pmatrix}_{\text{meas}} = -\mathbf{M}\vec{J}_c,$$

Coupling correction is a linear problem not needing CPU-intense random/genetic/non-linear optimizers

after correction $\varepsilon_y/\varepsilon_x \sim 1‰$





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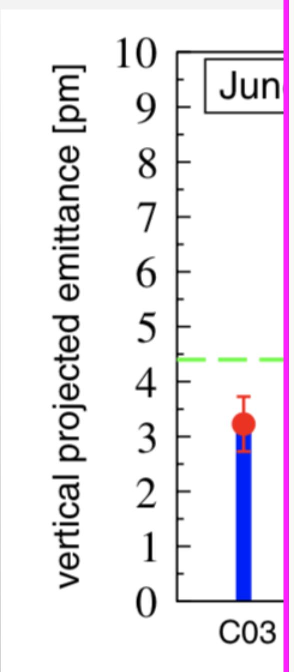
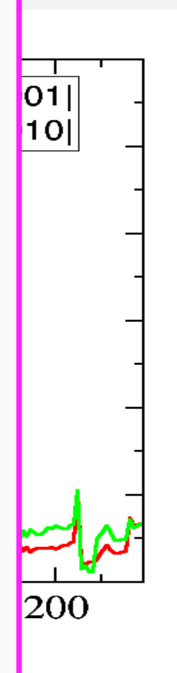
Coupling correction is a linear problem not needing CPU-intense random/genetic/non-linear optimizers

after c





C*, D

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 892, 1 June 2018, Pages 1-9

Coupling control and optimization at the Canadian Light Source

We calculate the six-dimensional beam envelop matrix and use it to produce a variety of objective functions for optimization using the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. MOPSO produces a number of skew quadrupole configurations that we apply to the storage ring. We use the X-ray synchrotron radiation diagnostic beamline to image the beam and we make measurements of the vertical dispersion and beam lifetime.

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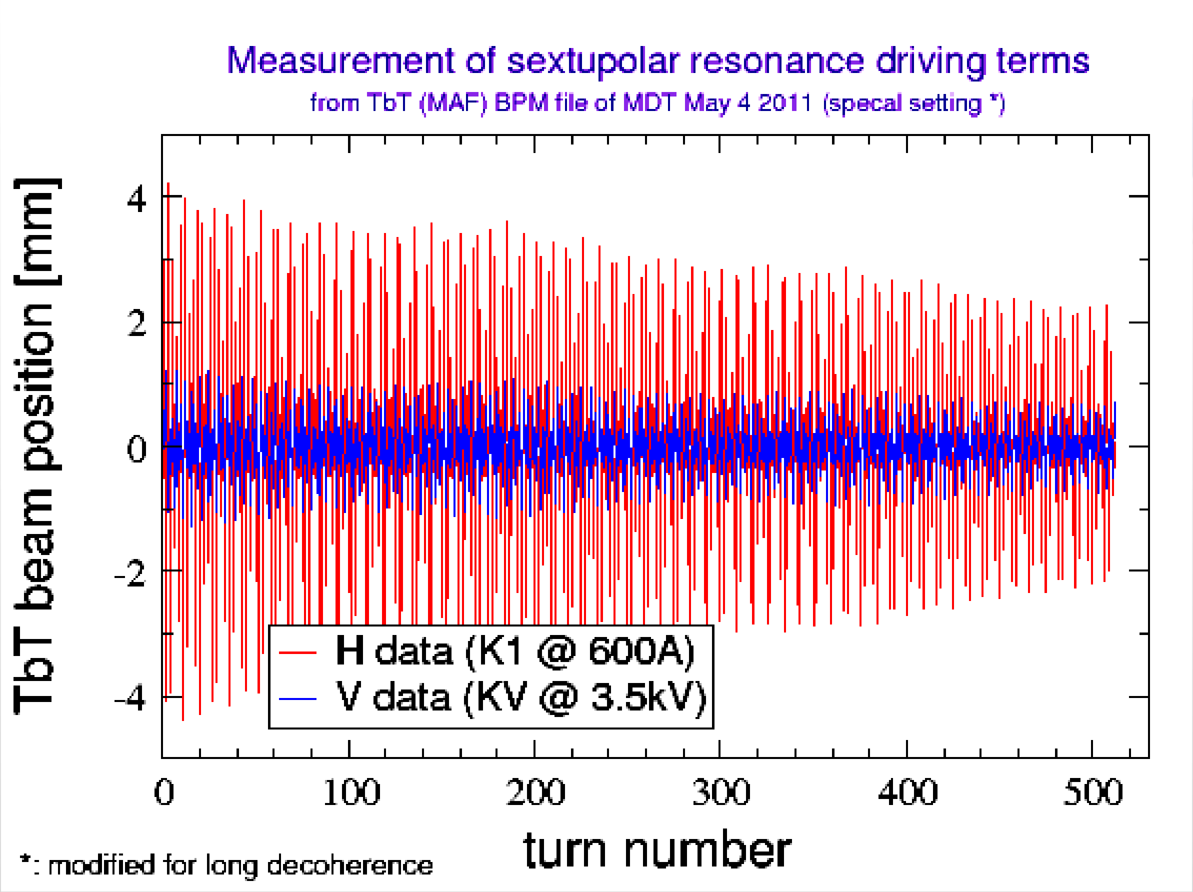
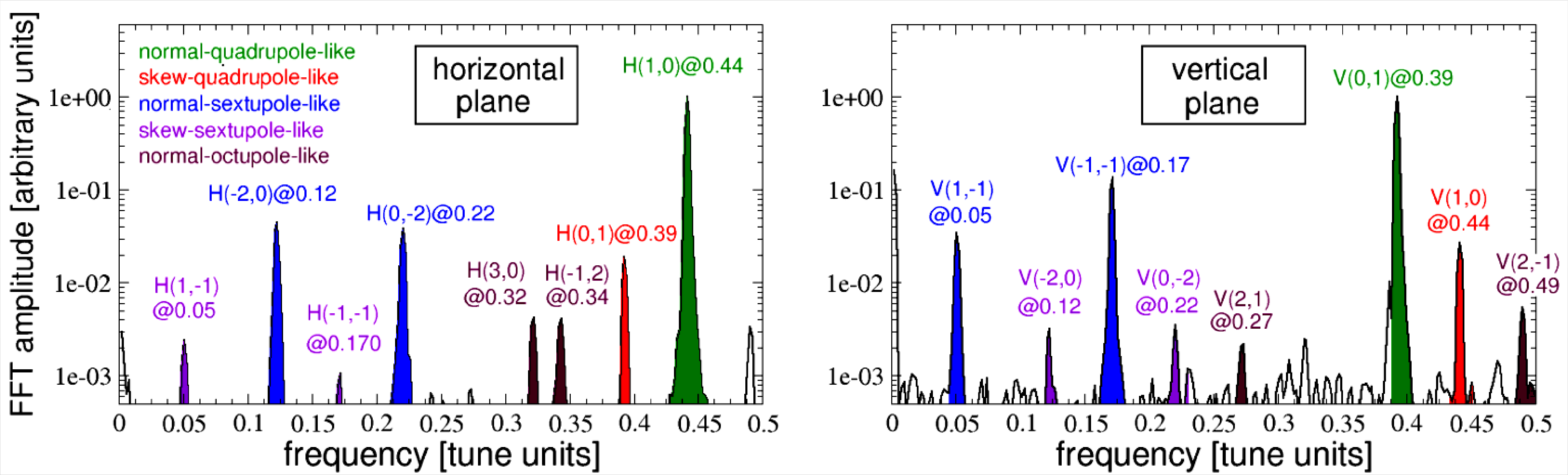


1. Get synchronized and *decent*(*) TbT BPM data in both planes

(*) from nonlinear optics with zero chromaticity and zero (linear) amplitude-dependent detuning

2. Perform a *suitable* FFT of the TbT data & look at the lines popping up in the spectra



Nonlinear optics & magnet calibration

RDTs require $(x, p_x), (y, p_y)$

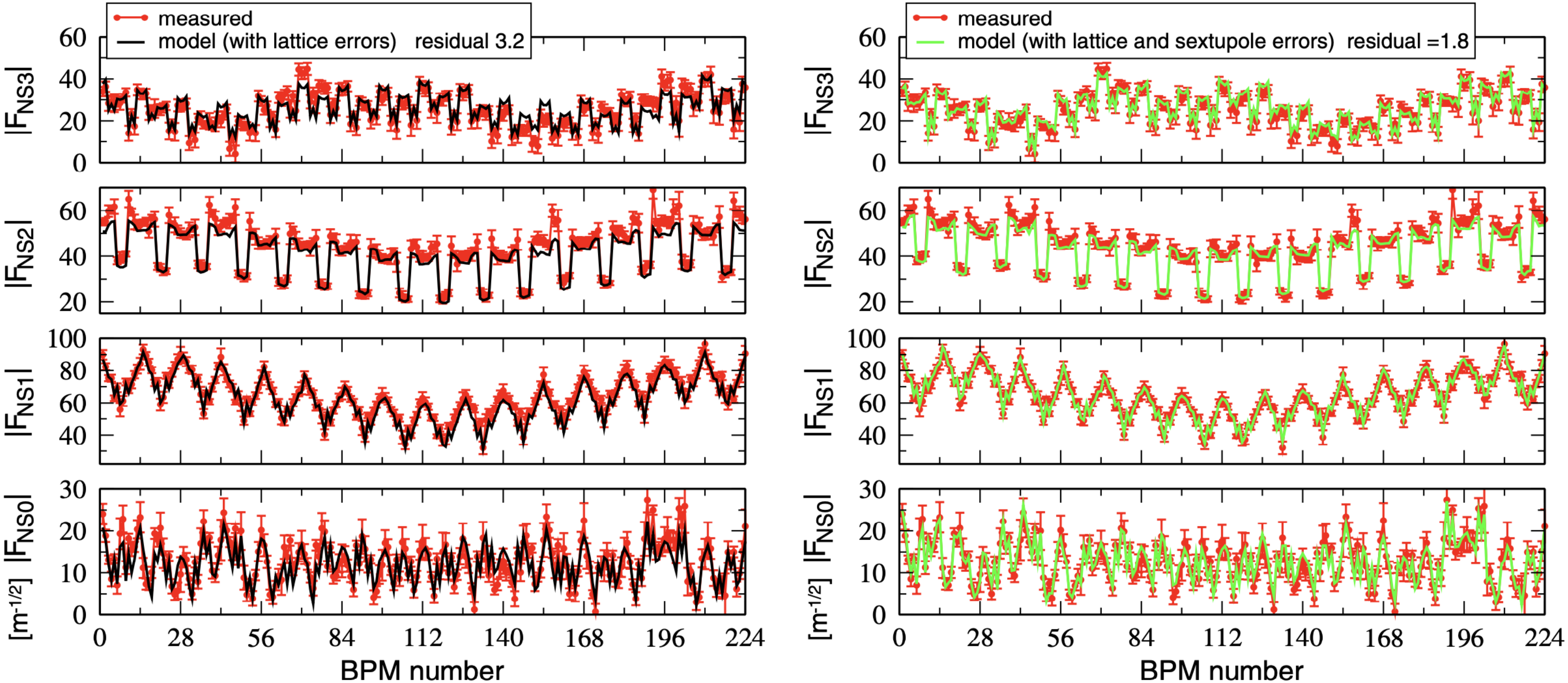
CRDTs require $(x, \cancel{p_x}), (y, \cancel{p_y})$

less information, but no systematic error from $p_{x,y}$

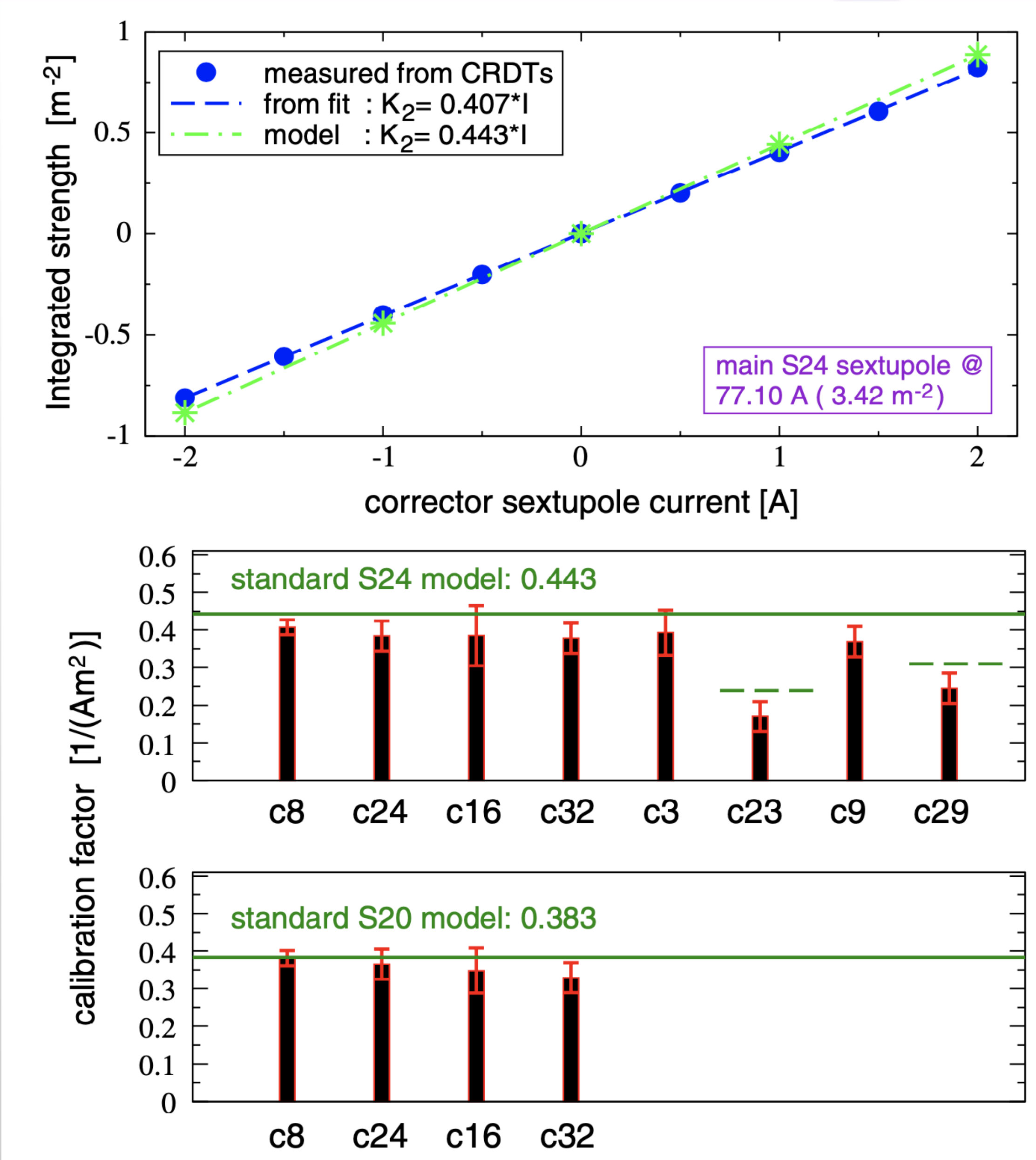
3. from the spectral lines infer the combined resonance driving terms (CRTDs) @ all BPMs

Combined RDT	Resonances	Magnetic term
$F_{xy} = f^{(1)}_{1001} - f^{(1)*}_{1010}$	$(1, 1), (1, -1)$	Skew quadrupole
$F_{yx} = f^{(1)*}_{1001} - f^{(1)*}_{1010}$	$(1, 1), (1, -1)$	Skew quadrupole
$F_{NS3} = 3f^{(1)}_{3000} - f^{(1)*}_{1200}$	(1,0),(3,0)	Normal sextupole
$F_{NS2} = f^{(1)}_{1020} - f^{(1)}_{0120}$	$(1, -2), (1, 2)$	Normal sextupole
. . .		Skew sextupole
. . .		Normal octupole

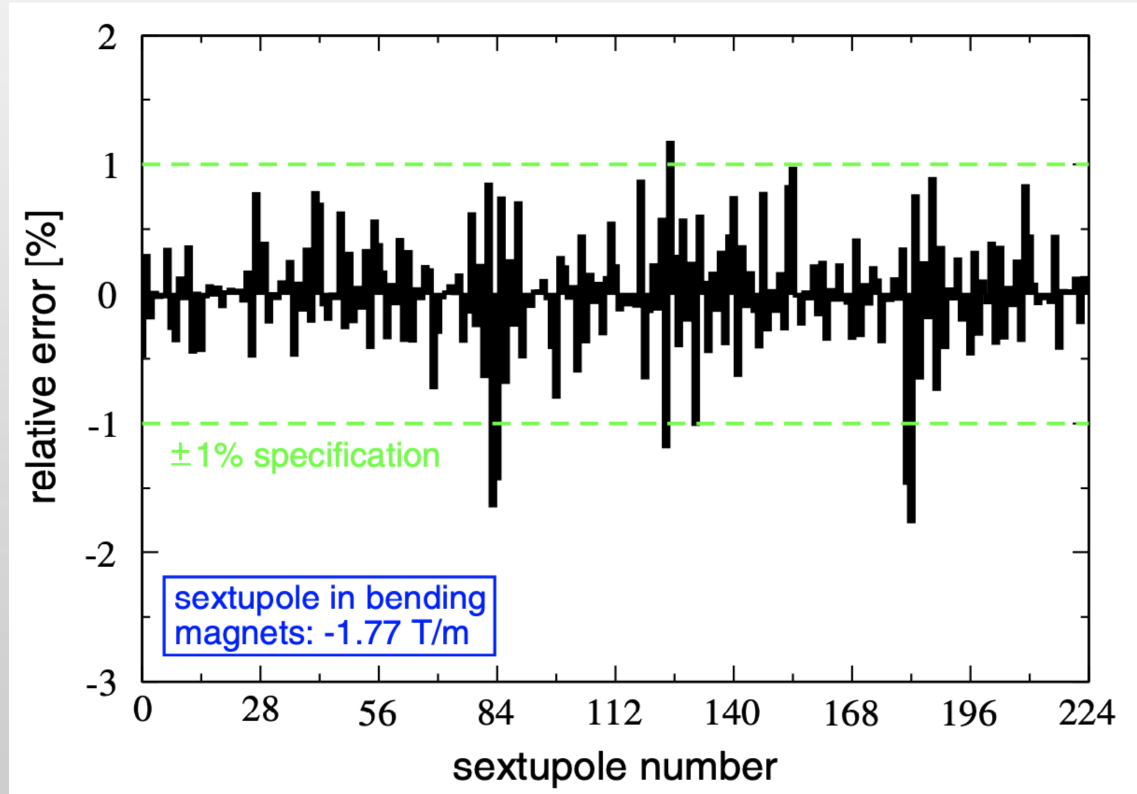
4. Compare & fit measured & model CRDTs



Nonlinear optics & magnet calibration



5. Compute your sextupole error model or calibrate individual magnets



Nonlinear optics & magnet calibration

6. (optionally) correct your sextupole error model & check beam lifetime

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 104002 (2008)

Correction of multiple nonlinear resonances in storage rings

@ Diamond light source

Applying these sextupole strength corrections to the real machine resulted in an increase in lifetime by 10%. This is a clear demonstration, in storage ring light sources, that a deterministic improvement of nonlinear beam dynamics leads to an improvement of the performance of the storage ring.

Nonlinear optics & magnet calibration

A light for Science

Not @ESRF: minor lifetime increase in low-intensity-per-bunch mode, detrimental for Touschek-dominated modes

6. (optionally) correct your sextupole error model & check beam lifetime

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 104002 (2008)

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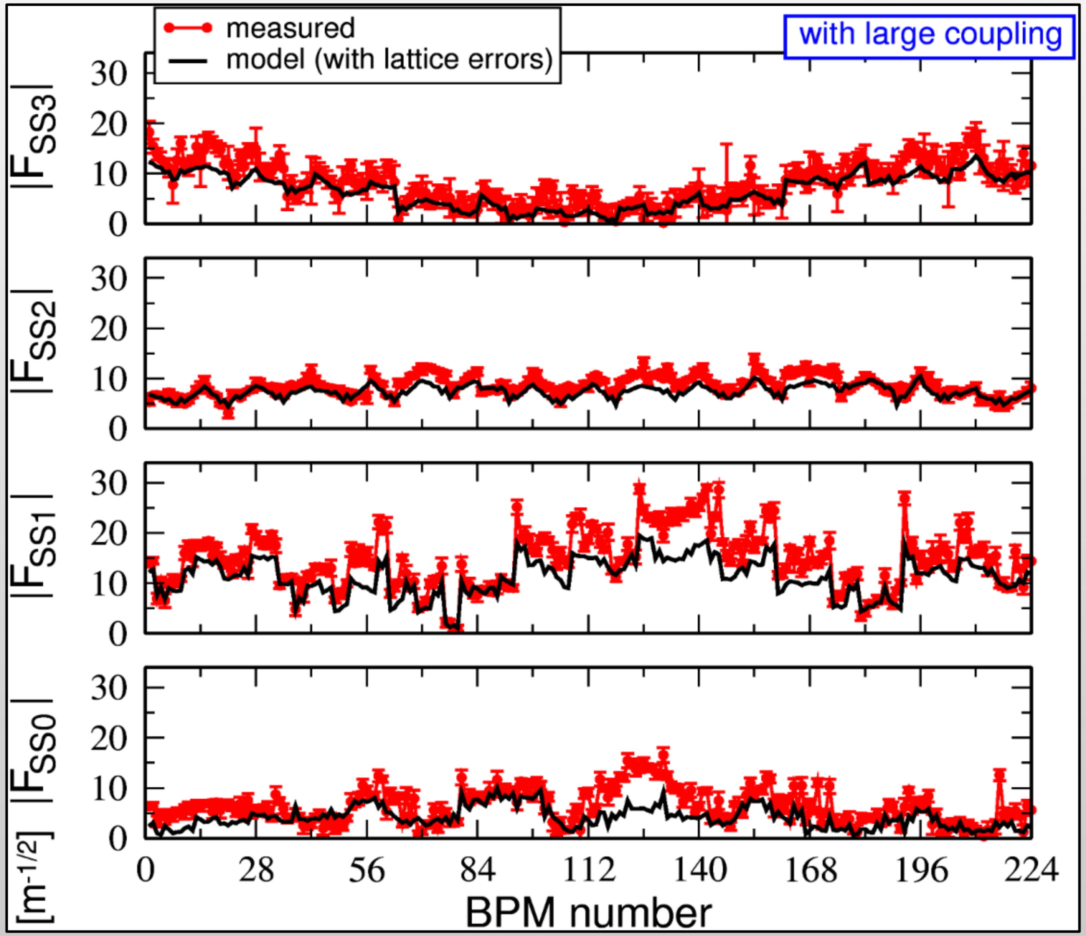
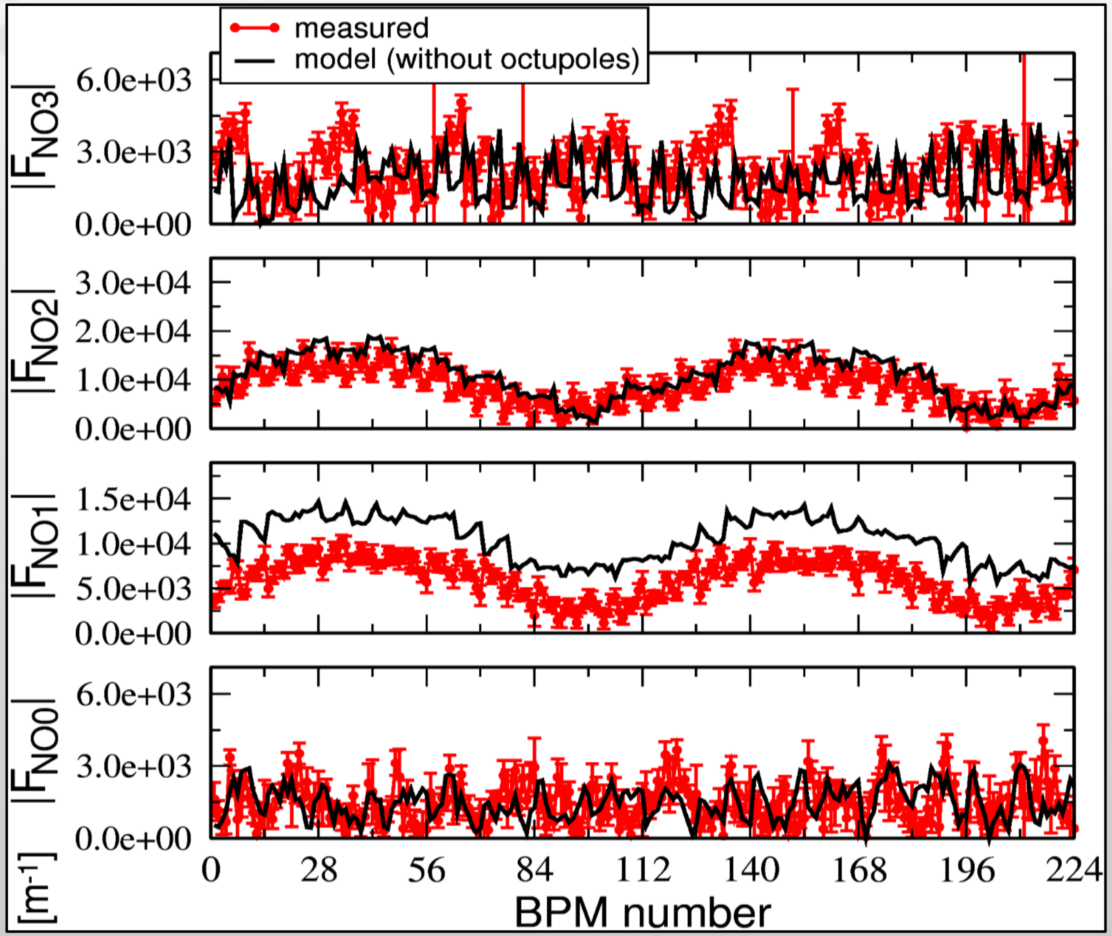
Nonlinear optics & magnet calibration

7. (for fun) measure second-order terms

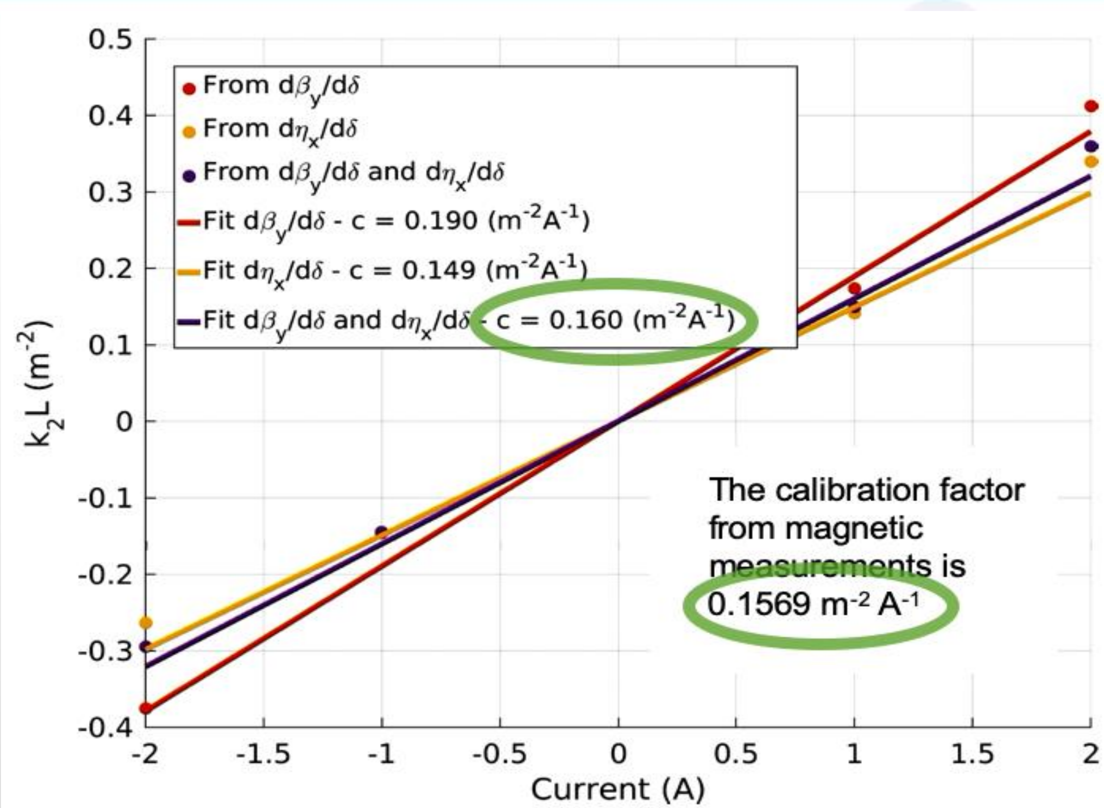
skew sextupole CRDTs



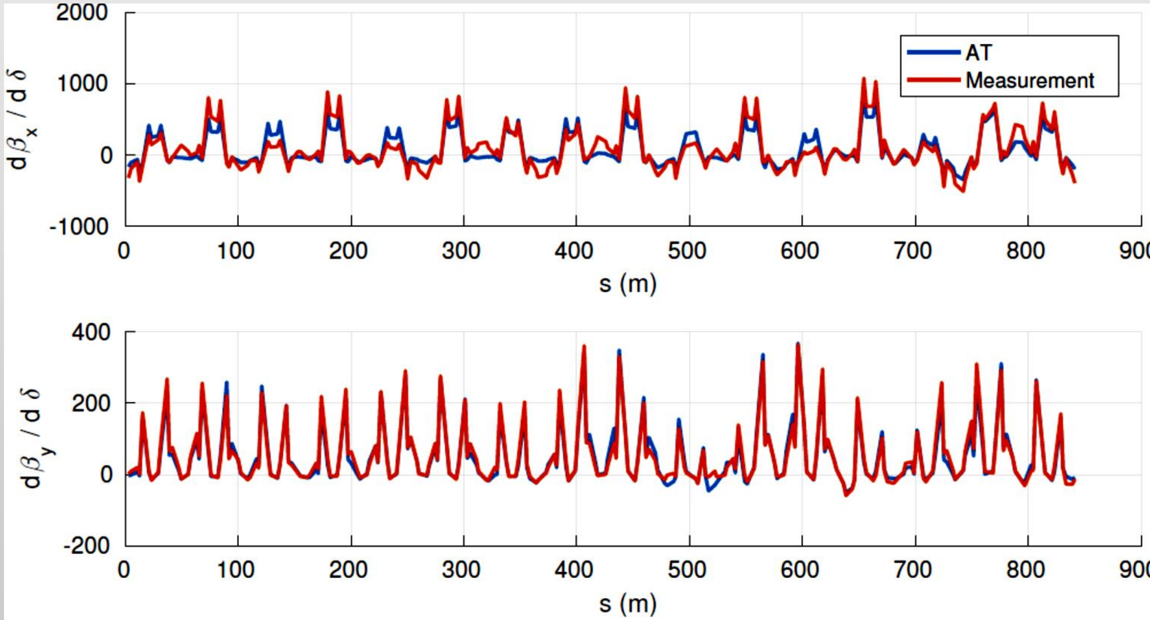
normal octupole CRDTs



Nonlinear optics & magnet calibration



Digression: a similar beam-based sextupole calibration performed via measurement & fit of off-energy ORM (chromatic functions dβ/dδ, D’, Q’)



momentum compaction	α value (10^{-4})
Ideal model	1.7795
Model with errors	1.8316
ID 20	1.76 ±0.14
ID 21	1.87 ± 0.11
hard x-ray camera	1.760 ± 0.003 (*)

collaboration with Laura Torino & Nicola Carmignani

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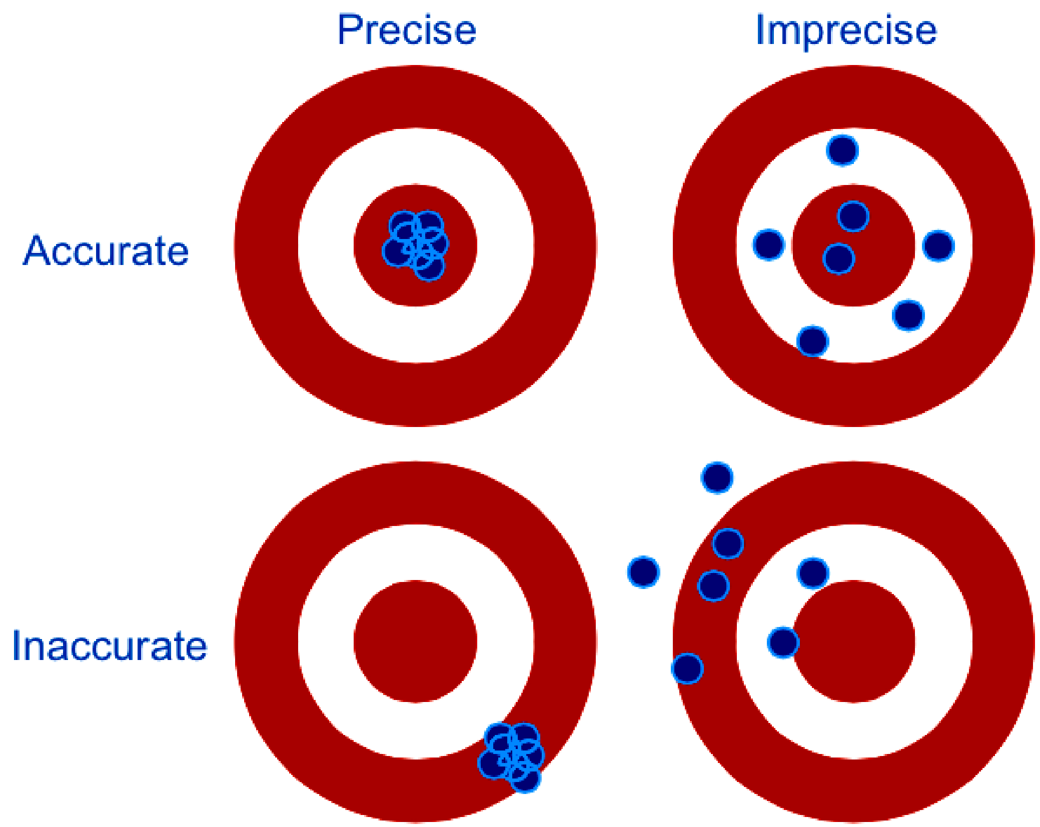
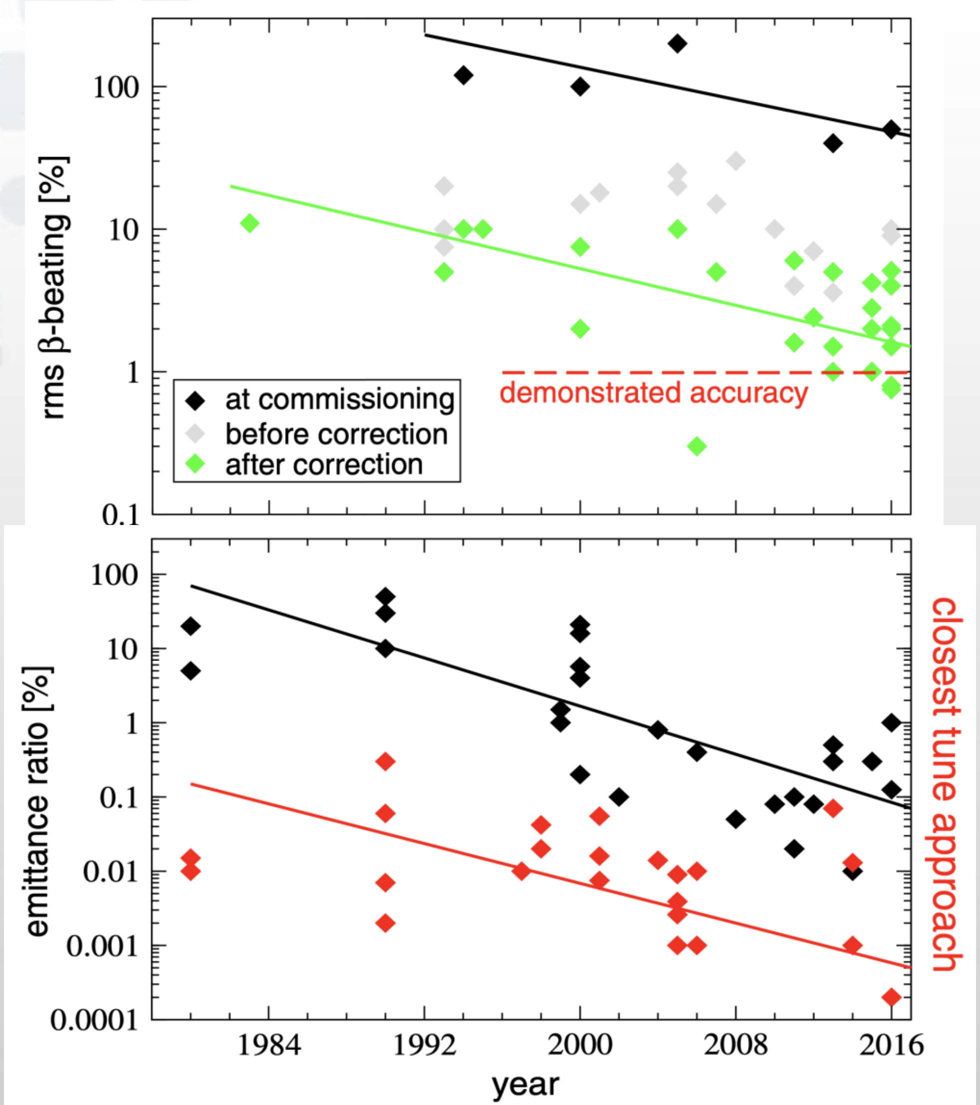
Precision / Accuracy

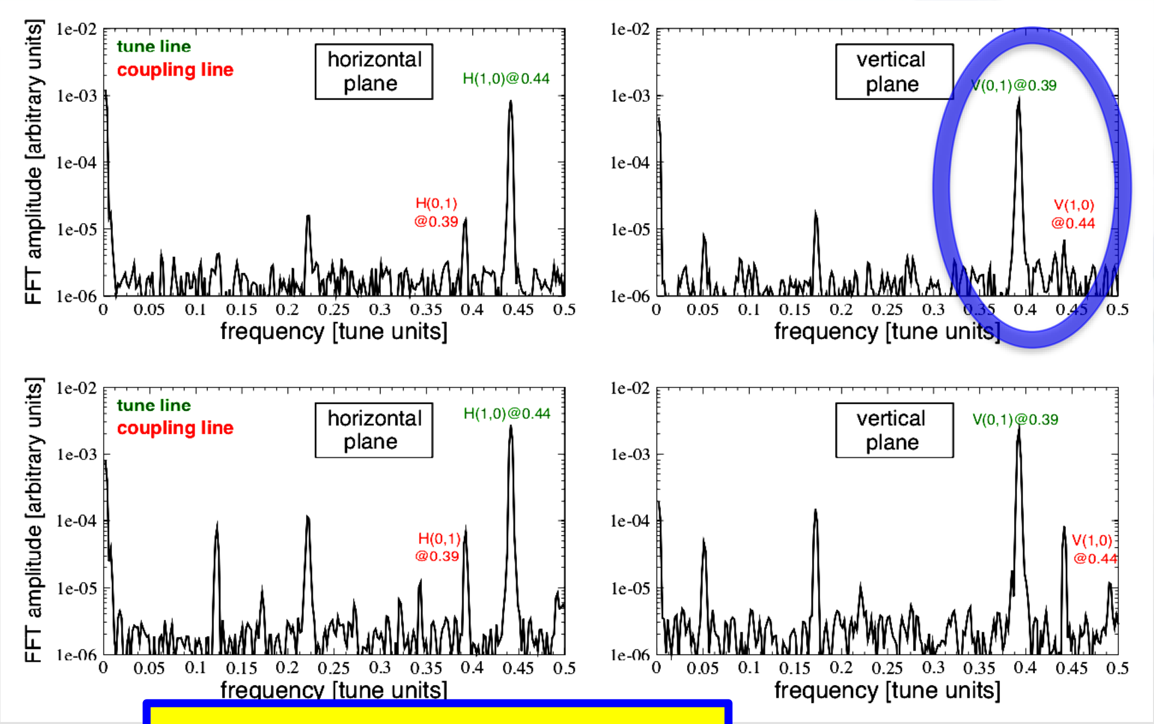


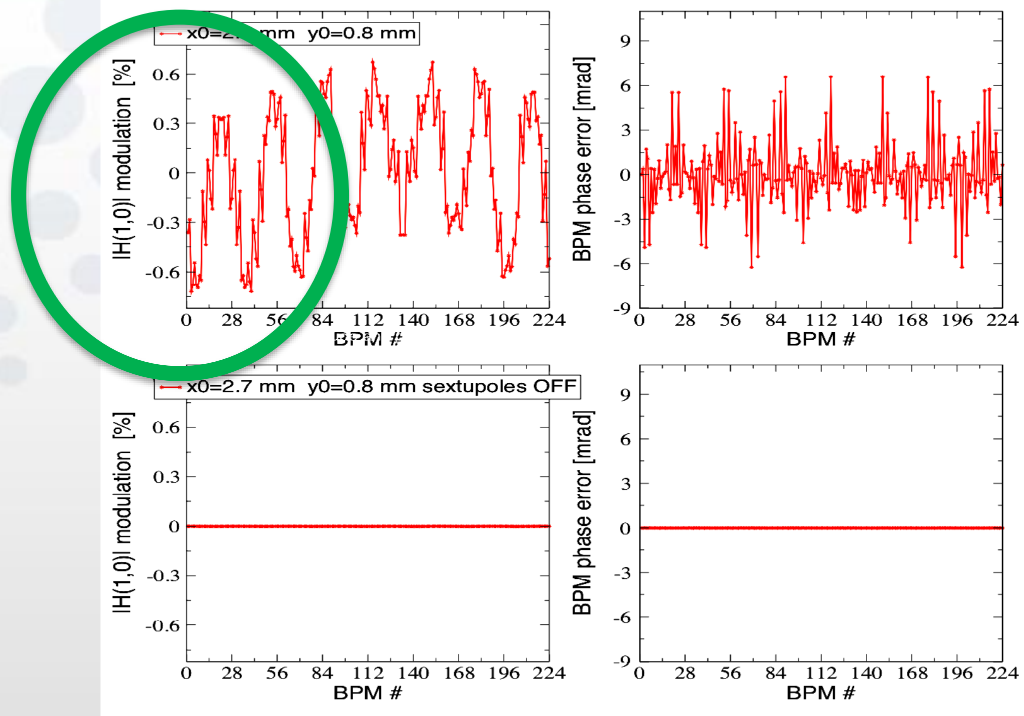


L. Malina et. al. PRAB 20, 082802 (2017)

R. Tomás et. al. PRAB 20, 054801 (2017)

Error analysis of linear optics measurements





low beam excitation incompatible with ultra-low coupling

large beam excitation incompatible with strong chromatic sextupoles

https://arxiv.org/abs/1603.00281

Error analysis of linear optics measurements

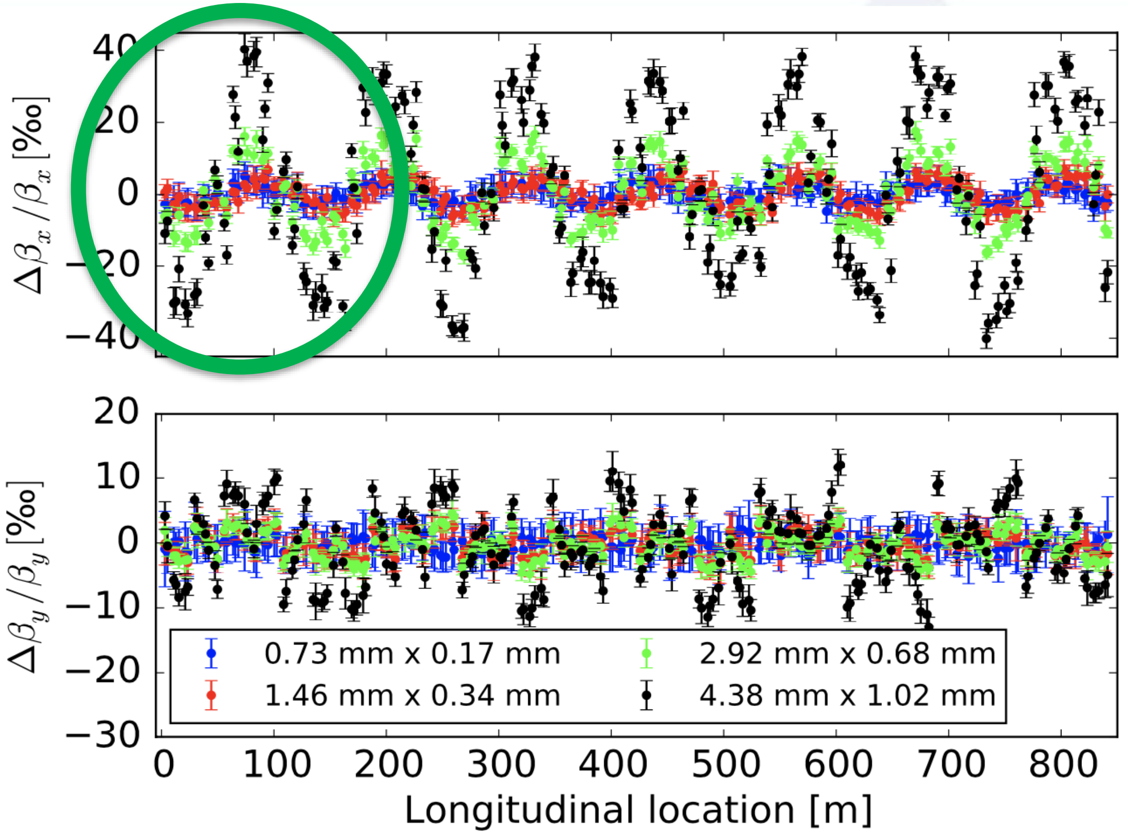
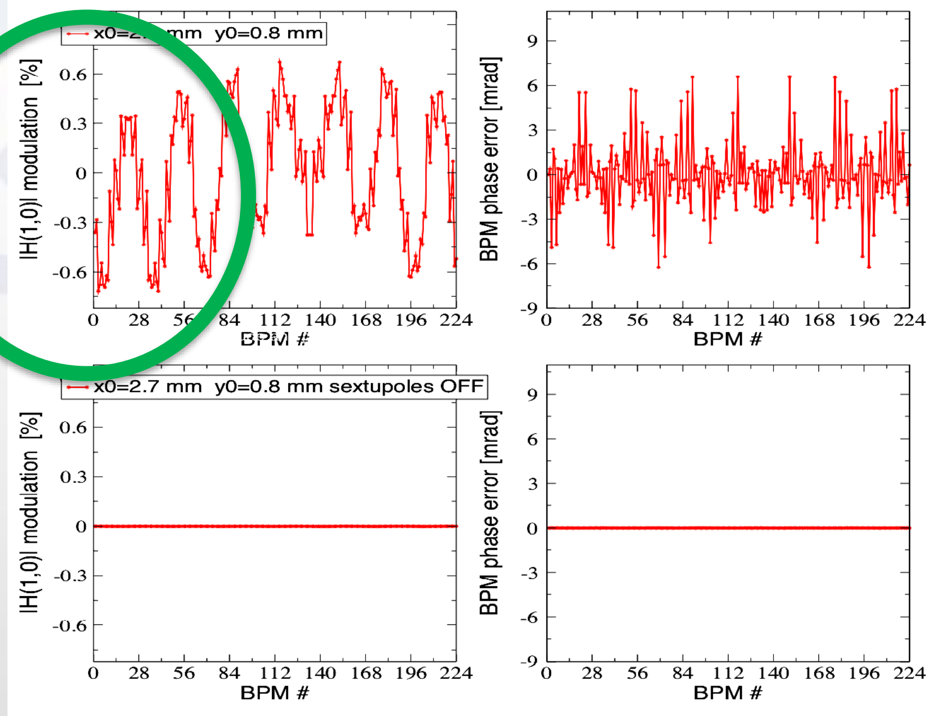


FIG. 4. Simulated artificial β-beating computed by N-BPM from single-particle simulations of the ESRF storage ring lattice



large beam excitation incompatible with strong chromatic sextupoles

L. Malina et. al. PRAB 20, 082802 (2017)

Error analysis of linear optics measurements

	TbT & tune ampli	TbT & tune phase	orbit & ORM
BPM calibration			
BPM synchro.			
Nonlinear. & chroma			
time consuming			DC / AC
model dependent			

measured β-functions
best precision TbT: 0.4%
best precision ORM: 0.5%
best accuracy ORM-TbT: ~1%

L. Malina et. al. PRAB 20, 082802 (2017)

Error analysis of linear optics measurements

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Error analysis of linear optics measurements

$$\beta_1^{(meas)} = \beta_1^{(mod)} \frac{\cot \Delta\phi_{12}^{(meas)} - \cot \Delta\phi_{13}^{(meas)}}{\cot \Delta\phi_{12}^{(mod)} - \cot \Delta\phi_{13}^{(mod)}} + O(\delta K_1)$$

Castro's formula (no error δk_1 between BPMs, model needed)

	TbT & tune ampli	TbT & tune phase	orbit & ORM
time consuming			DC / AC
model dependent			

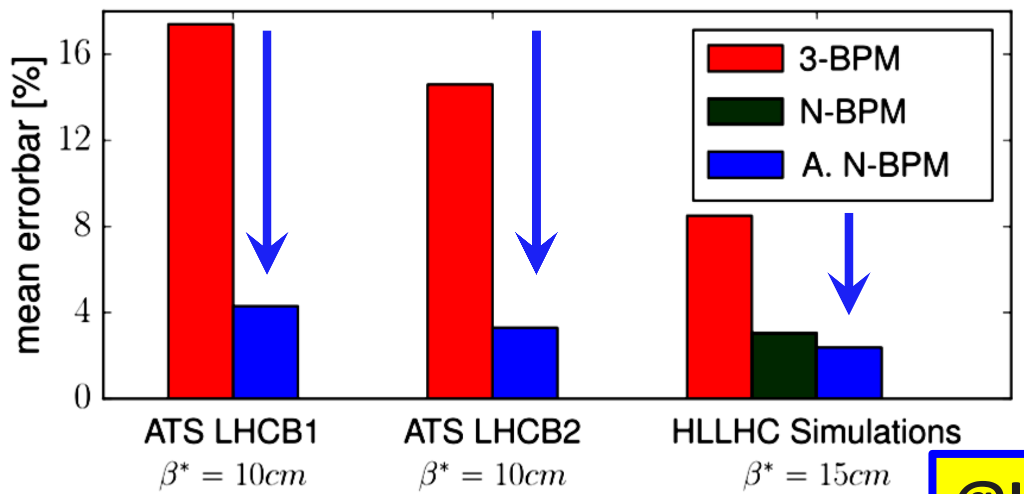
TbT & tune ampli	TbT & tune phase	orbit & ORM

$$\beta_1^{(meas)} = \beta_1^{(mod)} \frac{\cot \Delta\phi_{12}^{(meas)} - \cot \Delta\phi_{13}^{(meas)}}{\cot \Delta\phi_{12}^{(mod)} - \cot \Delta\phi_{13}^{(mod)} + (\bar{h}_{12} - \bar{h}_{13})} + O(\delta K_1^2)$$

New formula (with error δk_1 between BPMs, model needed)

DC

AC



@LHC

A. Wegscheider et. al. PRAB 20, 111002 (2017)

$$\bar{h}_{ij} = \mp \frac{\sum_{i<w<j} \beta_w^{(mod)} \delta K_{w,1} \sin^2 \Delta\phi_{wj}^{(mod)}}{\sin^2 \Delta\phi_{ij}^{(mod)}}$$

Error analysis of linear optics measurements

	TbT & tune ampli	TbT & tune phase	orbit & ORM
BPM calibration			
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Nonlinear. & chroma			
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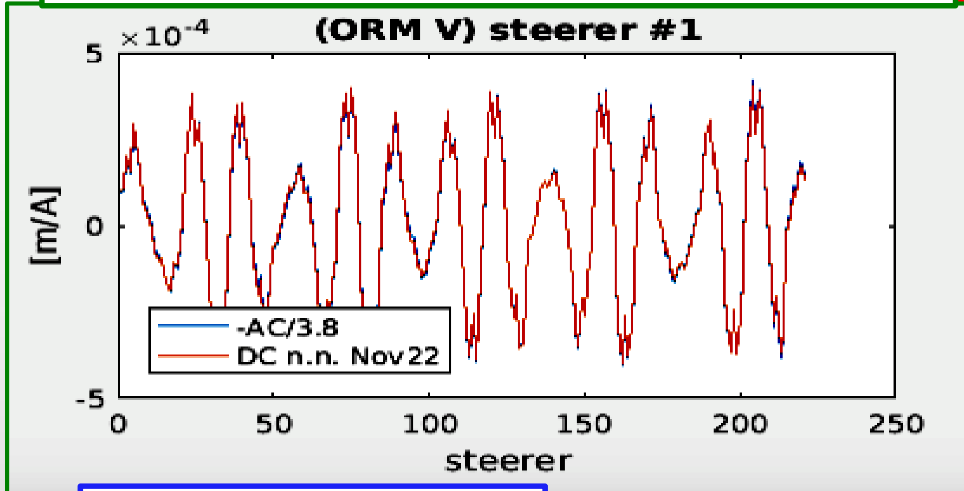
Applications of AC Orbit data

TbT & tune ampli | TbT & tune phase | orbit & ORM

ESRF ORM column: AC Vs DC



measurement

analysis

$$\begin{pmatrix}\delta\vec{O}^{(xx)}\\ \delta\vec{O}^{(yy)}\\ \delta\vec{D}_x\end{pmatrix} = \mathbf{N}\begin{pmatrix}\delta\vec{K}_1\\ \delta\vec{K}_0\end{pmatrix}$$

$$\begin{pmatrix}\delta\vec{O}^{(xy)}\\ \delta\vec{O}^{(yx)}\\ \delta\vec{D}_y\end{pmatrix} = \mathbf{S}\begin{pmatrix}\vec{J}_1\\ \vec{J}_0\end{pmatrix}.$$

DC

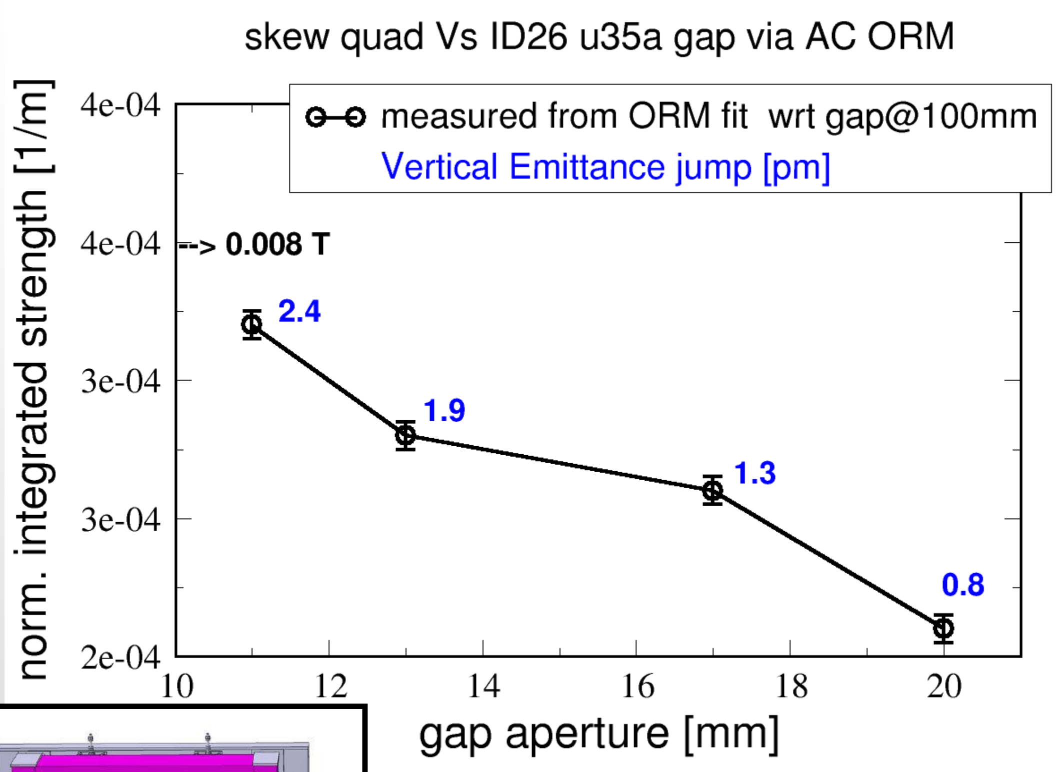
AC

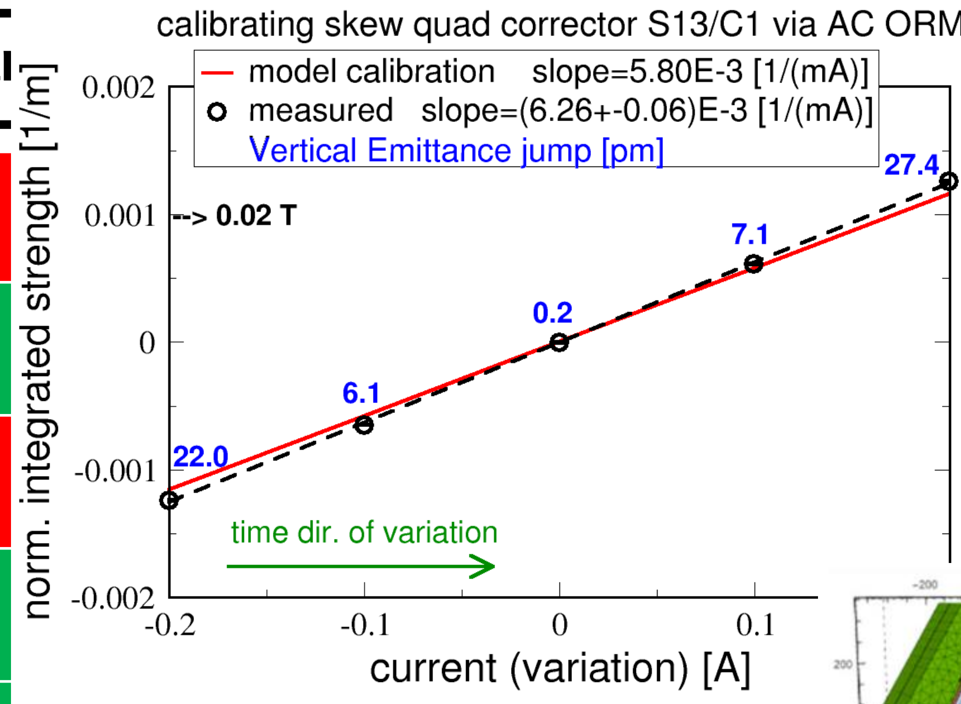
Orbit response matrix (ORM) @ESRF:
~1 h (DC steerer excitation + numerical response*)
~3’ (AC steerer excitation + analytical response*)

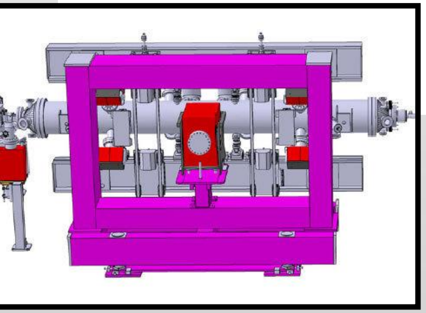
* response : **N** & **S** (large matrices)
(AC excitation pioneered @Diamond)

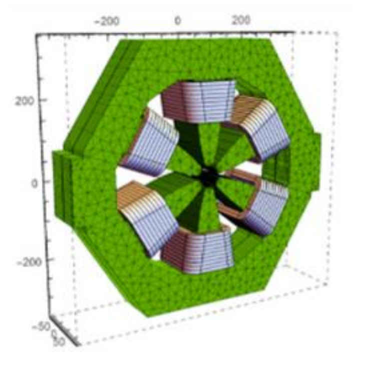
http://arxiv.org/abs/1711.06589

Applications of AC Orbit data









beam-based measurement of skew-quadrupole fields induced by undulators & skew quad correctors

Orbit response matrix (ORM) @ESRF:
~1 h (DC steerer excitation)
~3’ (AC steerer excitation)

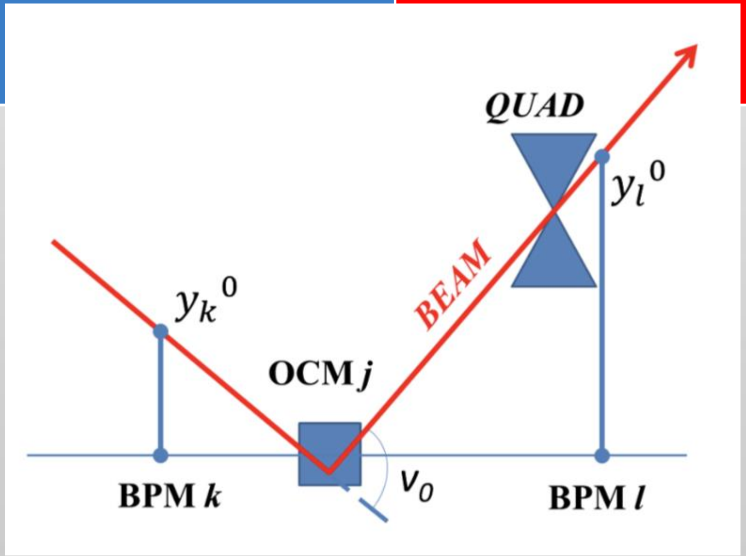
Applications of AC Orbit data

Digression: fast AC beam-based quadrupole alignment derived & applied to ALBA light source (120 quadrupoles):

- serial DC steerer excitation: 5h, precision ~50 μm
- parallel AC steerer excitation: 10', precision ~15 μm

applied to sextupoles too.

			orbit & ORM
			DC / AC
model dependent			



Z. Marti e. al. PRAB 23, 012802 (2019)

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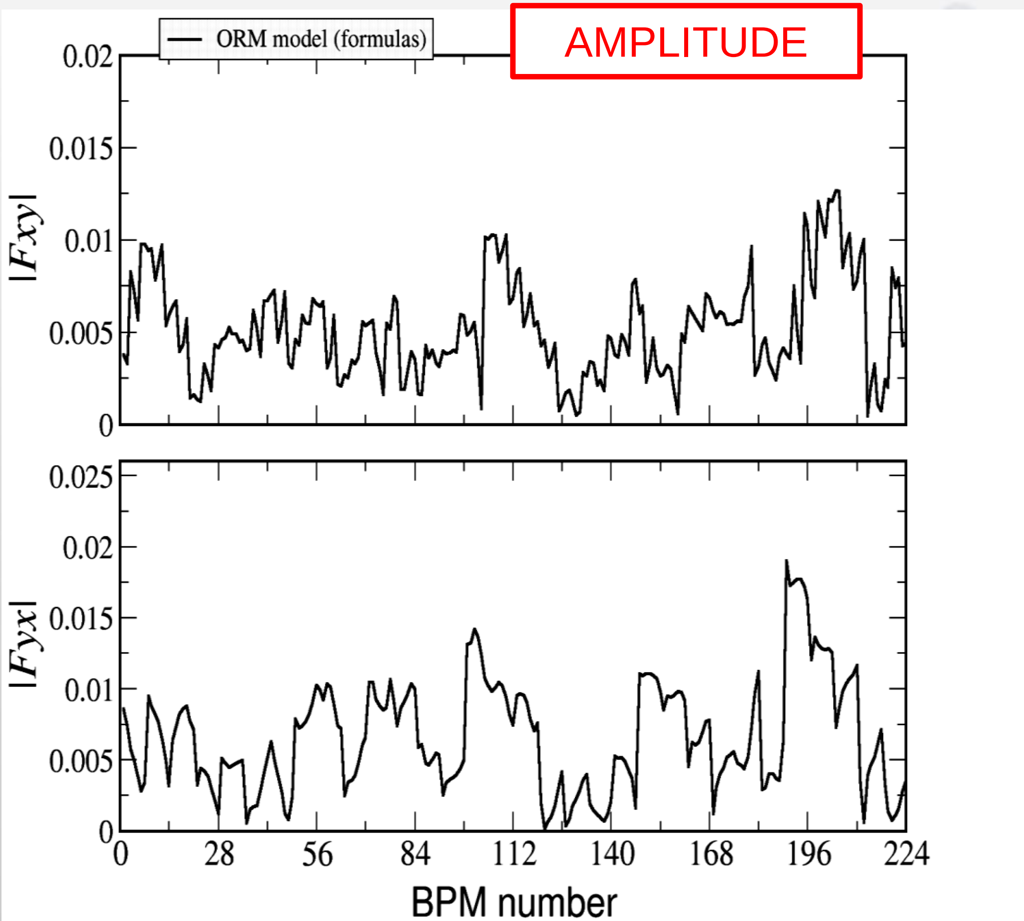
Experience of AC dipole & TbT BPM data

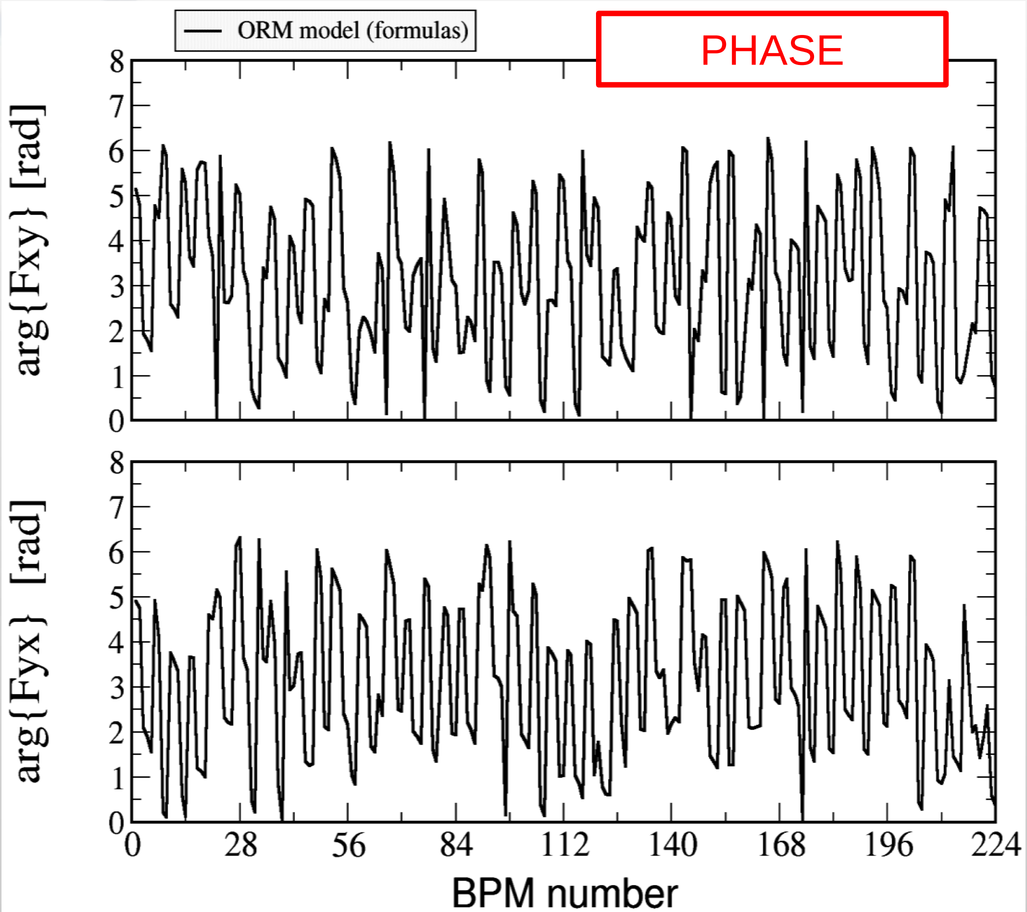
Betatron coupling described by two CRDTs

$$Fxy = (f_{1001} - f_{1010}^{*}) \;\&\; Fyx = (f_{1001}^{*} - f_{1010}^{*})$$

Measurement with **low chroma (0,0) & detuning sext. optics**

compare ($\varepsilon_y/\varepsilon_x$~1‰) ORM model ...





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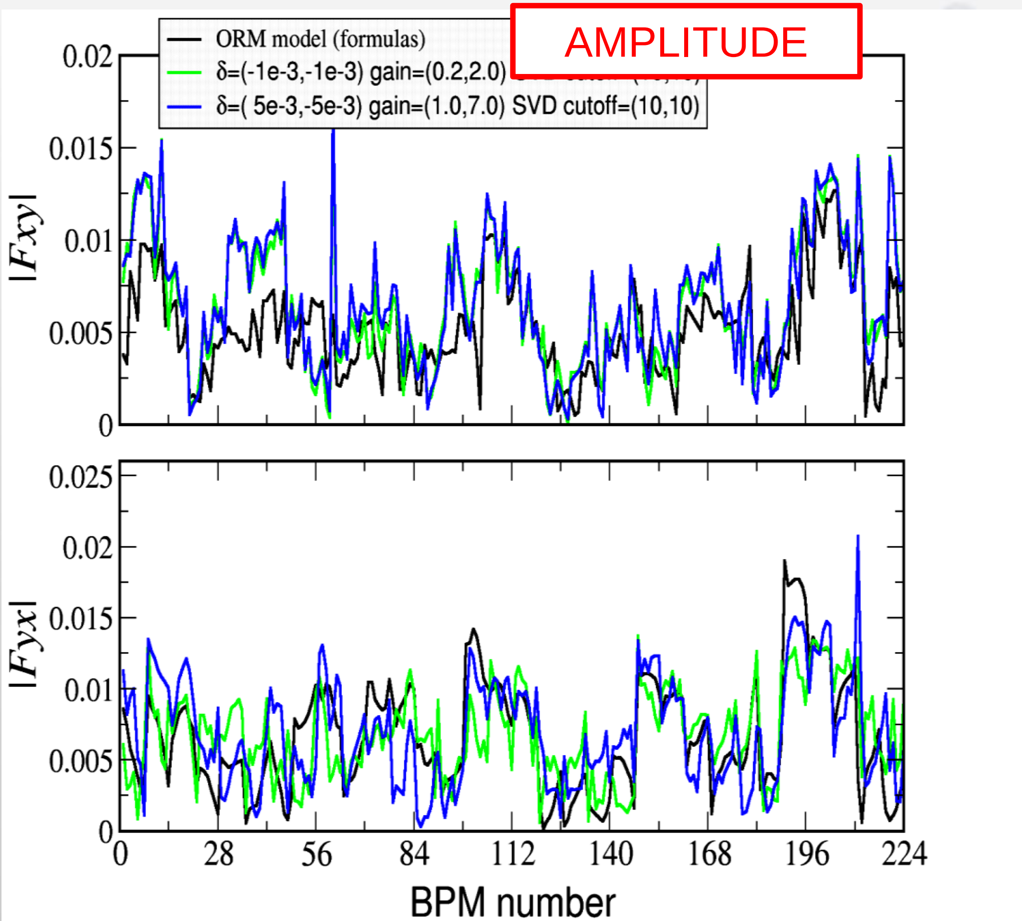
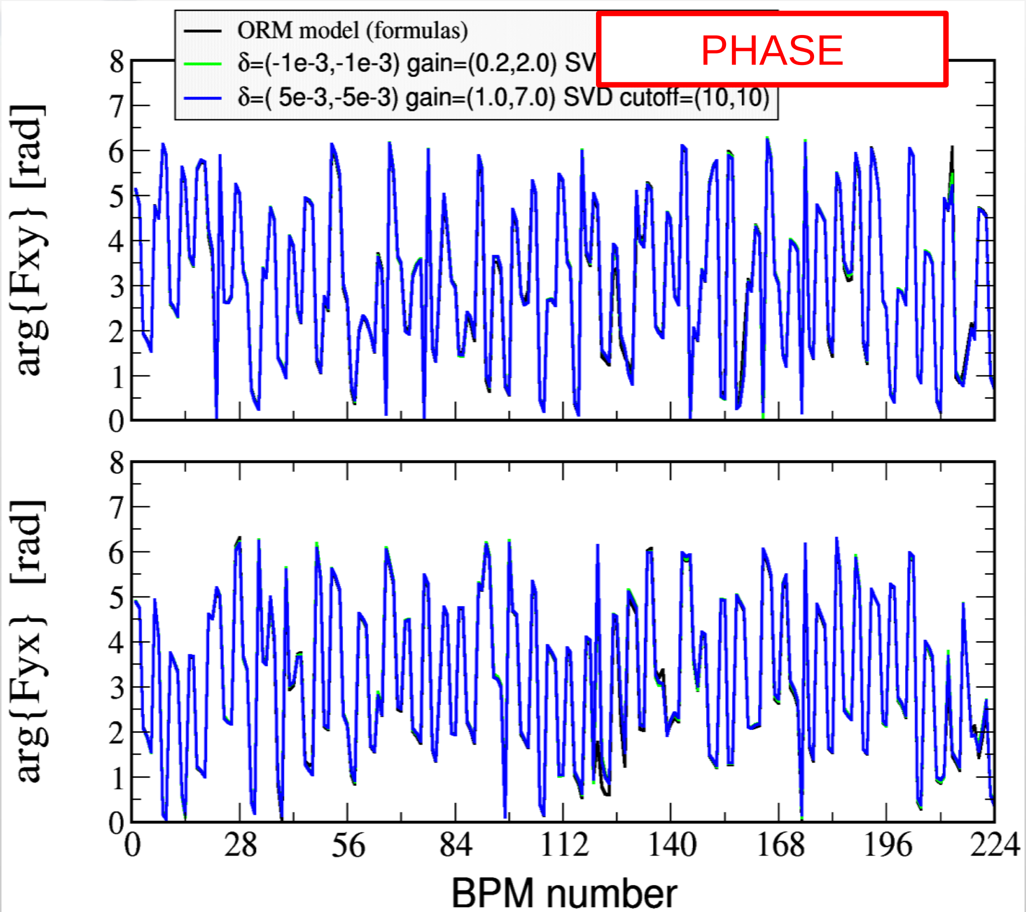
compare ($\varepsilon_y/\varepsilon_x$~1‰) ORM model with TbT harmonic analysis



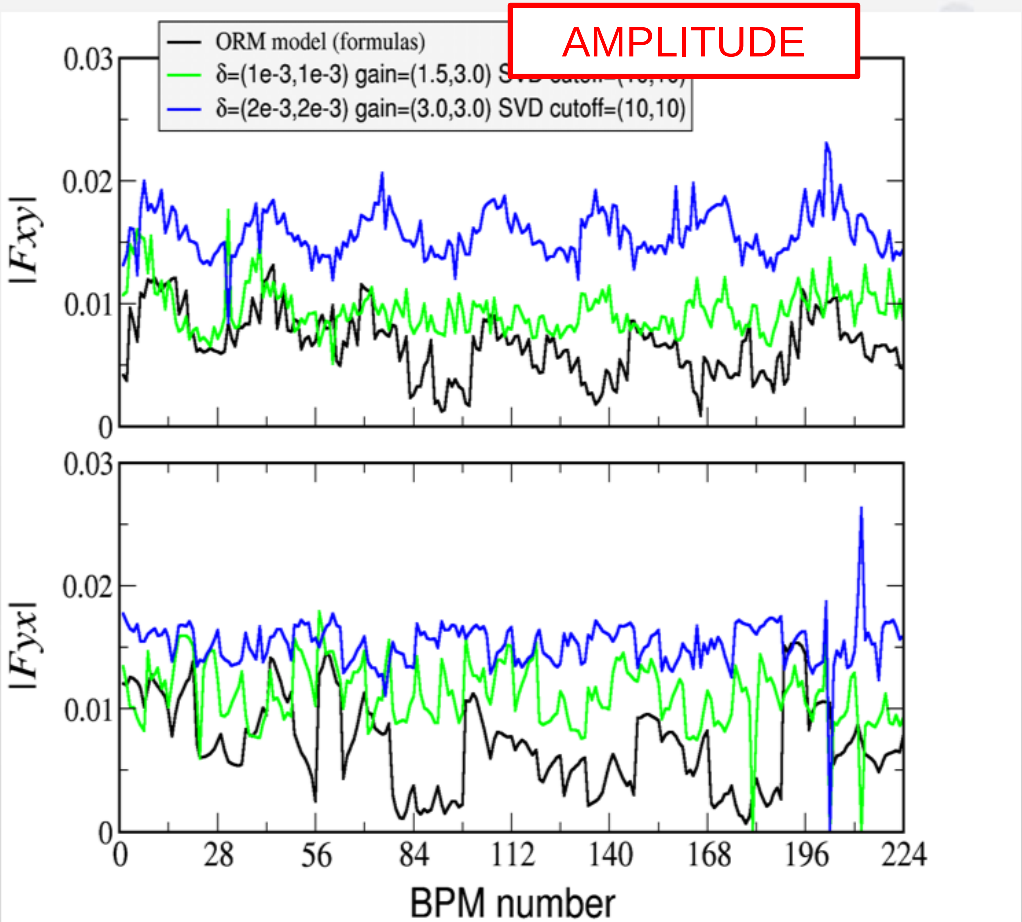


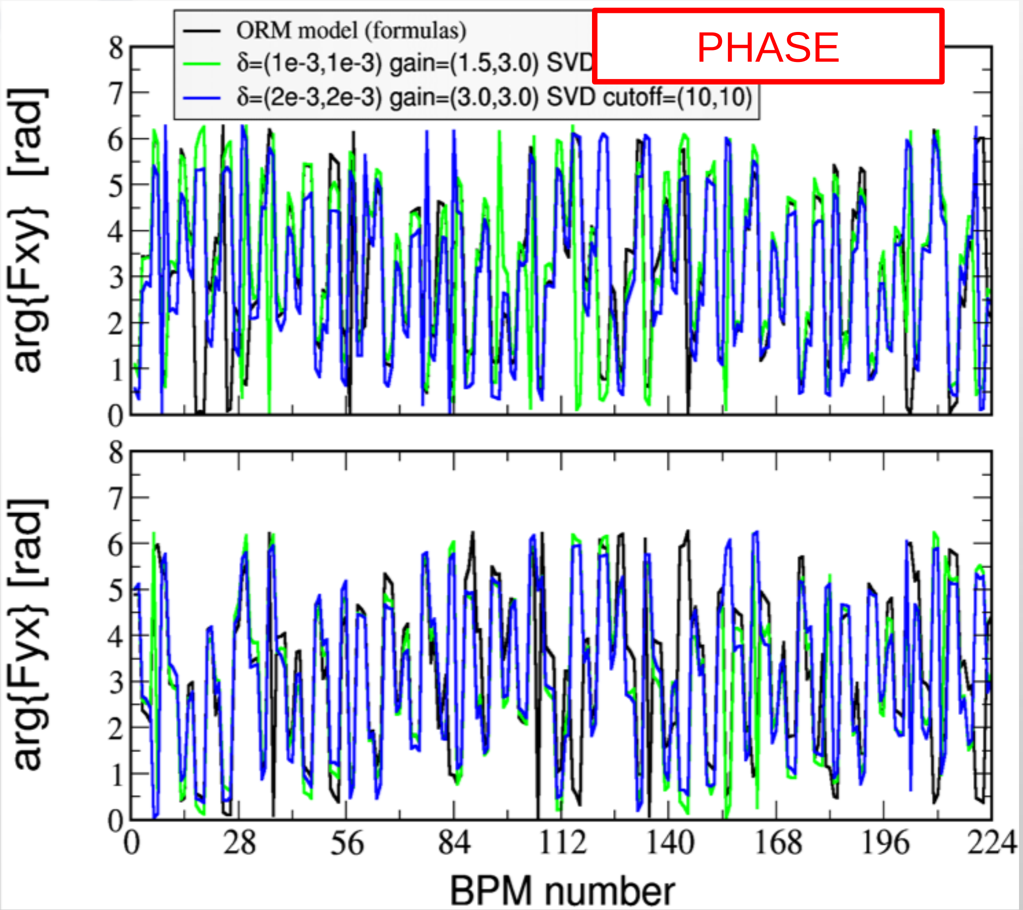
Betatron coupling described by two CRDTs

$$Fxy = (f_{1001} - f_{1010}^{*}) \ \& \ Fyx = (f_{1001}^{*} - f_{1010}^{*})$$

Measurement with **large chroma (8,13) operational optics**

compare ($\varepsilon_y/\varepsilon_x$~1‰) ORM model with TbT harmonic analysis

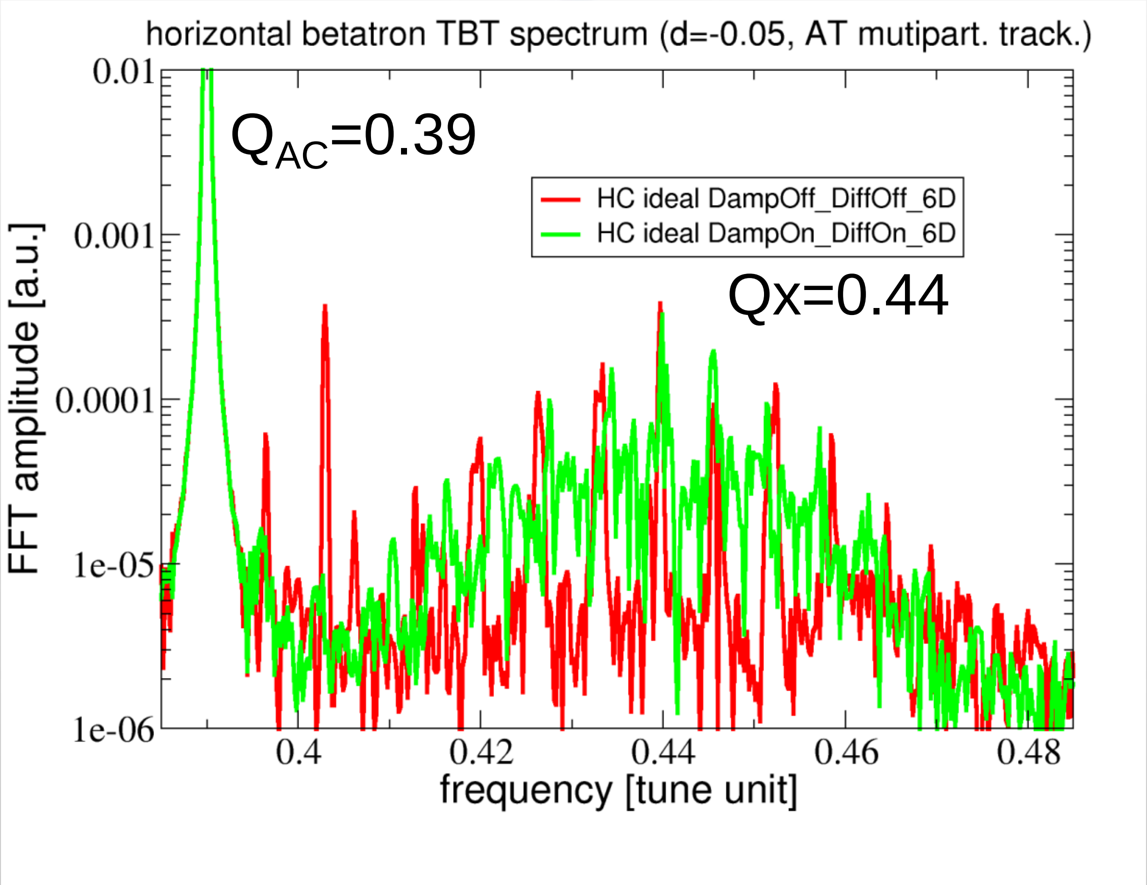


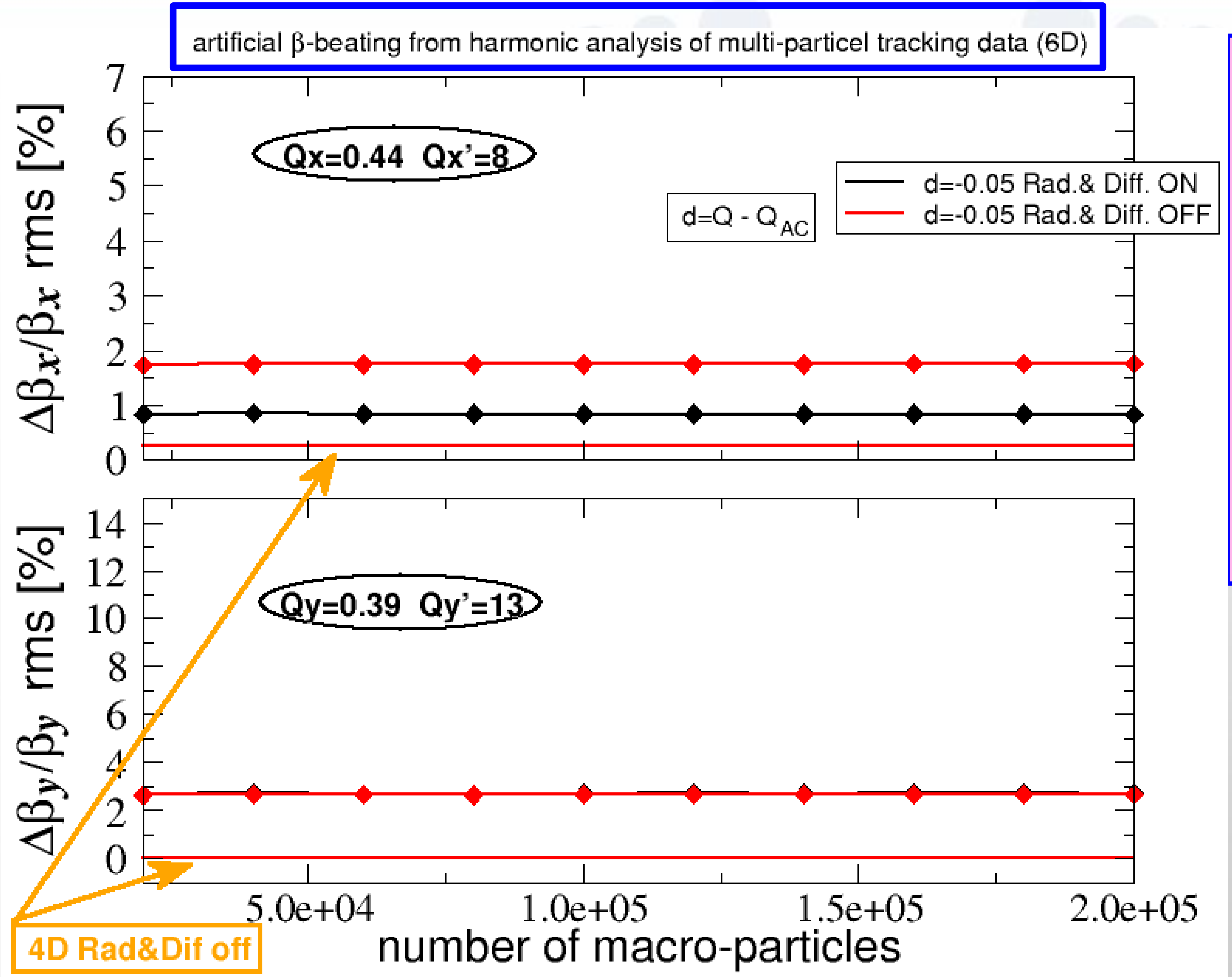


Experience of AC dipole & TbT BPM data

1st experimental observation: AC dipole tuning tedious with high chromaticity: beam lost with setting used for low-chroma optics.

High (8,13) chroma sextupole optics:
RAD OFF & ON (multi-particle simulations)





2nd experimental & numerical observation:

synchrotron radiation + diffusion & high chroma => limited accuracy.

AC dipole & data cleaning OK for low-chroma lepton rings.

Outlines

- Understanding & correcting linear coupling (2009-2010)
- Nonlinear optics & magnet calibration via turn-by-turn (TbT) BPM data (2010-2013)
- Error analysis of linear optics measurements via orbit & TbT analysis (2016-2017)
- Applications of AC Orbit data (2016-2019)
- Experience of AC dipole & TbT BPM data (2016-2018)

Thank you for your attention