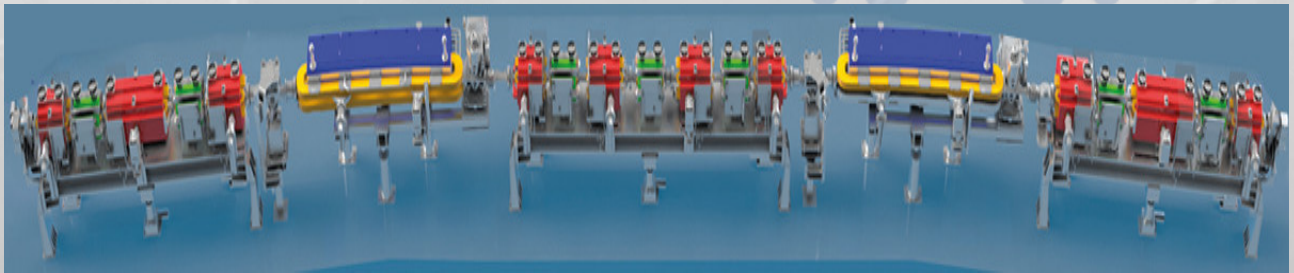
Characterizing the magnetic lattice of circular accelerators via beam position data (orbit Vs turn-by-turn)



Andrea Franchi

Thanks to: N. Carmignani, M. Dubrulle, F. Epaud, F. Ewald, L. Farvacque, G. Le Bec, S. Liuzzo, K. B. Scheidt , F. Taoutaou, operation@esrf, optics@cern (L. Malina, T. Persson, P. Skowronski, R. Tomas)

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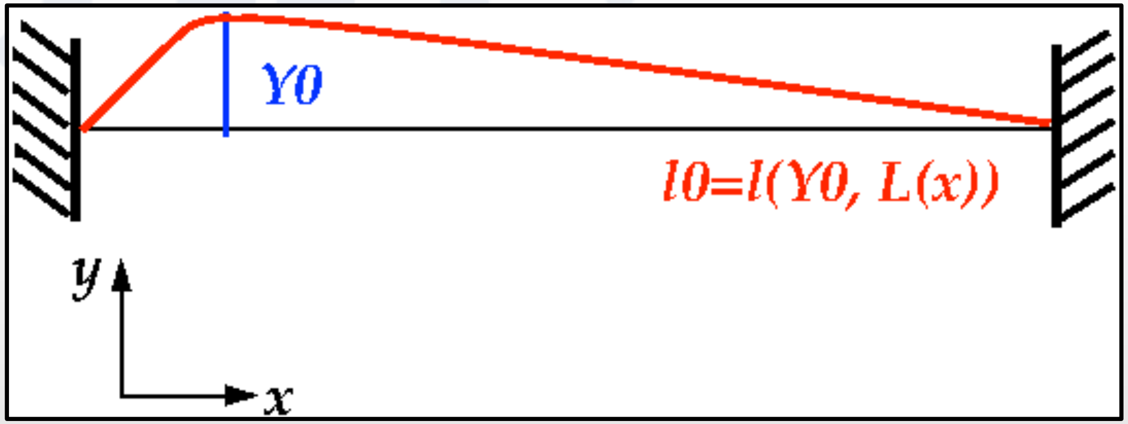
How do we characterize guitar strings?



method 1: geometric (static) approach

1. stretch and hold a string at a given position *Y0*

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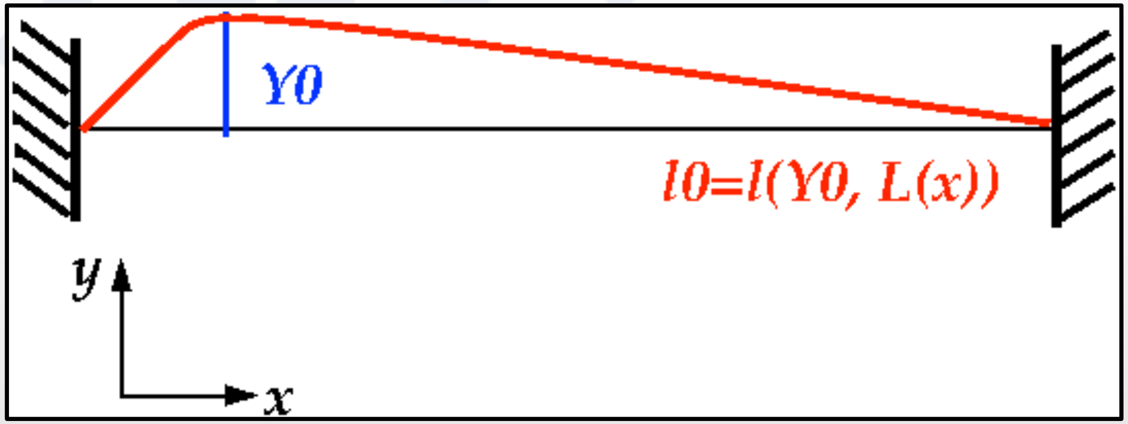

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2. measure the string distortion *l0*

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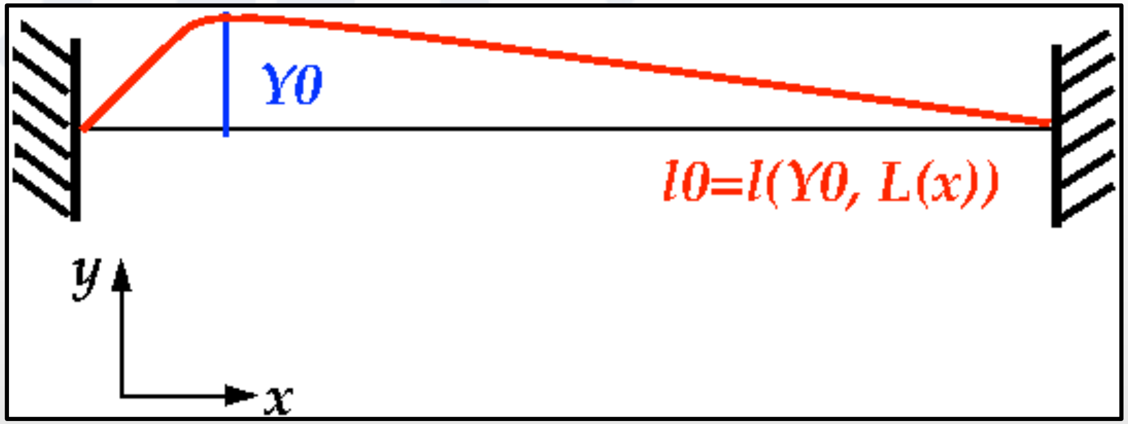

method 1: geometric (static) approach

1. stretch and hold a string at a given position *Y0*
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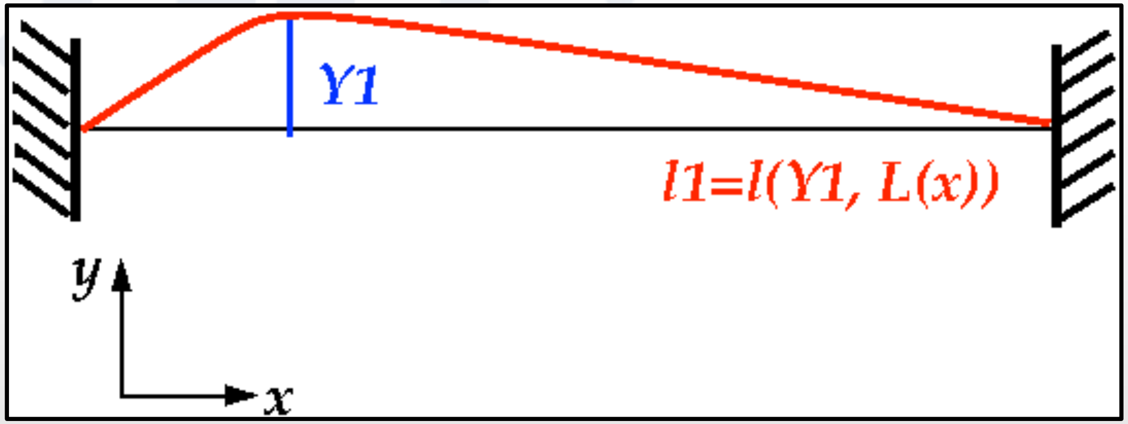
How do we characterize guitar strings?



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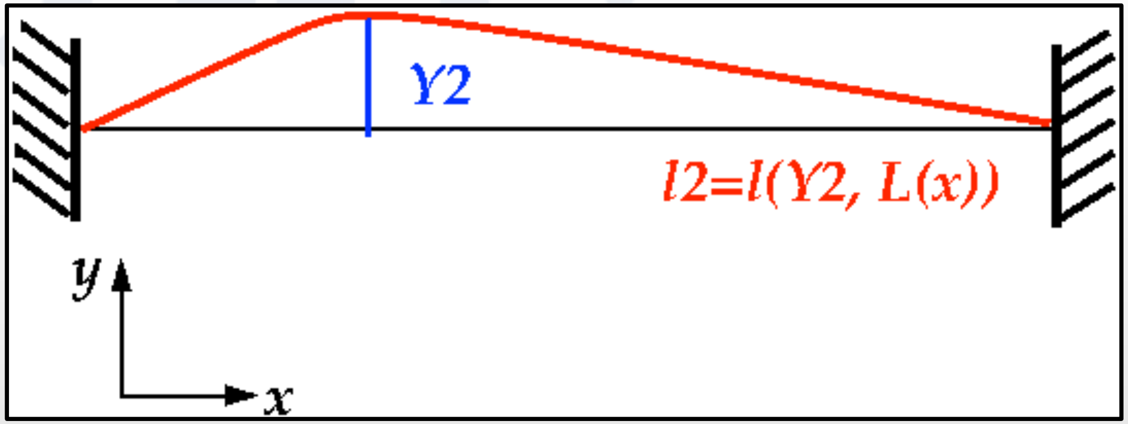

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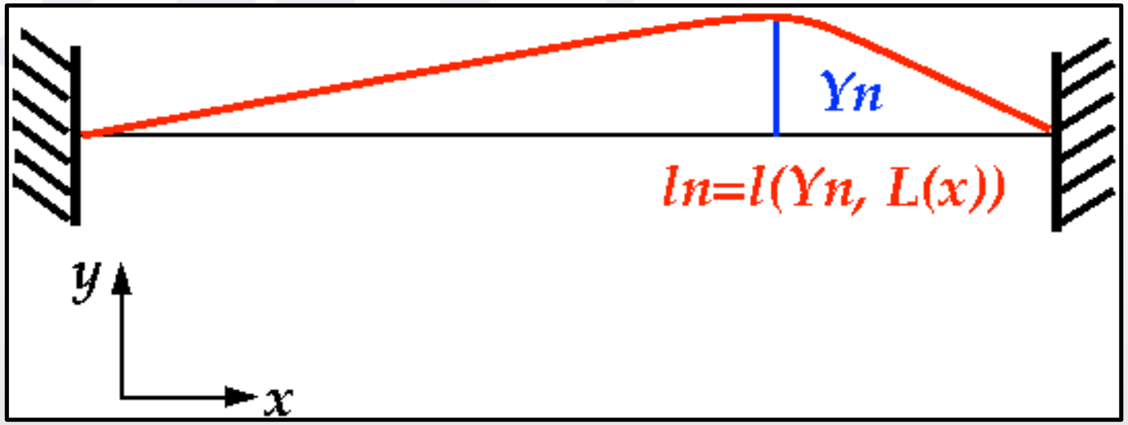

method 1: geometric (static) approach

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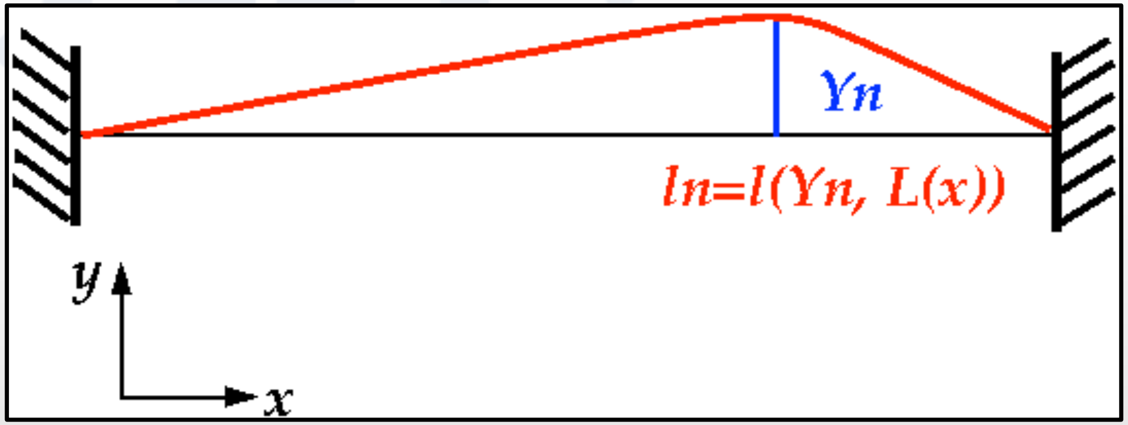
3. repeat the measurement at different *Y1, Y2, …, Yn*

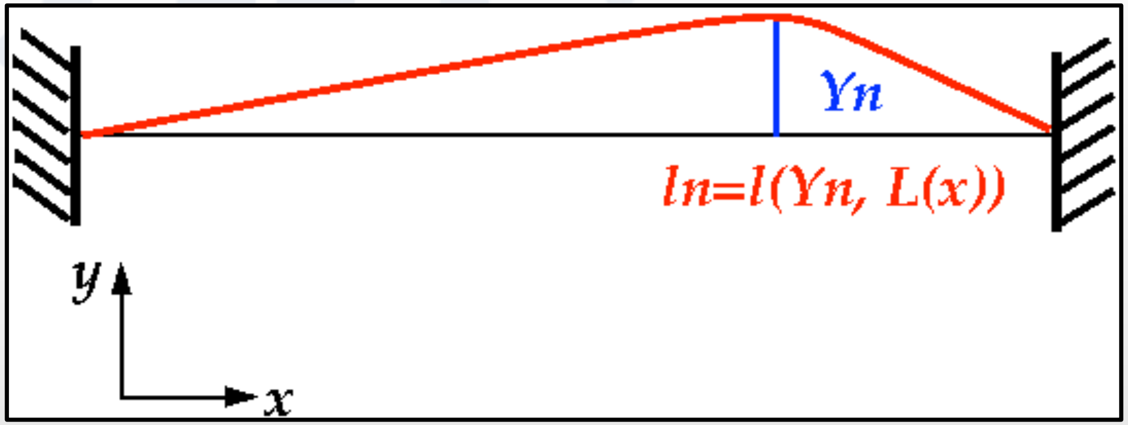
How do we characterize guitar strings?



method 1: geometric (static) approach

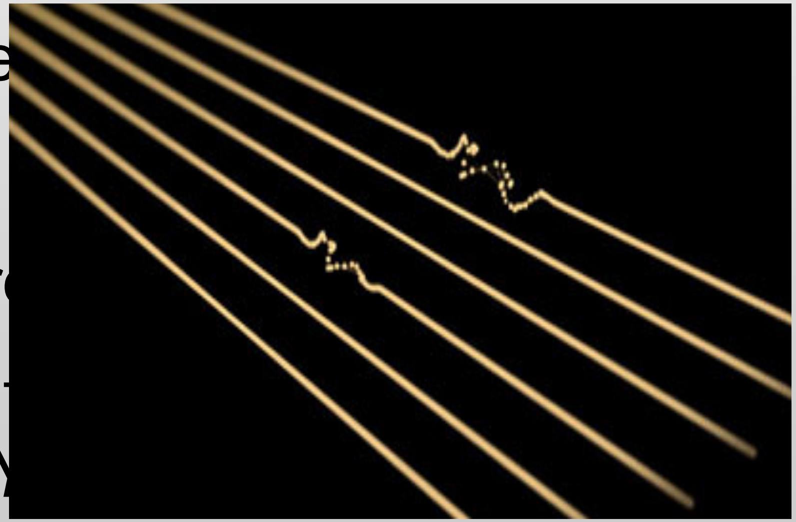
1. stretch and hold a string at a given position *Y0*
2. measure the string distortion *l0*
3. repeat the measurement at different *Y1, Y2, …, Yn*
4. The linear density L(x) may be inferred from the distortion response vector (d*l1*/d*Y1*,d*l2*/d*Y2*,…, d*ln*/d*Yn*)

How do we characterize guitar strings?



method 1: geometric (static) approach

Any deviation of dL(x)/dY from the expected ideal density is due to string imperfections and/or damages which can be localized and diagnosed



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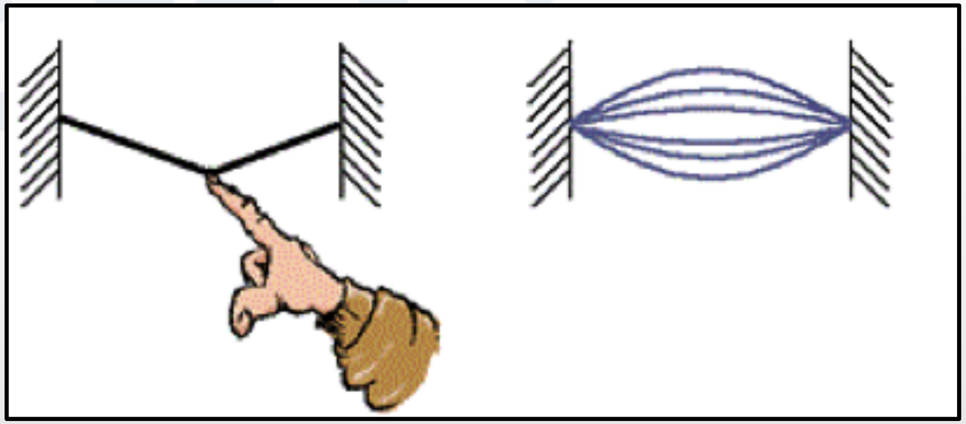
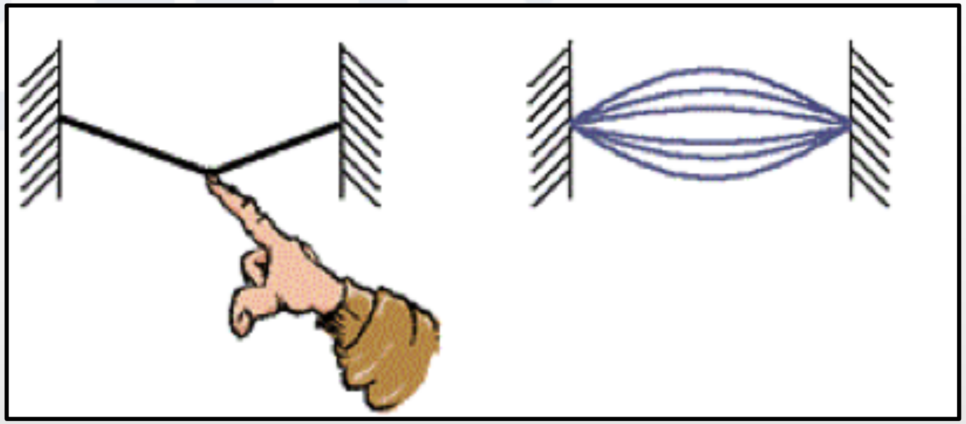


method 2: harmonic (dynamic) approach

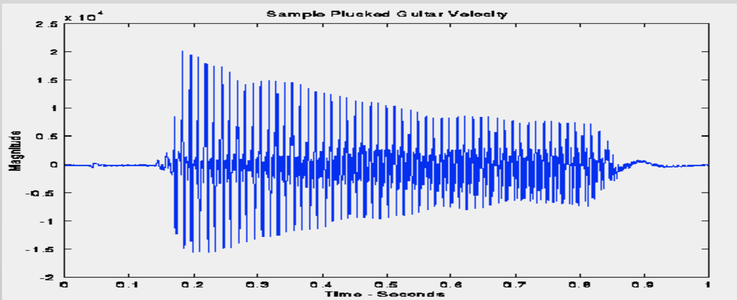
1. pinch a string, let it vibrate freely

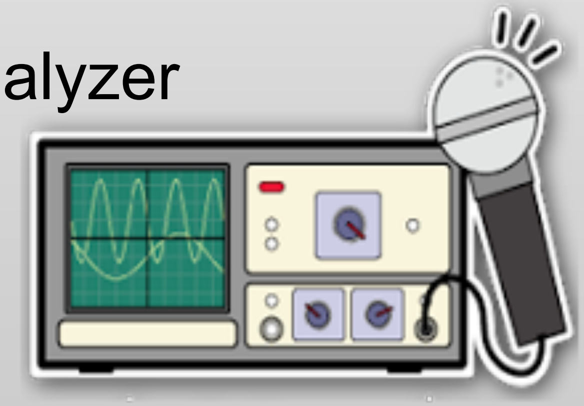
How do we characterize guitar strings?



method 2: harmonic (dynamic) approach

1. pinch a string, let it vibrate freely
2. record its sound into a spectrum analyzer





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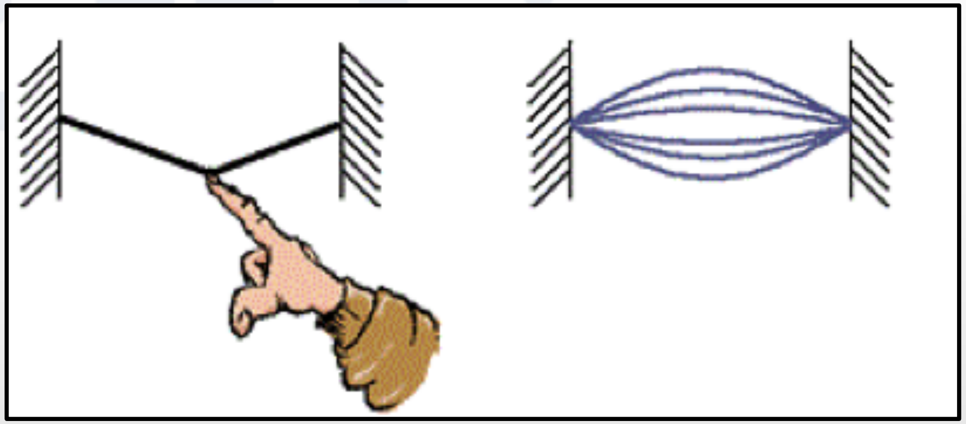
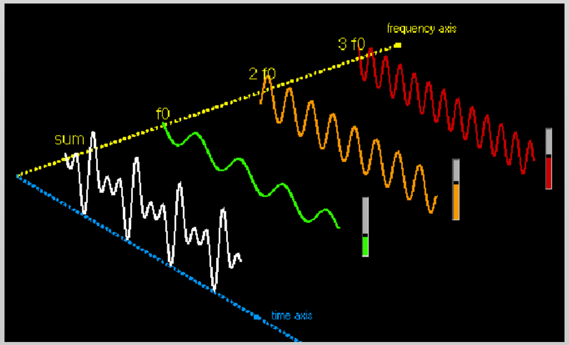
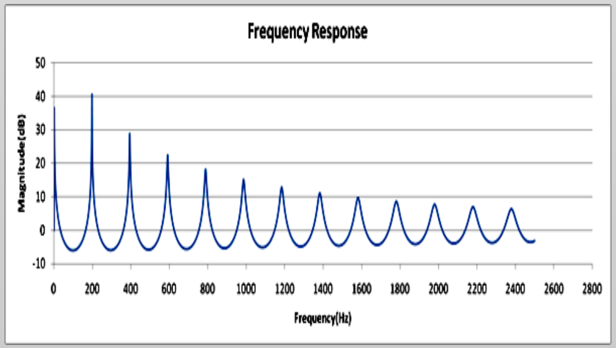


method 2: harmonic (dynamic) approach

1. pinch a string, let it vibrate freely
2. record its sound into a spectrum analyzer
3. perform an FFT





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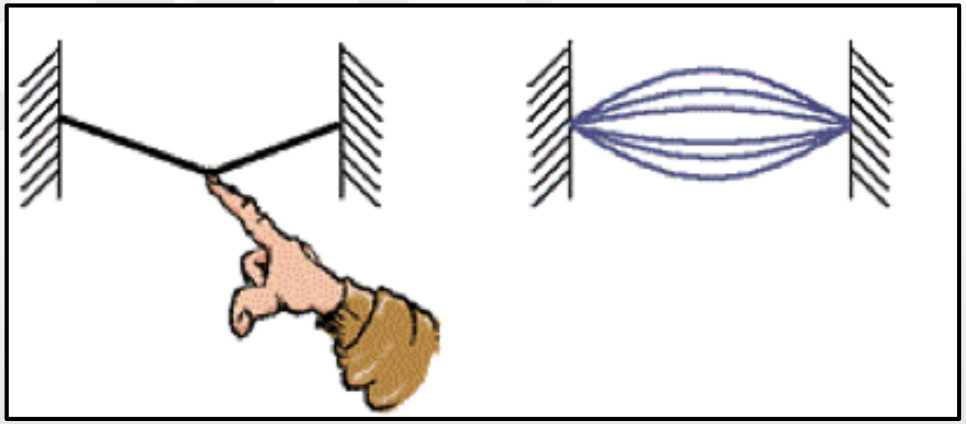
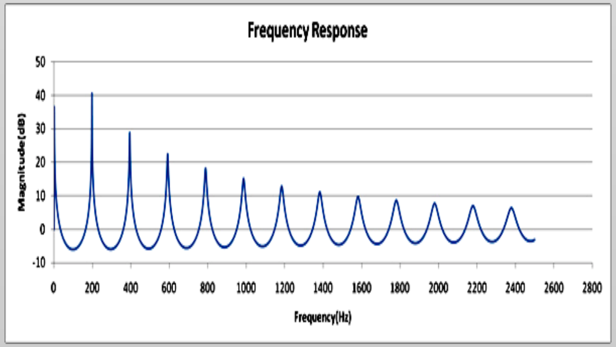


method 2: harmonic (dynamic) approach

1. pinch a string, let it vibrate freely
2. record its sound into a spectrum analyzer
3. perform an FFT
4. store amplitude and phase of each harmonic (A_i,ϕ_i)



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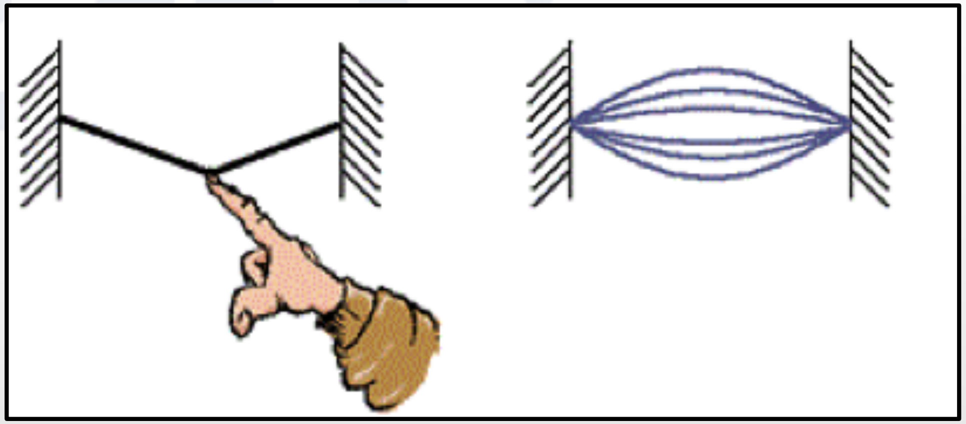
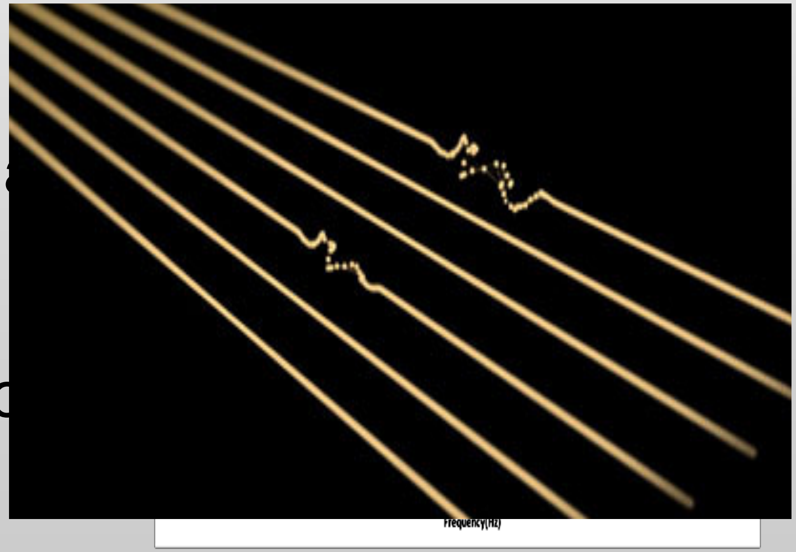


method 2: harmonic (dynamic) approach

Deviations between ideal and measured harmonics (A_i,ϕ_i), as well as additional ones, are due to string imperfections and/or damages which can be localized and diagnosed



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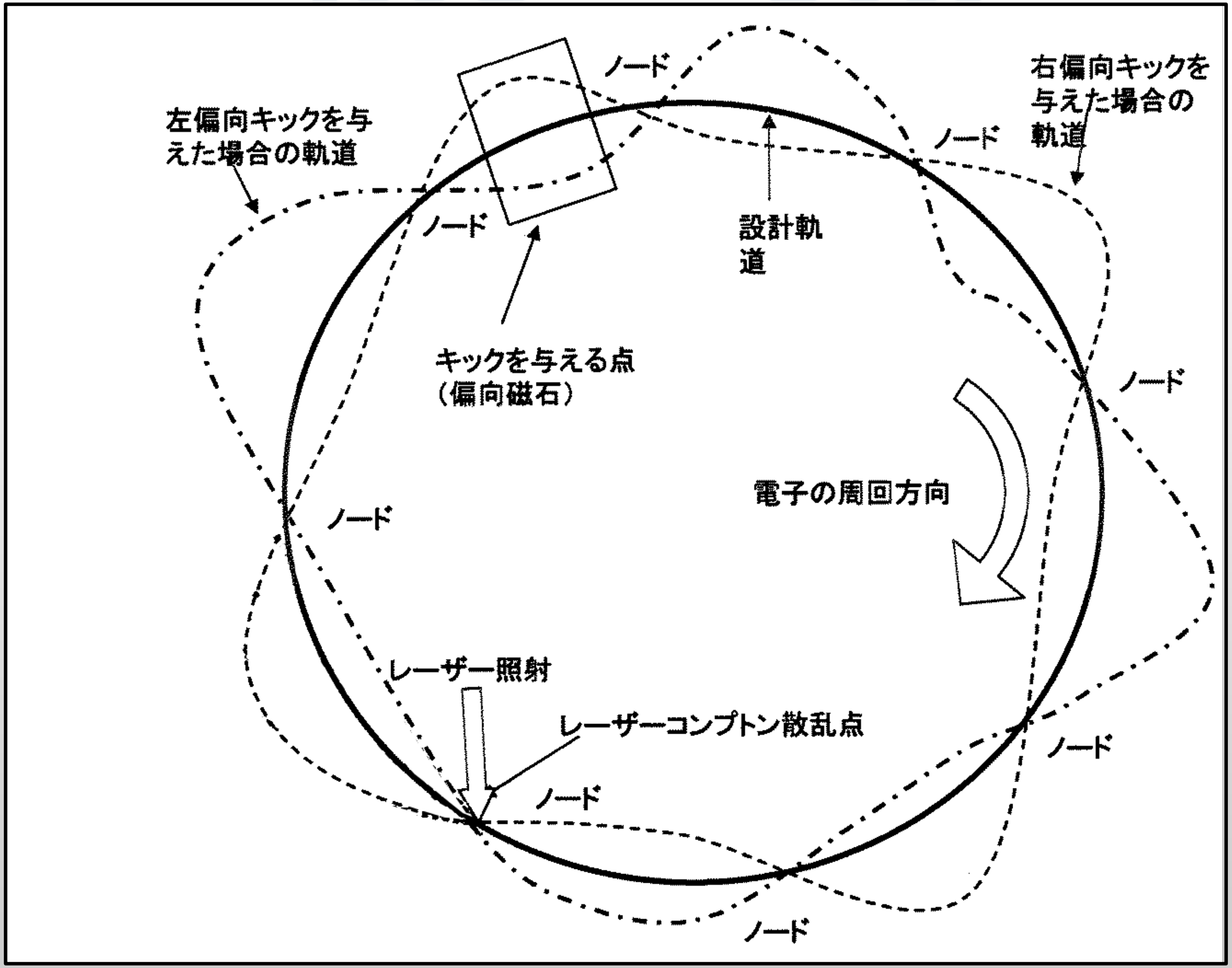

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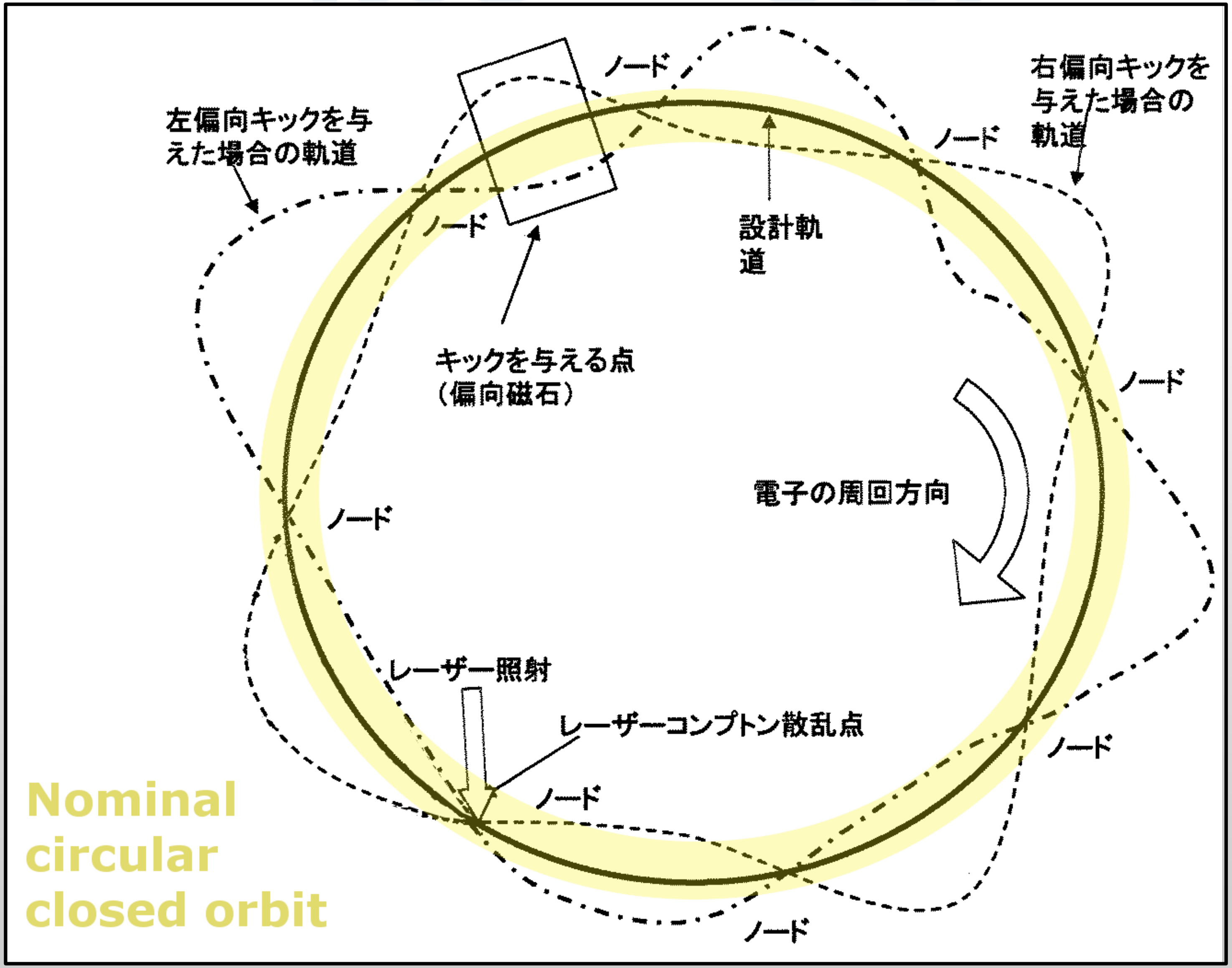

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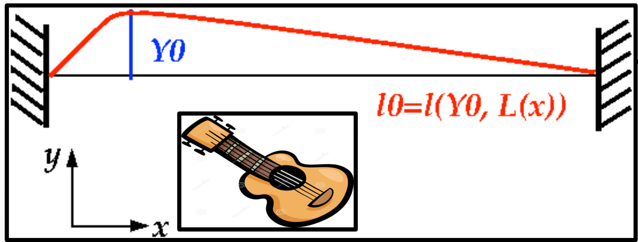
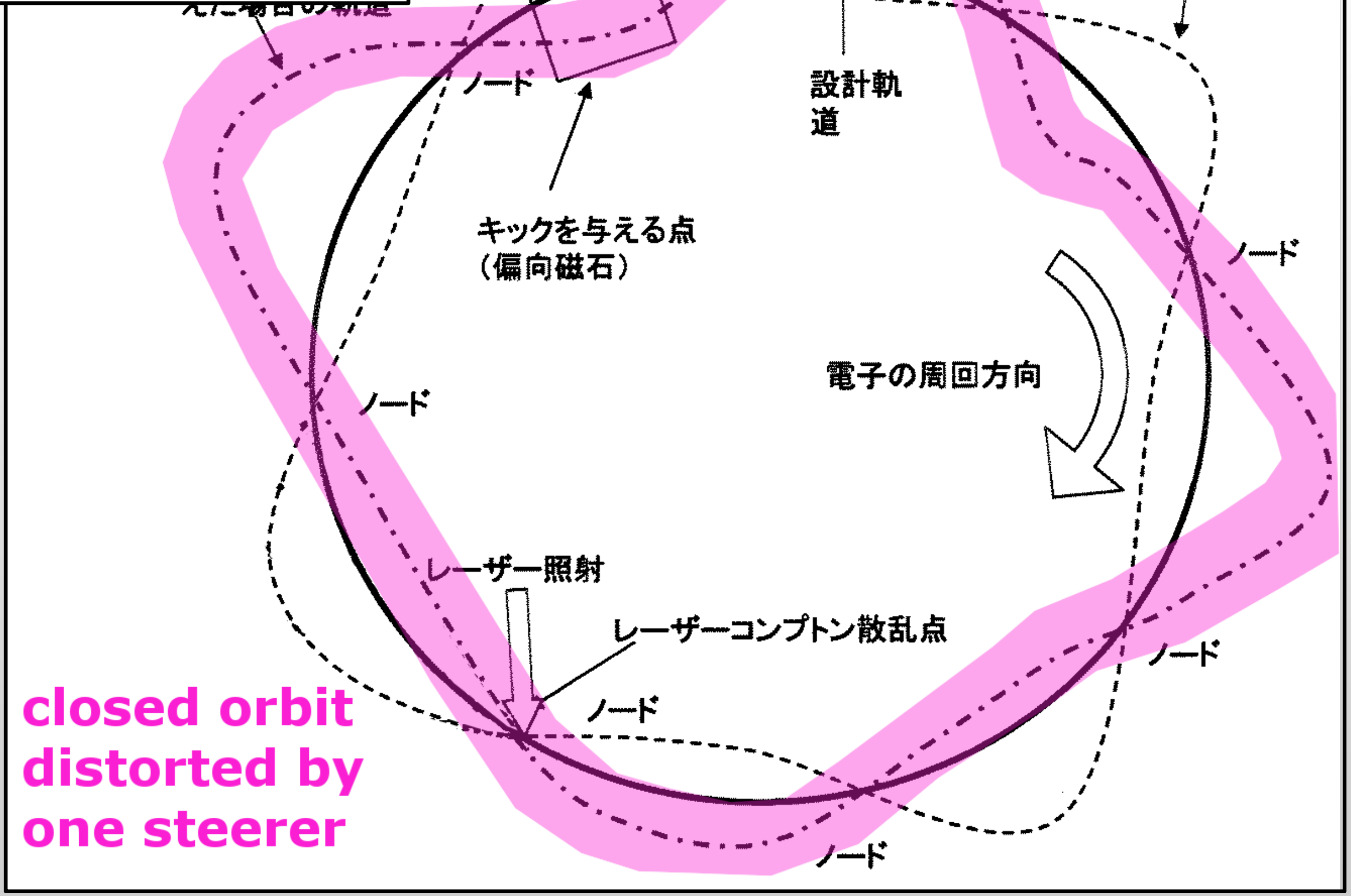
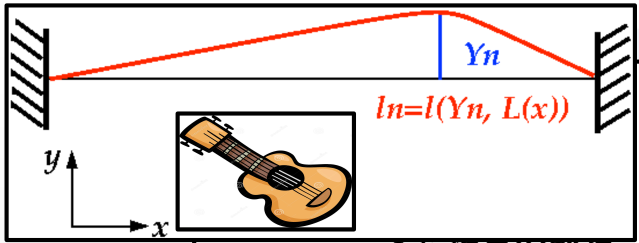
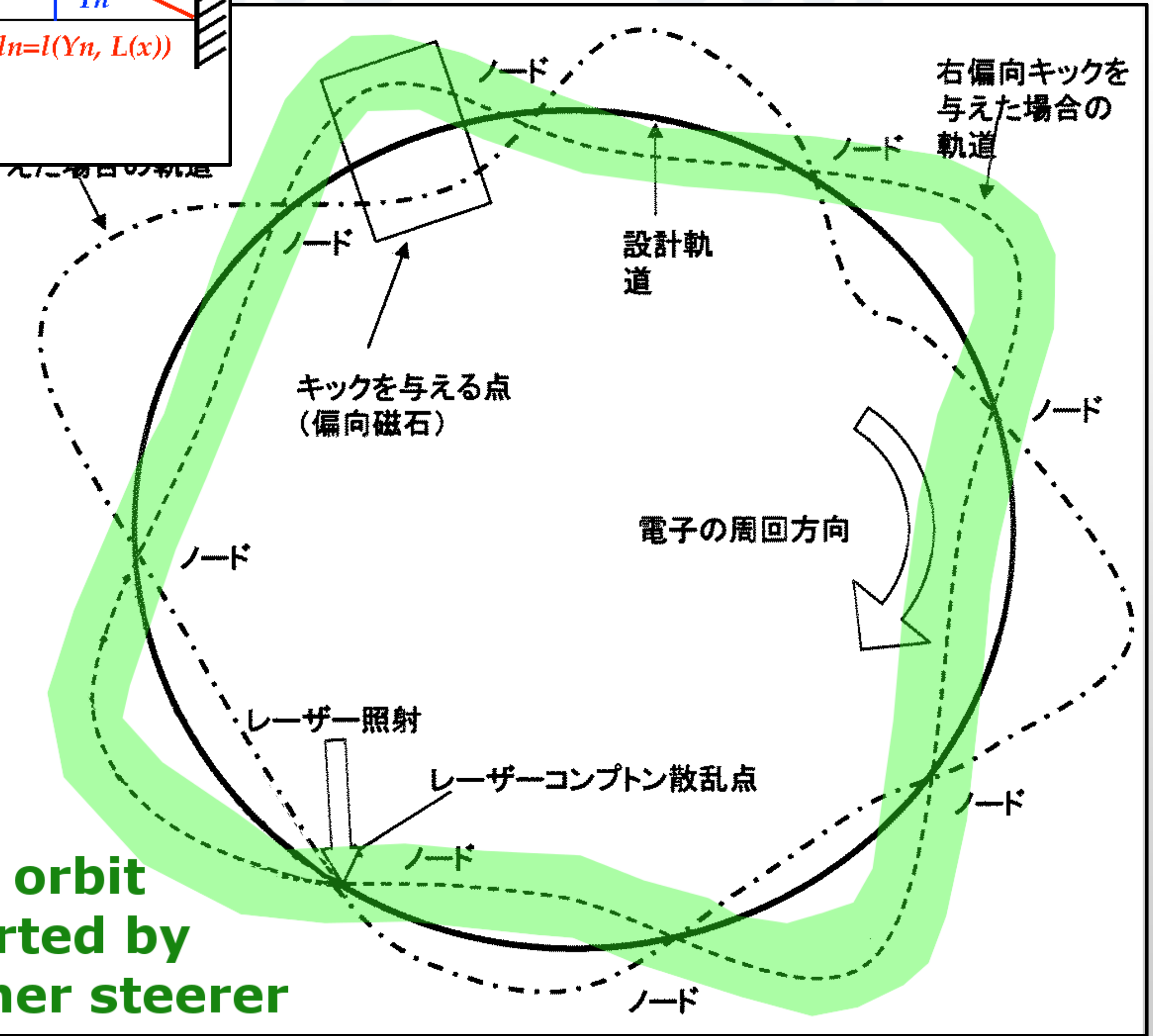




closed orbit distorted by one steerer

from orbit BPM data to linear magnetic model





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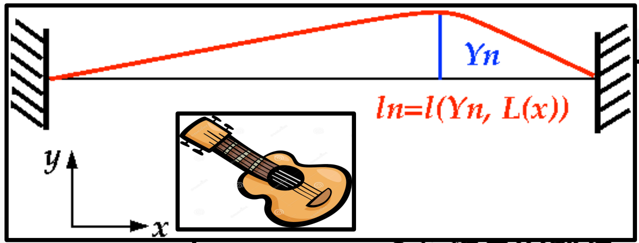

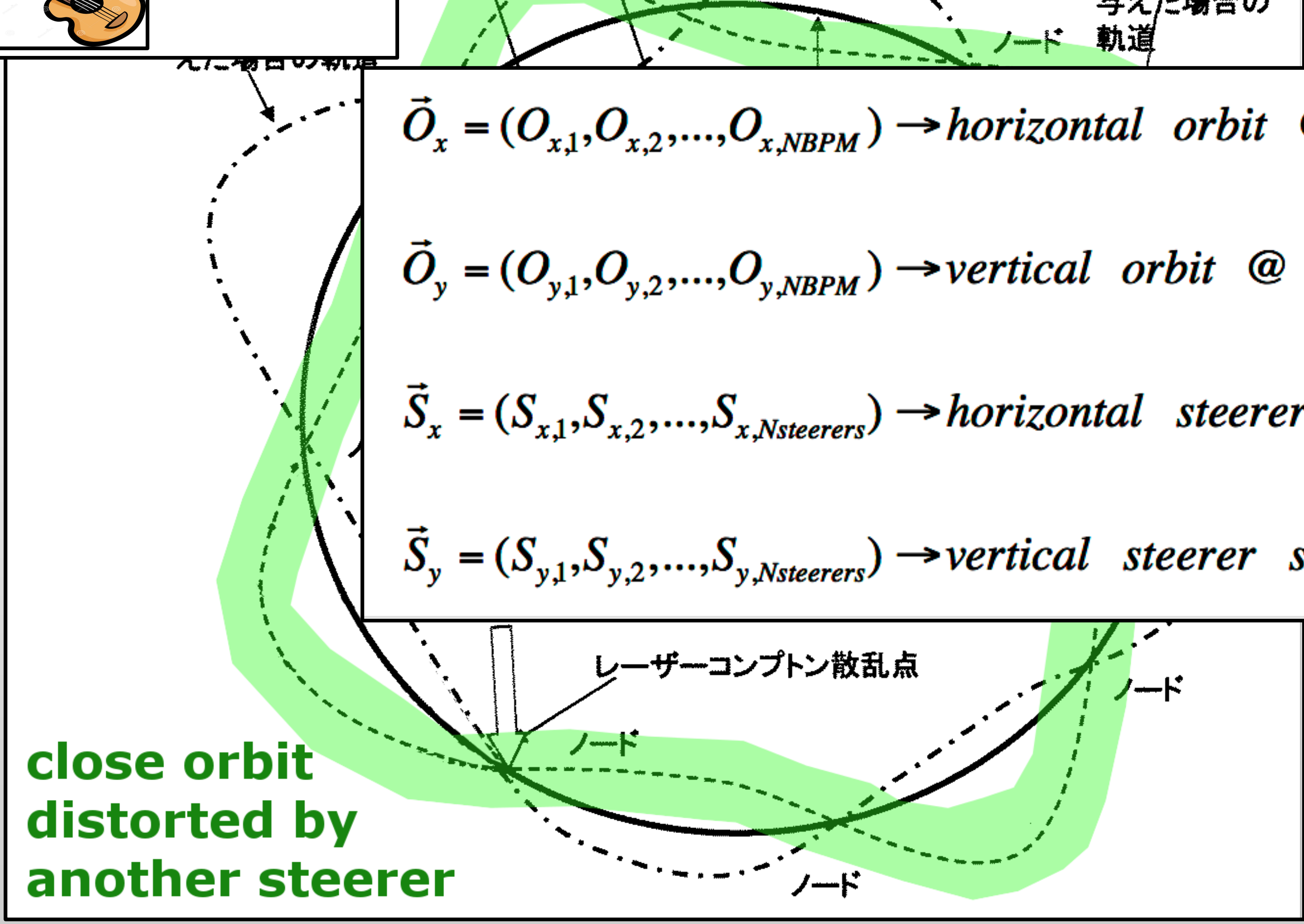

$$\vec{O}_x = (O_{x,1}, O_{x,2}, \ldots, O_{x,NBPM}) \rightarrow horizontal \quad orbit \quad @ \quad BPMs$$

$$\vec{O}_y = (O_{y,1}, O_{y,2}, \ldots, O_{y,NBPM}) \rightarrow vertical \quad orbit \quad @ \quad BPMs$$

$$\vec{S}_x = (S_{x,1}, S_{x,2}, \ldots, S_{x,Nsteerers}) \rightarrow horizontal \quad steerer \quad strengths$$

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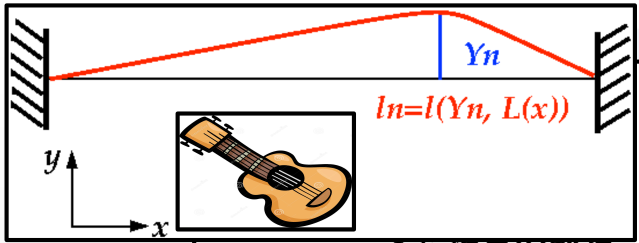
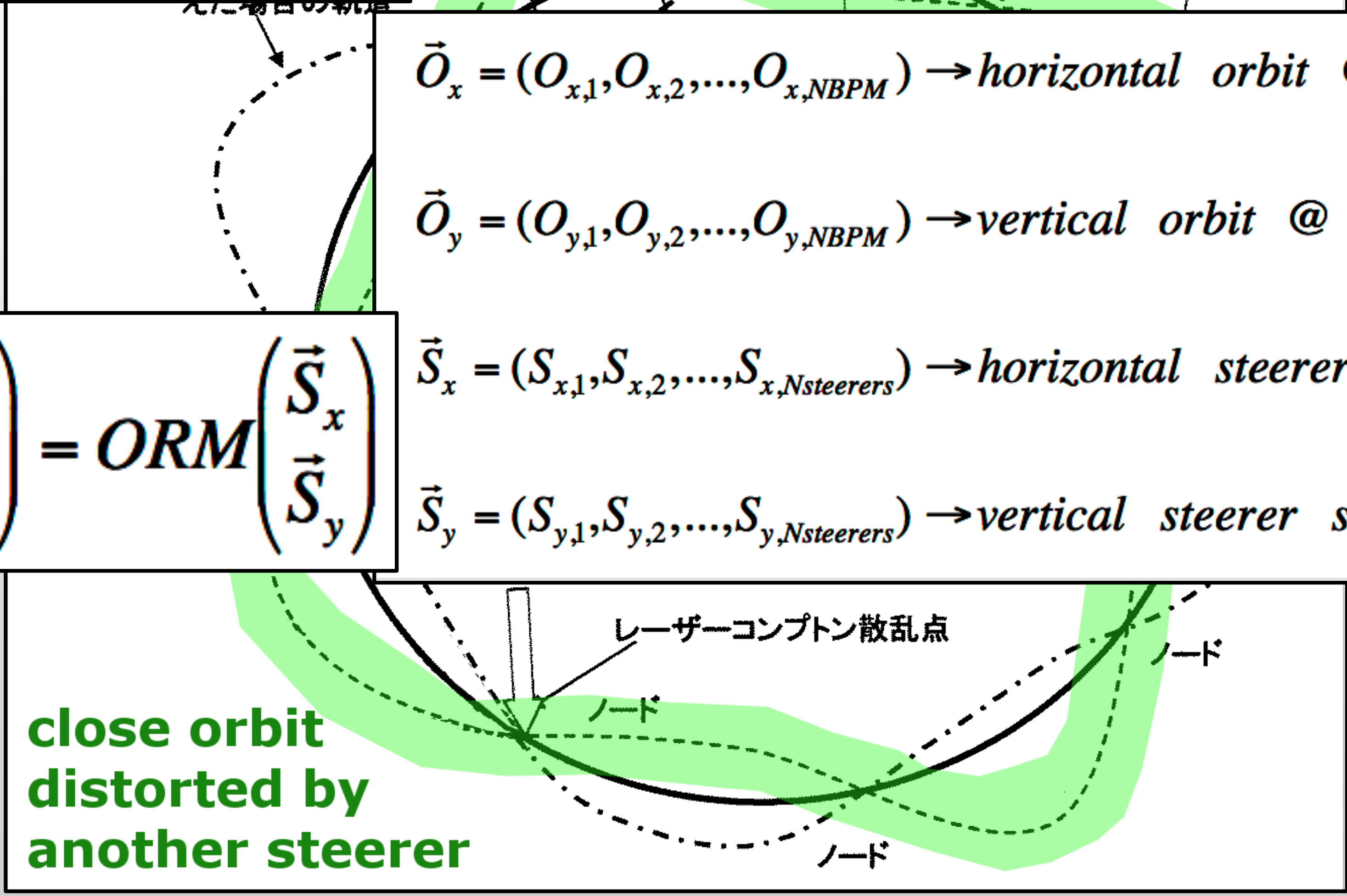
from orbit BPM data to linear magnetic model





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$$\begin{pmatrix} \vec{O}_x \\ \vec{O}_y \end{pmatrix} = ORM \begin{pmatrix} \vec{S}_x \\ \vec{S}_y \end{pmatrix}$$

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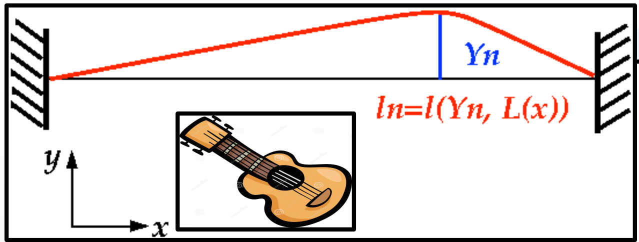

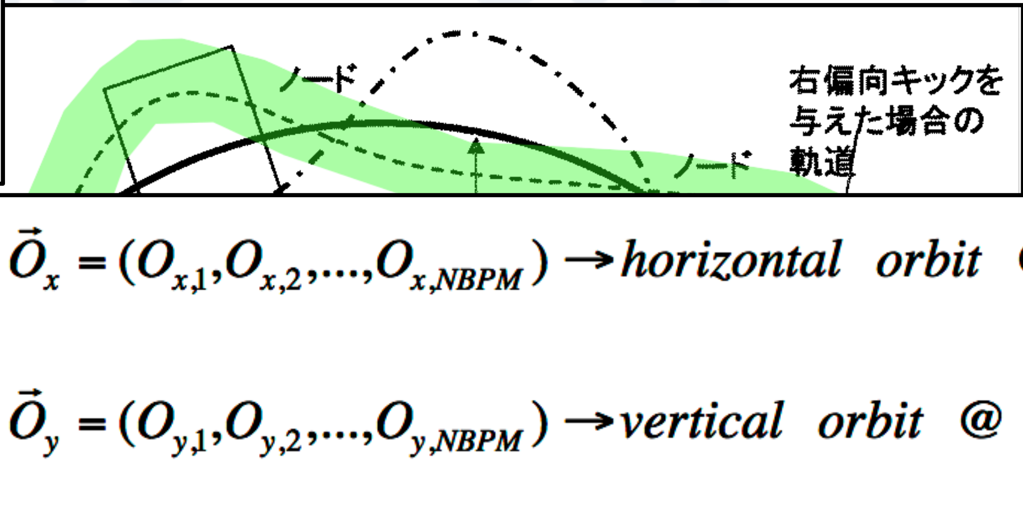

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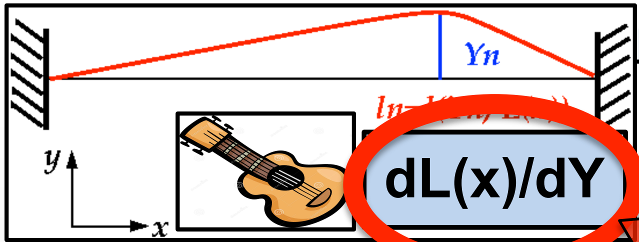

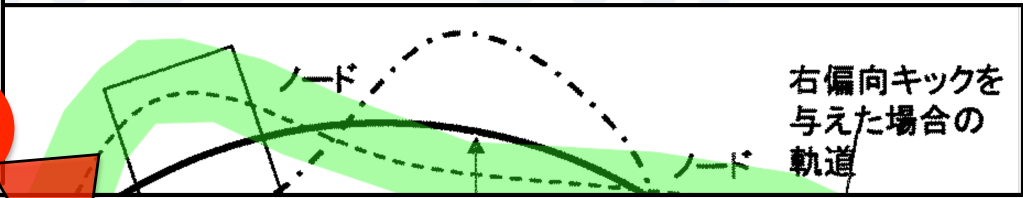

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from orbit BPM data to linear magnetic model

$$\delta O_{xx} = O_{xx}^{(meas)} - O_{xx}^{(ideal)}$$

$$\delta O_{yy} = O_{yy}^{(meas)} - O_{yy}^{(ideal)}$$

$$\delta D_{x} = D_{x}^{(meas)} - D_{x}^{(ideal)}$$

$D_x^{(ideal)}$ $O_{xx}^{(ideal)}$ $O_{yy}^{(ideal)}$

from codes (MADX, AT,...)

or from analytic formulas

$$ORM = \begin{pmatrix} O_{xx} & O_{xy} \\ O_{yx} & O_{yy} \end{pmatrix} \longrightarrow \textit{Orbit Response Matrix}$$

$\vec{D}_x, \vec{D}_y \rightarrow$ *hor., ver. dispersion*

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from orbit BPM data to linear magnetic model

$$\delta O_{xx} = O_{xx}^{(meas)} - O_{xx}^{(ideal)}$$

$$\delta O_{yy} = O_{yy}^{(meas)} - O_{yy}^{(ideal)}$$

$$\delta D_{x} = D_{x}^{(meas)} - D_{x}^{(ideal)}$$

$D_x^{(ideal)}$ $O_{xx}^{(ideal)}$ $O_{yy}^{(ideal)}$

from codes (MADX, AT,...)
or from analytic formulas

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

M_{normal} *from codes (MADX, AT,...)*
soon from analytic formulas

quad & bend field errors

$$ORM = \begin{pmatrix} O_{xx} & O_{xy} \\ O_{yx} & O_{yy} \end{pmatrix} \longrightarrow \text{Orbit Response Matrix}$$

$\vec{D}_x, \vec{D}_y \rightarrow$ *hor., ver. dispersion*

$$O_{xx,ij} = \frac{\partial O_{x,i}}{\partial S_{x,j}} \qquad O_{yy,ij} = \frac{\partial O_{y,i}}{\partial S_{y,j}} \qquad O_{xy,ij} = \frac{\partial O_{x,i}}{\partial S_{y,j}} \qquad O_{yx,ij} = \frac{\partial O_{y,i}}{\partial S_{x,j}}$$

from orbit BPM data to linear magnetic model

known

unknown

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

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from orbit BPM data to linear magnetic model

known

unknown

this linear system can be pseudo-inverted via Single Value Decomposition (SVD) to infer quad & bend field errors δK_0 & δK_1

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

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from orbit BPM data to linear magnetic model

known

unknown

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

this linear system can be pseudo-inverted via Single Value Decomposition (SVD) to infer quad & bend field errors δK_0 & δK_1

warning: quad & sext offsets (or misalignments) affects the l.h.s. . They are “absorbed” by effective field errors (so that reference and closed orbit are the same)

$$ORM = \begin{pmatrix} O_{xx} & O_{xy} \\ O_{yx} & O_{yy} \end{pmatrix} \longrightarrow Orbit\ \ Response\ \ Matrix$$

$$\vec{D}_x , \vec{D}_y \rightarrow hor.,ver.\ dispersion$$

$$O_{xx,ij} = \frac{\partial O_{x,i}}{\partial S_{x,j}} \qquad O_{yy,ij} = \frac{\partial O_{y,i}}{\partial S_{y,j}} \qquad O_{xy,ij} = \frac{\partial O_{x,i}}{\partial S_{y,j}} \qquad O_{yx,ij} = \frac{\partial O_{y,i}}{\partial S_{x,j}}$$

known

unknown

$$\begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

this linear system can be pseudo-inverted via Single Value Decomposition (SVD) to infer quad & bend tilts ϑ(quad) & ϑ(bend)

warning: sextupole offsets (or misalignments) affects the l.h.s. . They are “absorbed” by effective rotations (so that reference and closed orbit are the same)

$$ORM = \begin{pmatrix} O_{xx} & O_{xy} \\ O_{yx} & O_{yy} \end{pmatrix} \longrightarrow \quad Orbit \quad Response \quad Matrix$$

$$\vec{D}_x, \vec{D}_y \rightarrow hor., ver. dispersion$$

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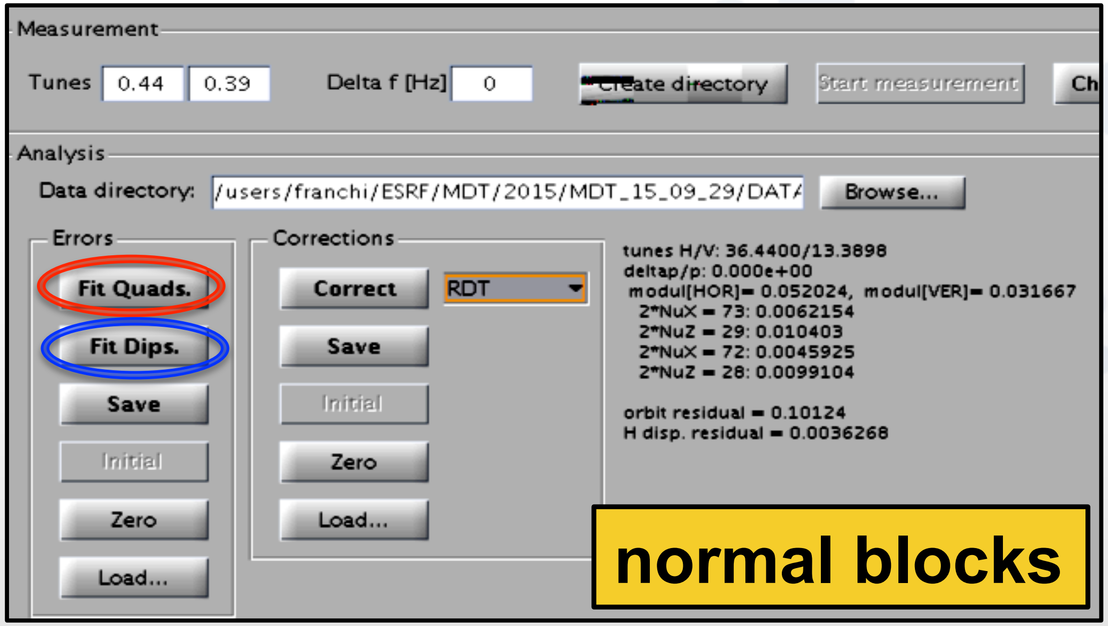
from orbit BPM data to linear magnetic model



$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

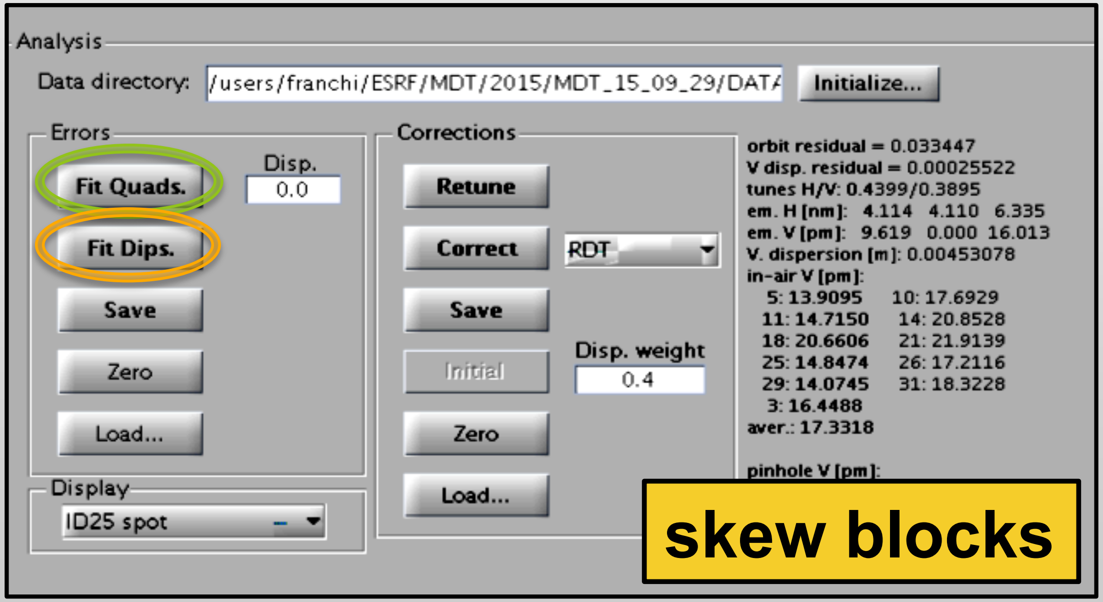
Typical rms residuals after fit [mm/A]

Rn(xx,yy) ~ 1E-1

Dx ~ 4E-3

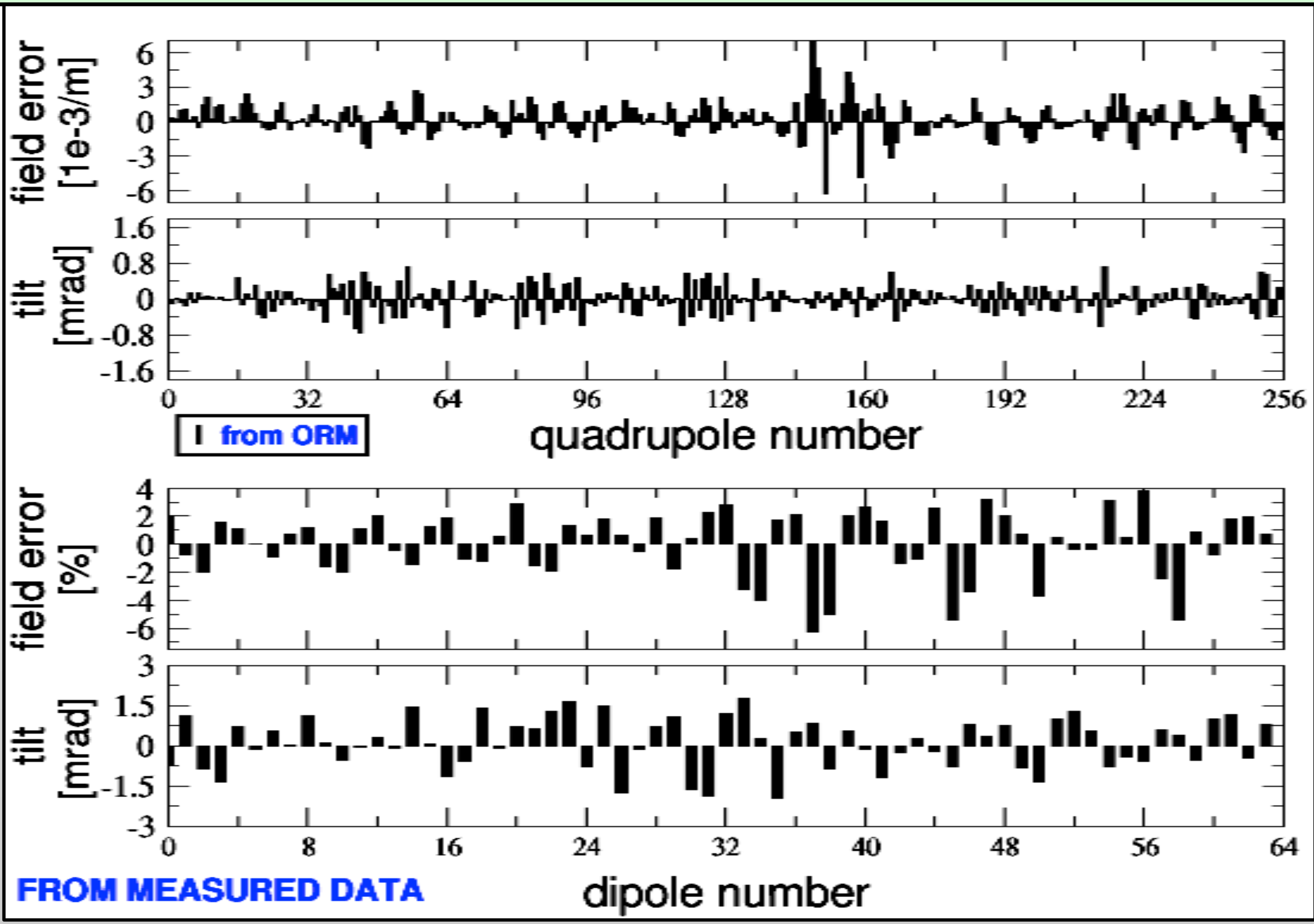
Rs(xy,yx) ~ 3E-2

Dy ~ 3E-4

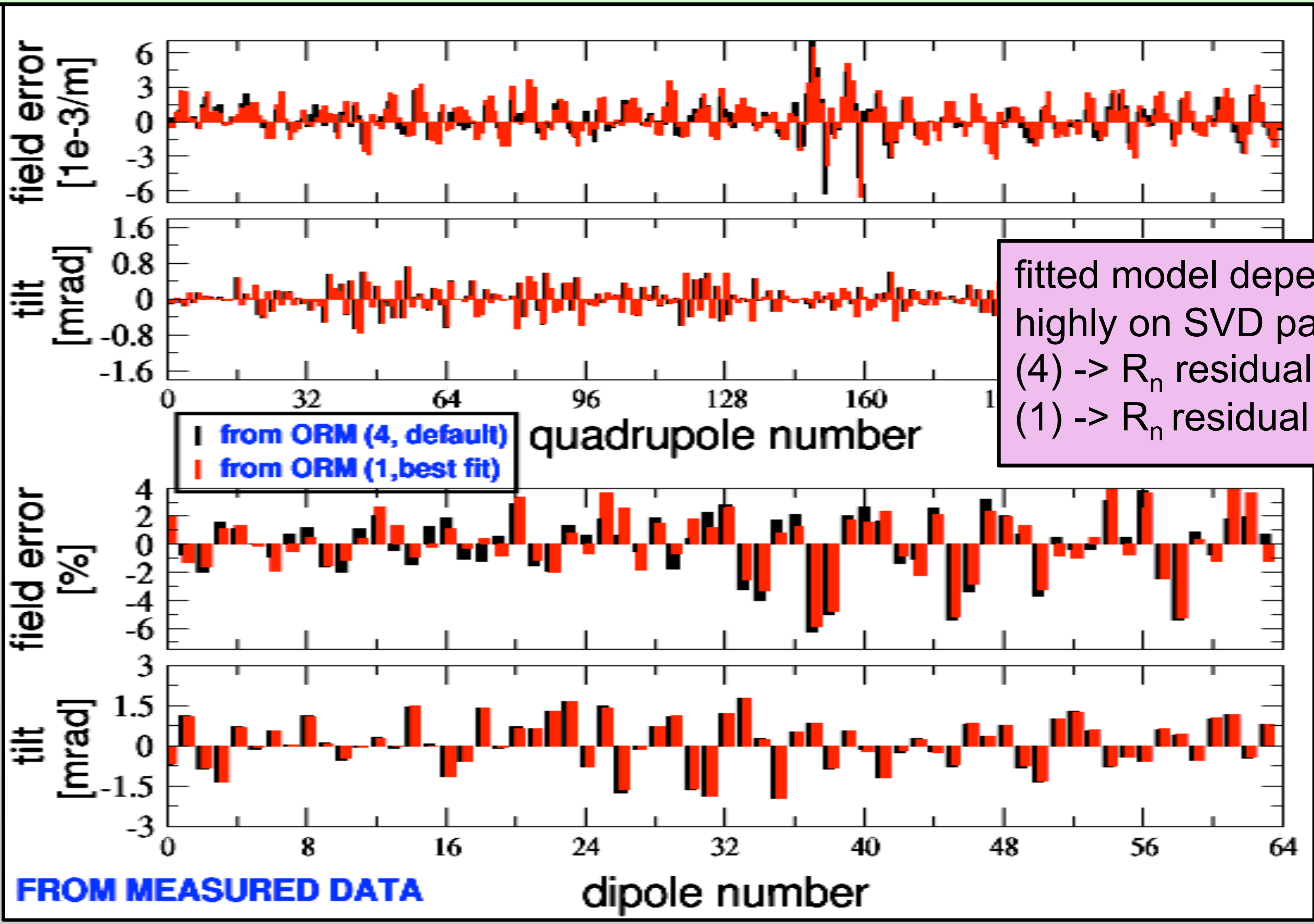


$$\begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

inferred linear model ("effective", accounting for magnet displ. too)



inferred linear model ("effective", accounting for magnet displ. too)



fitted model depends highly on SVD param.:
(4) -> R_n residual 0.11
(1) -> R_n residual 0.08

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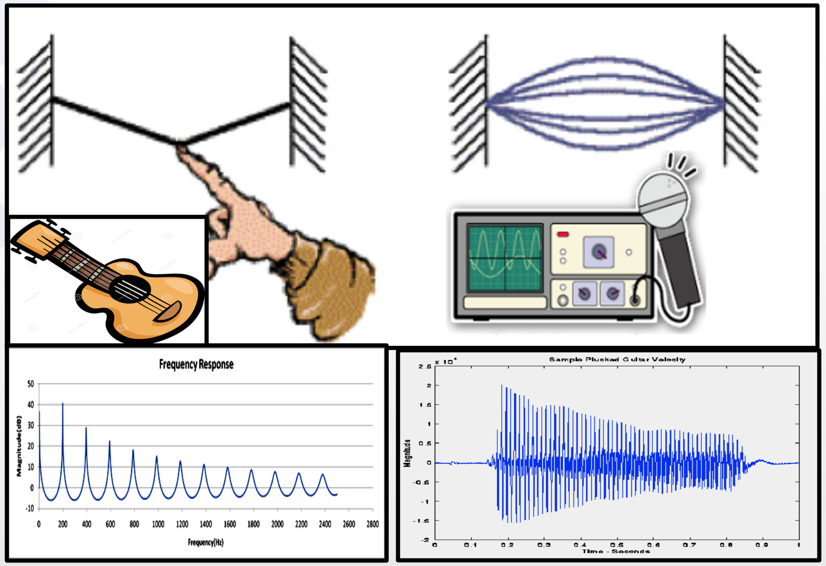
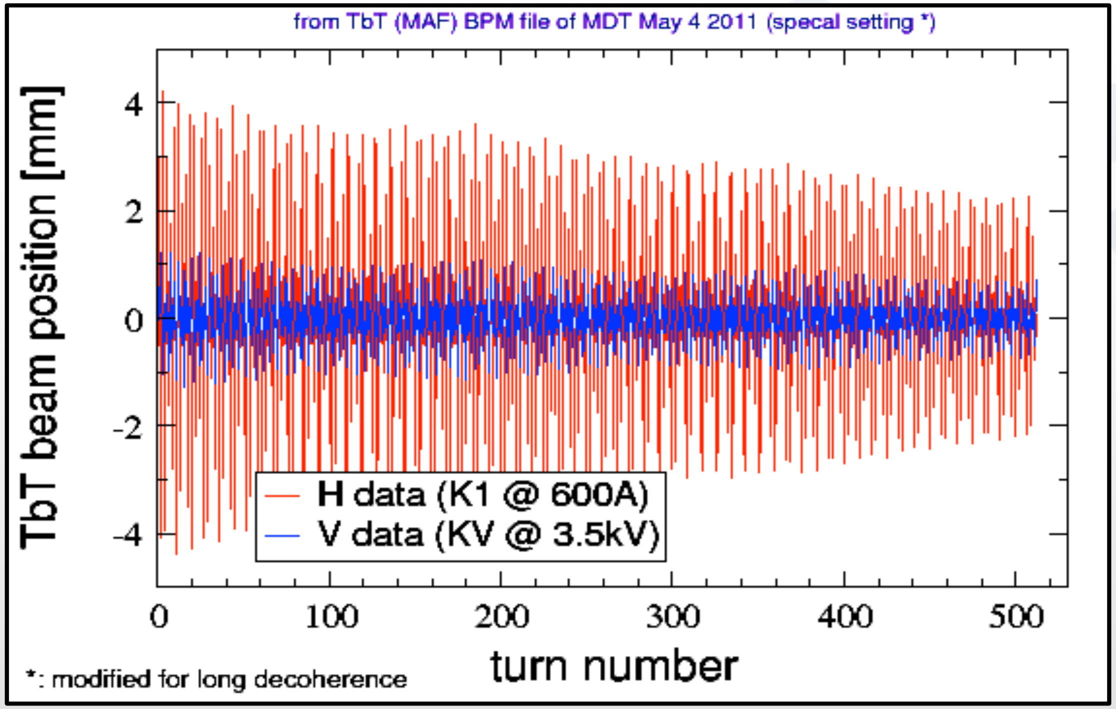
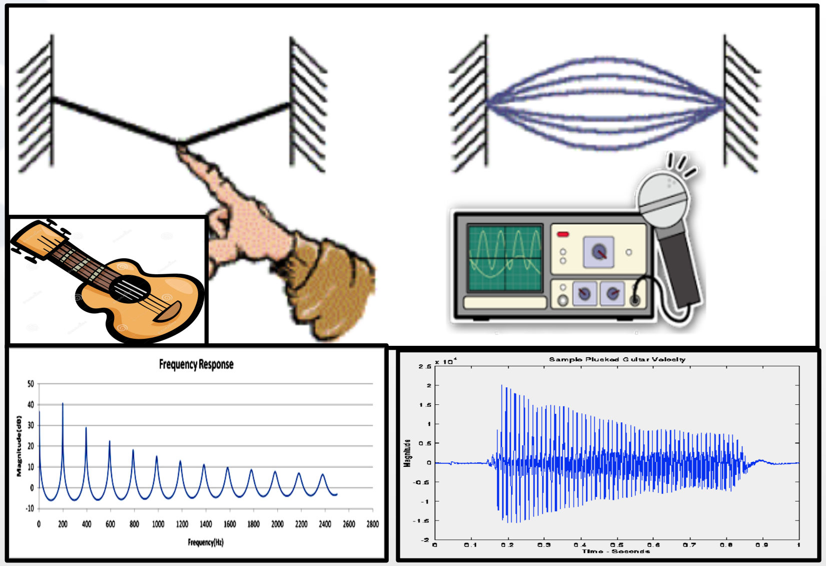
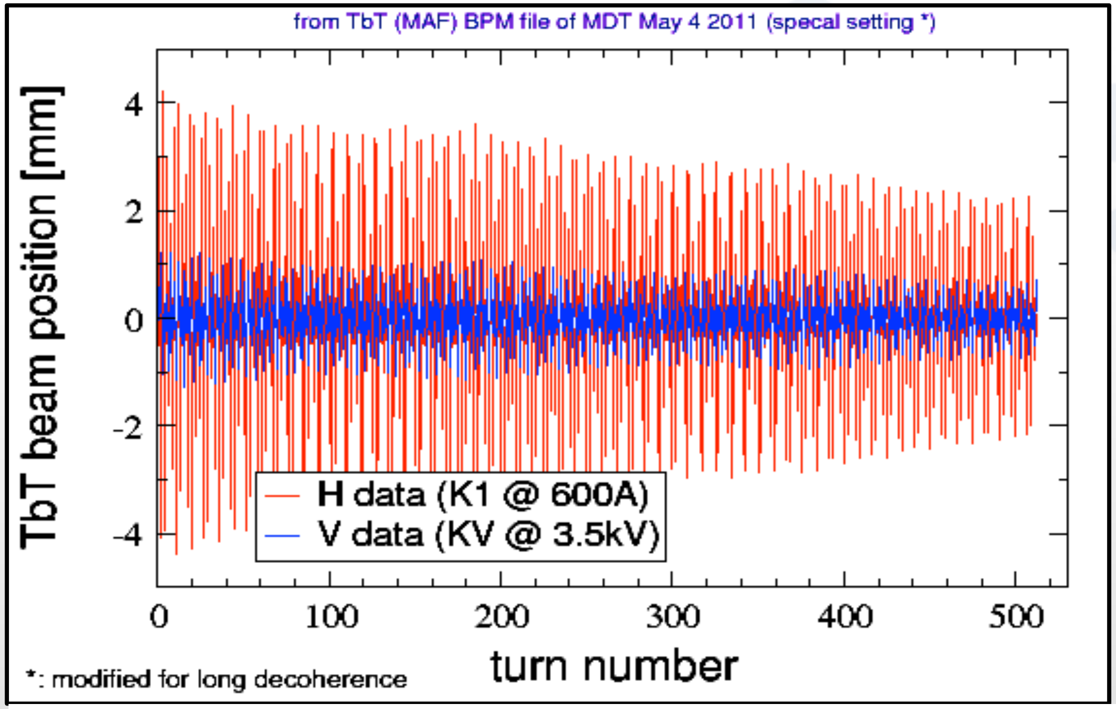

Frequency Response
Sample Plucked Guitar Velocity

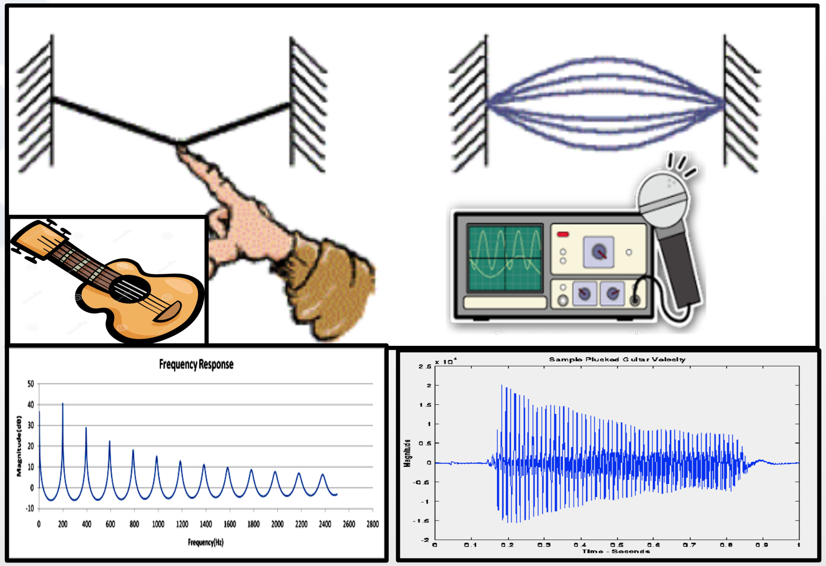
from TbT BPM data to linear magnetic model

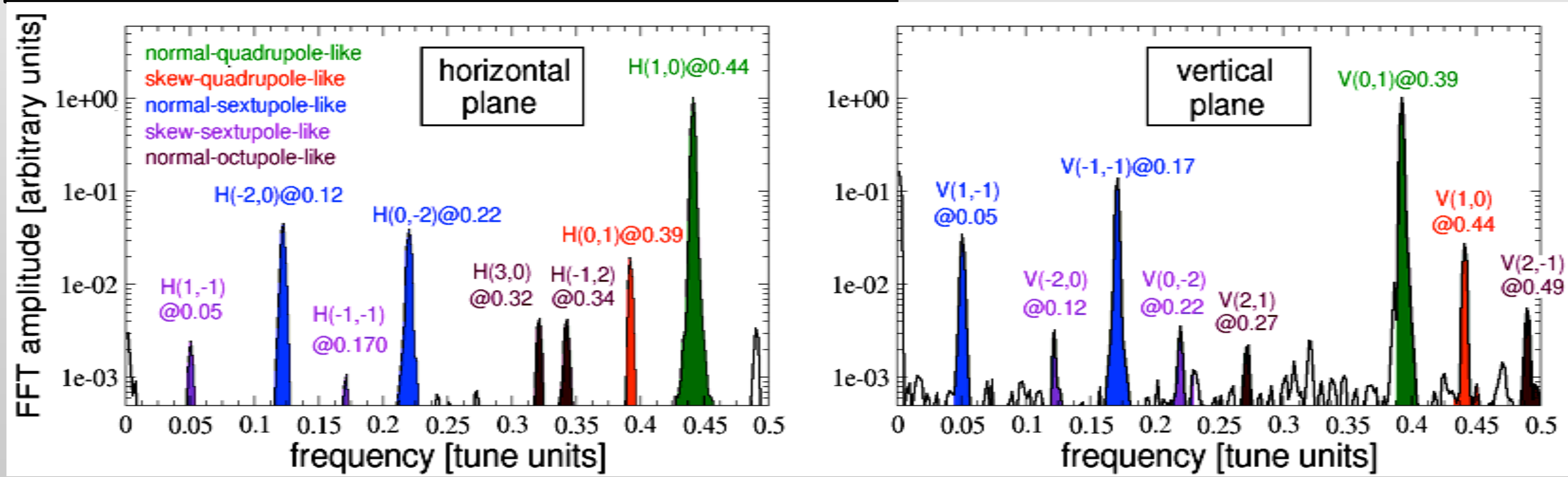




from TbT BPM data to linear magnetic model

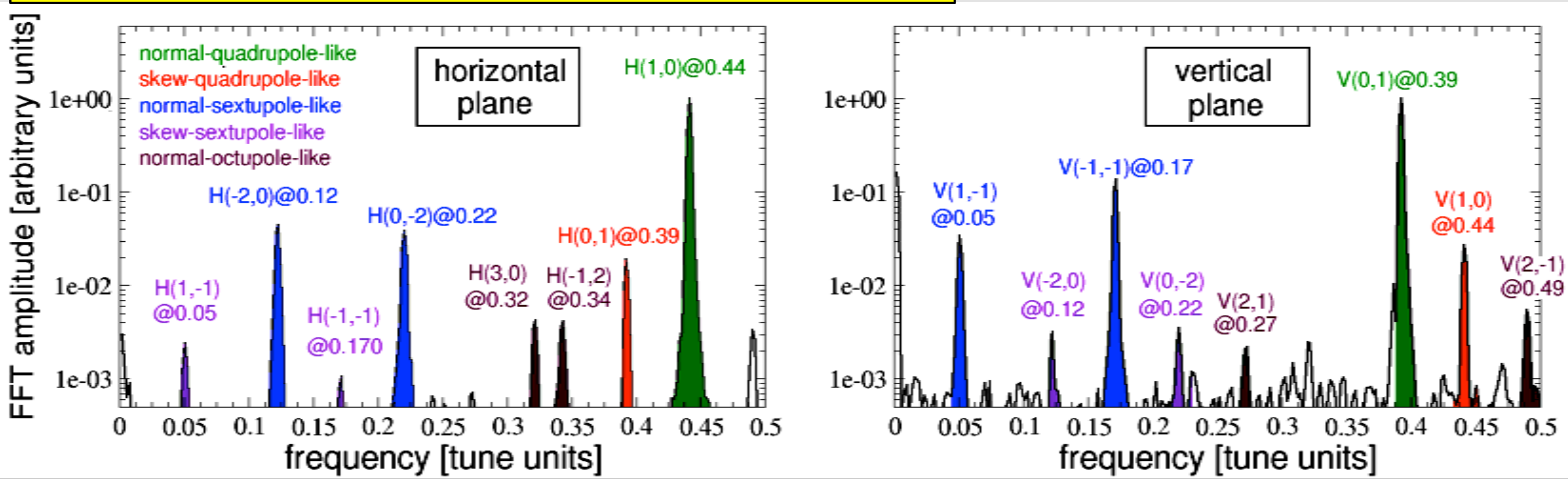


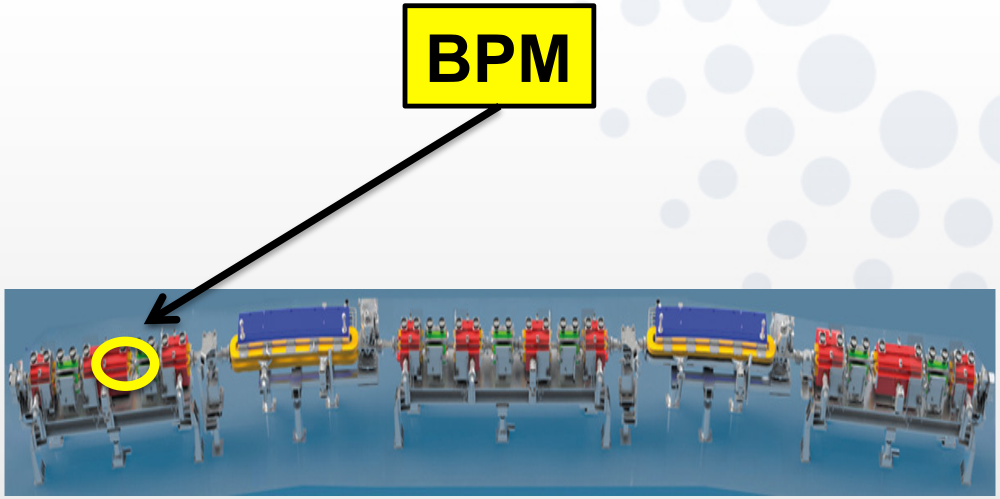




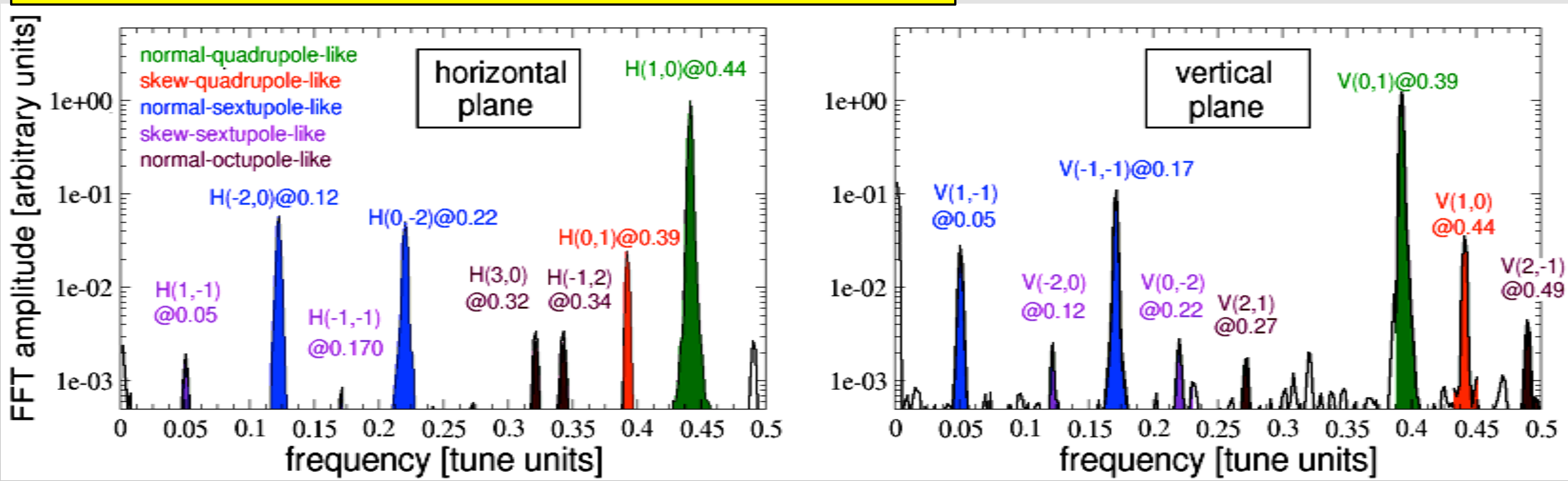
BPM

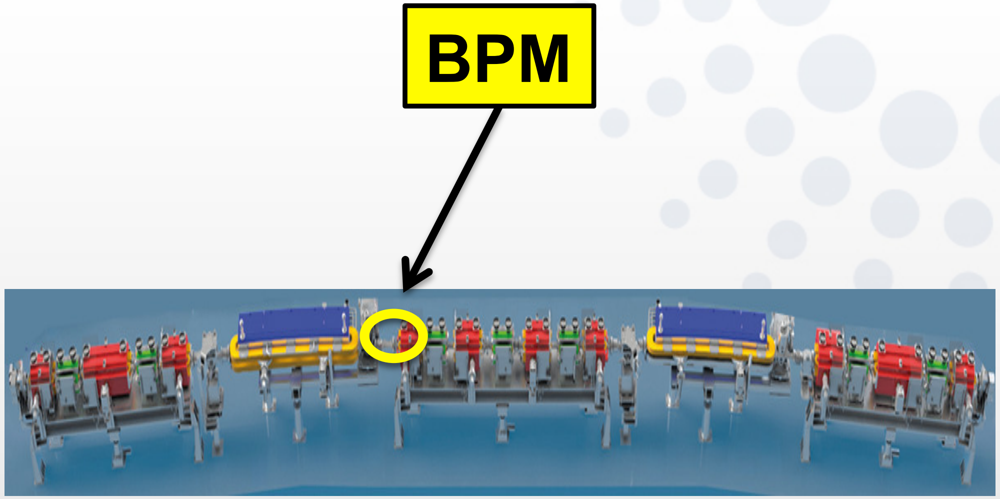
Storage Ring’s transverse spectra



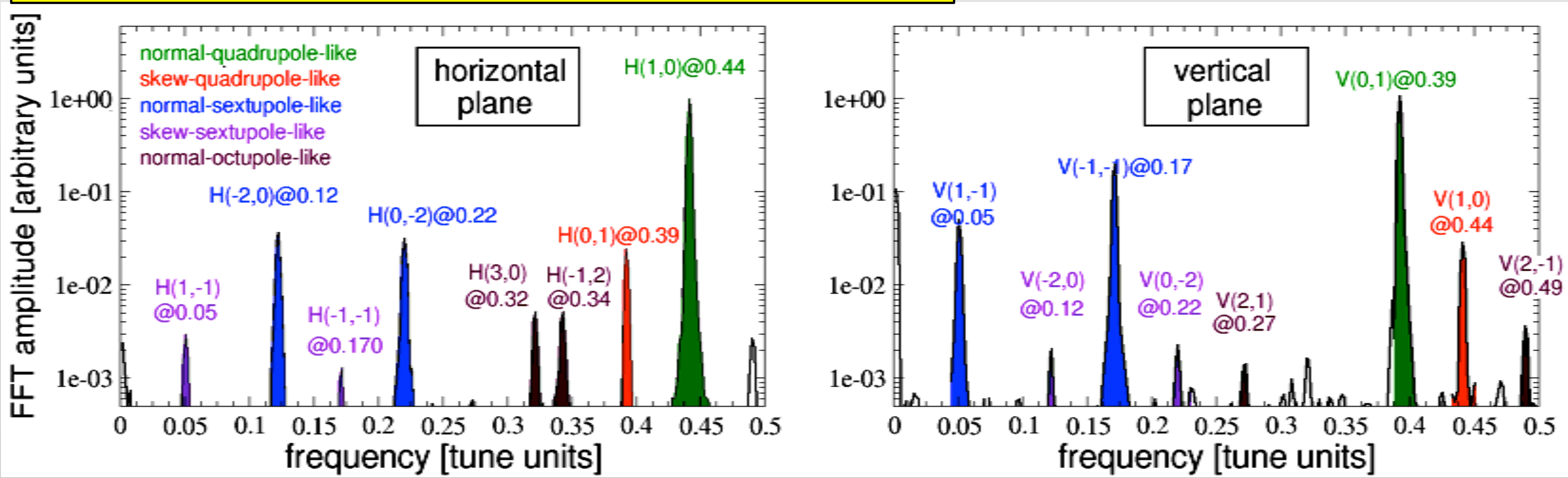


Storage Ring's transverse spectra

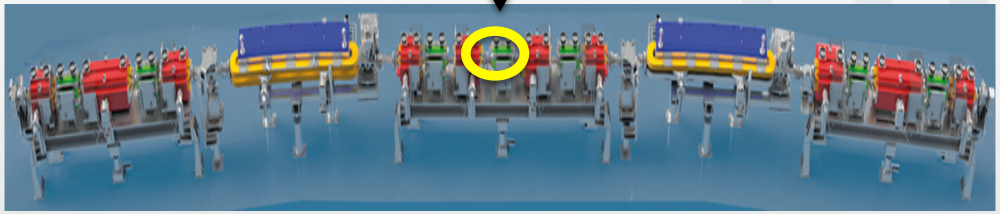




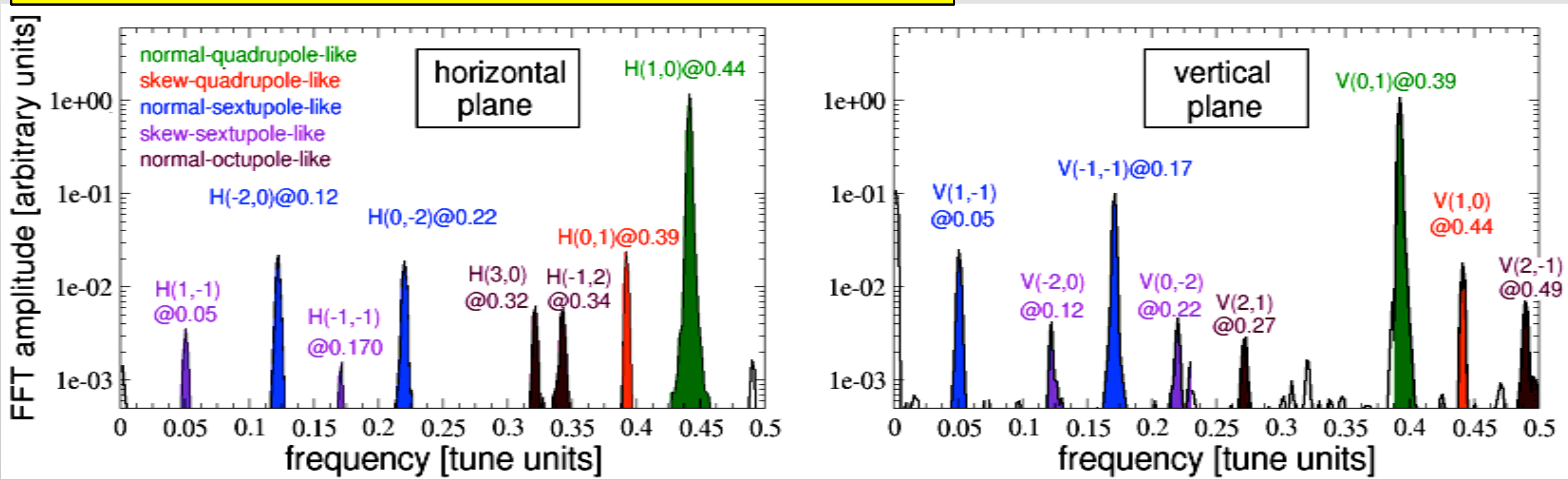
Storage Ring's transverse spectra



BPM



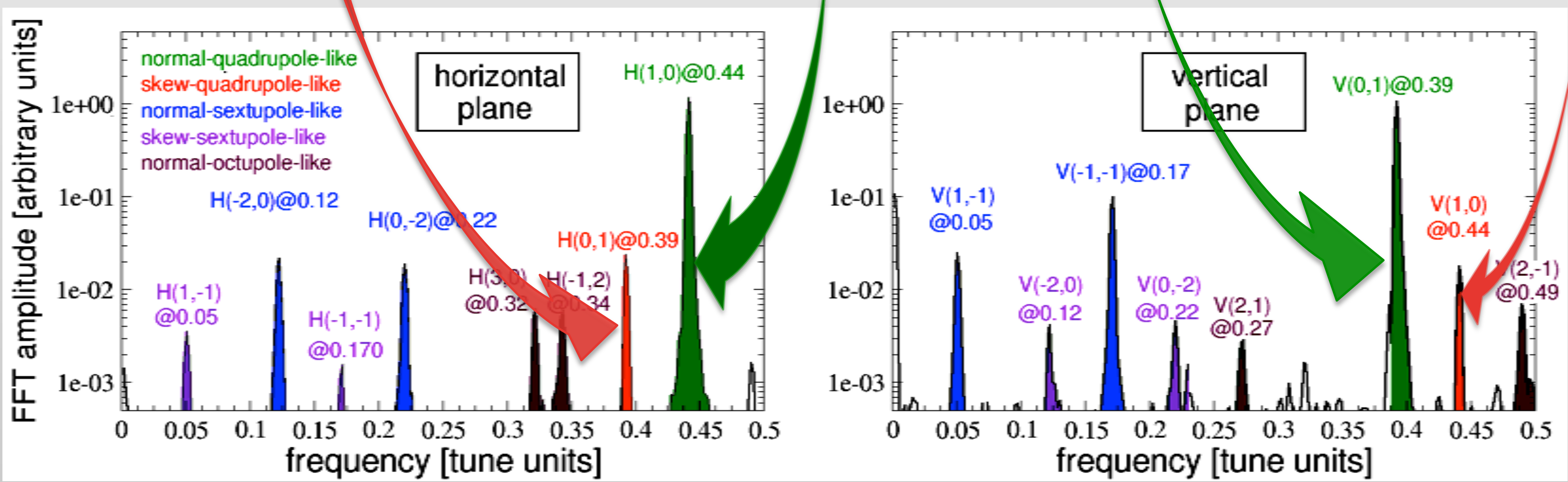
Storage Ring's transverse spectra



The observables at the nth BPM

$$\frac{\vec{x}_n^{(TbT)}}{\sqrt{\beta_{x,n}^{(ideal)}}} \xrightarrow{FFT} \begin{cases} |H_n(1,0)|, & \phi_{n,H(1,0)} \\ |H_n(0,1)|, & \phi_{n,H(0,1)} \end{cases}$$

$$\frac{\vec{y}_n^{(TbT)}}{\sqrt{\beta_{y,n}^{(ideal)}}} \xrightarrow{FFT} \begin{cases} |V_n(0,1)|, & \phi_{n,V(0,1)} \\ |V_n(1,0)|, & \phi_{n,V(1,0)} \end{cases}$$



The observables at the nth BPM

$$\frac{\vec{x}_n^{(TbT)}}{\sqrt{\beta_{x,n}^{(ideal)}}} \xrightarrow{FFT} \begin{cases} |H_n(1,0)|, & \phi_{n,H(1,0)} \\ |H_n(0,1)|, & \phi_{n,H(0,1)} \end{cases}$$

$$\frac{\vec{y}_n^{(TbT)}}{\sqrt{\beta_{y,n}^{(ideal)}}} \xrightarrow{FFT} \begin{cases} |V_n(0,1)|, & \phi_{n,V(0,1)} \\ |V_n(1,0)|, & \phi_{n,V(1,0)} \end{cases}$$

$$\Delta\phi_{x,n}^{(meas)} = \phi_{n,H(1,0)} - \phi_{n-1,H(1,0)}$$

$$\Delta\phi_{y,n}^{(meas)} = \phi_{n,V(0,1)} - \phi_{n-1,V(0,1)}$$

$$\delta\Delta\phi_{x,n} = \Delta\phi_{x,n}^{(meas)} - \Delta\phi_{x,n}^{(ideal)}$$

$$\delta\Delta\phi_{y,n} = \Delta\phi_{y,n}^{(meas)} - \Delta\phi_{y,n}^{(ideal)}$$

$$\begin{pmatrix} \delta\Delta\vec{\phi}_x \\ \delta\Delta\vec{\phi}_y \\ \delta\vec{D}_x \end{pmatrix} = P_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta K_0^{(bend)} \end{pmatrix}$$

unknown

known

this linear system can be pseudo-inverted via Single Value Decomposition (SVD) to infer quad & bend field errors δK_0 & δK_1

The observables at the n^th BPM

$$\frac{\vec{x}_n^{(TbT)}}{\sqrt{\beta_{x,n}^{(ideal)}}} \xrightarrow{FFT} \begin{cases} |H_n(1,0)|, & \phi_{n,H(1,0)} \\ |H_n(0,1)|, & \phi_{n,H(0,1)} \end{cases}$$

$$\frac{\vec{y}_n^{(TbT)}}{\sqrt{\beta_{y,n}^{(ideal)}}} \xrightarrow{FFT} \begin{cases} |V_n(0,1)|, & \phi_{n,V(0,1)} \\ |V_n(1,0)|, & \phi_{n,V(1,0)} \end{cases}$$

$$|F_{n,xy}^{(meas)}| = \frac{|H_n(0,1)|}{2|V_n(1,0)|}\ , \quad \phi_{n,Fxy}^{(meas)} = \phi_{n,H(0,1)} - \phi_{n,V(0,1)} - \frac{3}{2}\pi$$

$$|F_{n,yx}^{(meas)}| = \frac{|V_n(1,0)|}{2|H_n(0,1)|}\ , \quad \phi_{n,Fyx}^{(meas)} = \phi_{n,V(1,0)} - \phi_{n,H(1,0)} - \frac{3}{2}\pi$$

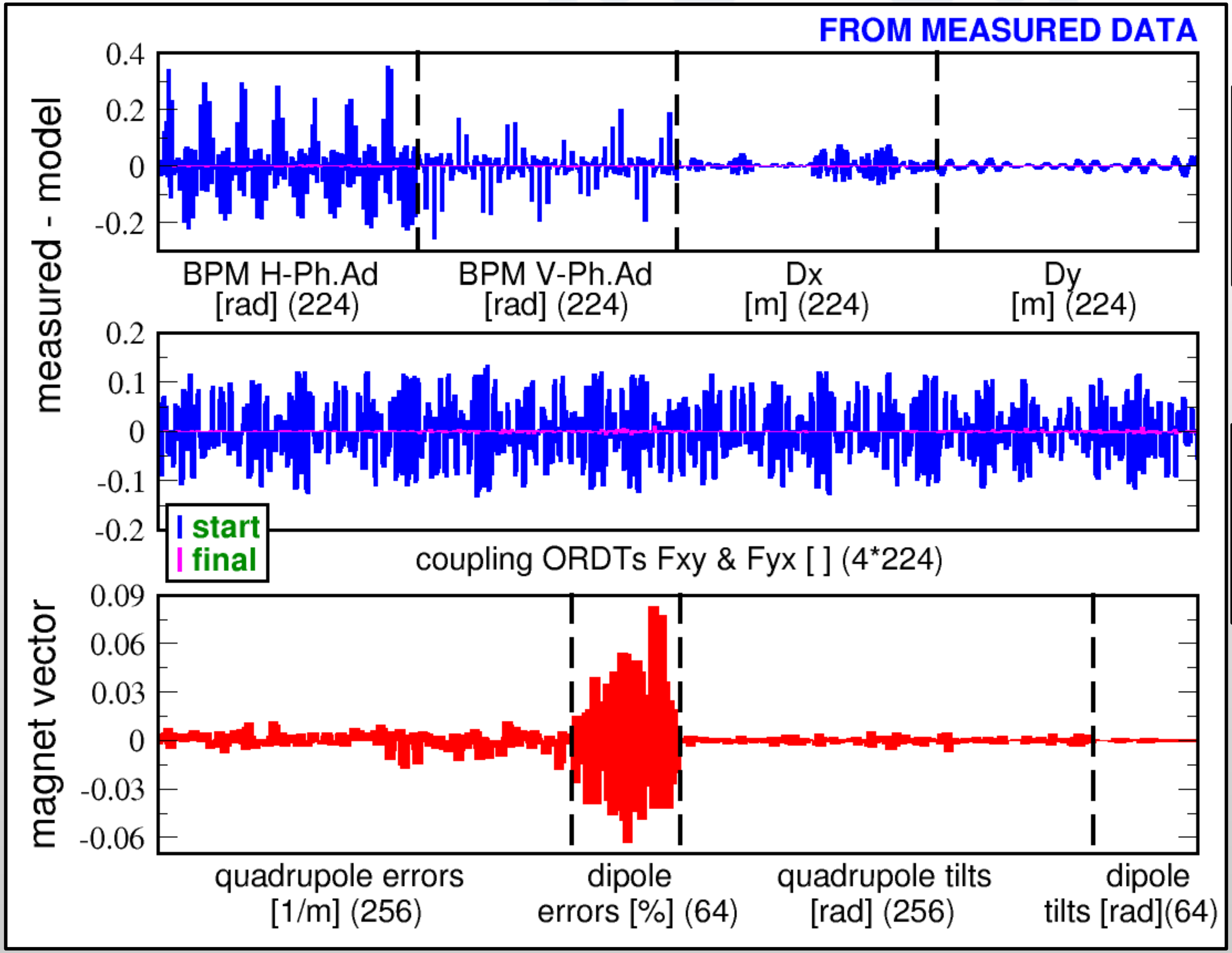
$$\begin{pmatrix} \delta\vec{F}_{xy} \\ \delta\vec{F}_{yx} \\ \delta\vec{D}_y \end{pmatrix} = P_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

unknown

known

this linear system can be pseudo-inverted via Single Value Decomposition (SVD) to infer quad & bend field tilts ϑ(quad) & ϑ(bend)

MDT 29/09/2015: TbT measurement and fit #1 (all at once)



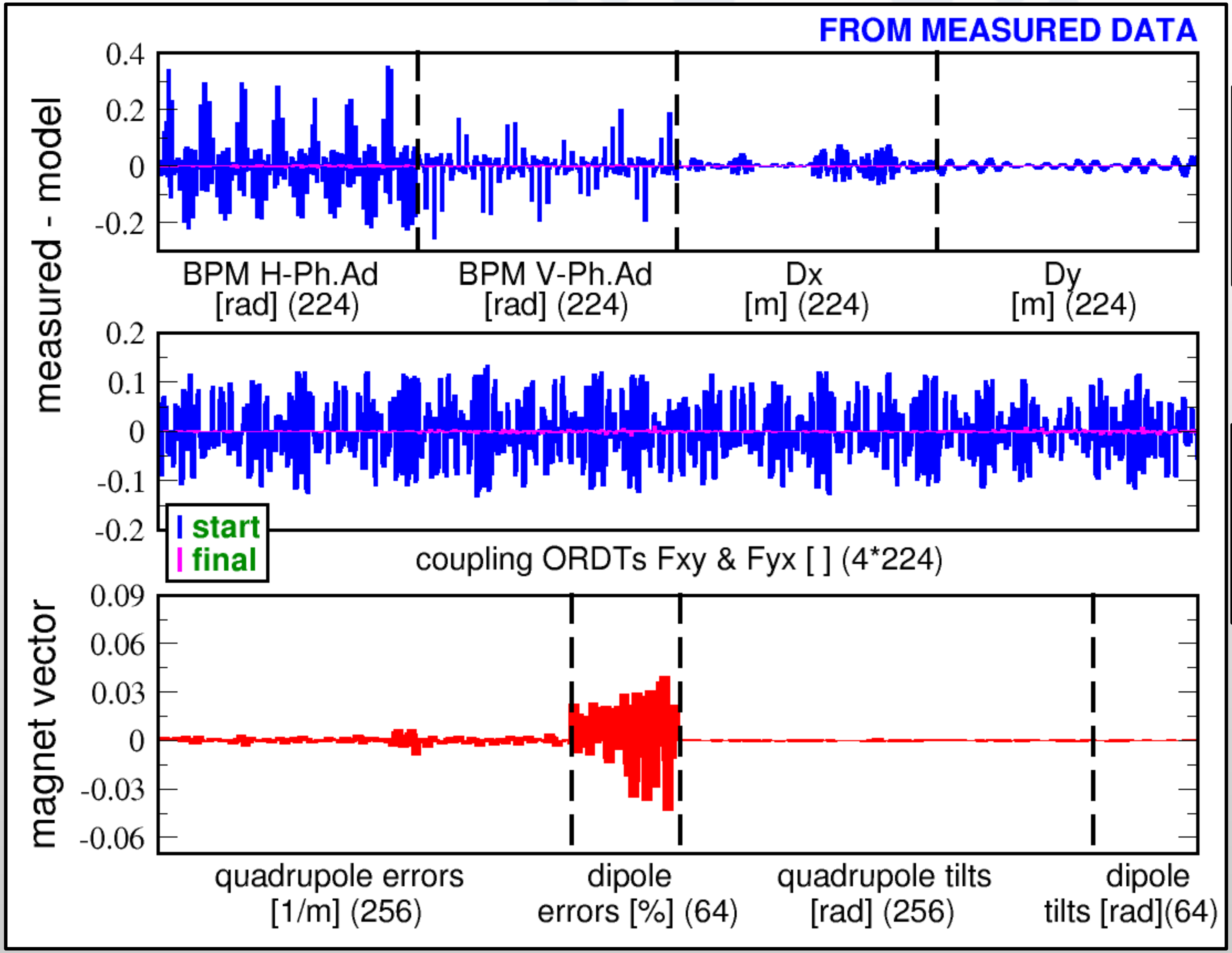
normal block

$$\begin{pmatrix} \delta\Delta\vec{\phi}_x \\ \delta\Delta\vec{\phi}_y \\ \delta\vec{D}_x \end{pmatrix} = P_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

skew block

$$\begin{pmatrix} \delta\vec{F}_{xy} \\ \delta\vec{F}_{yx} \\ \delta\vec{D}_y \end{pmatrix} = P_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

MDT 29/09/2015: TbT measurement and fit #2 (normal 1st, skew 2nd)



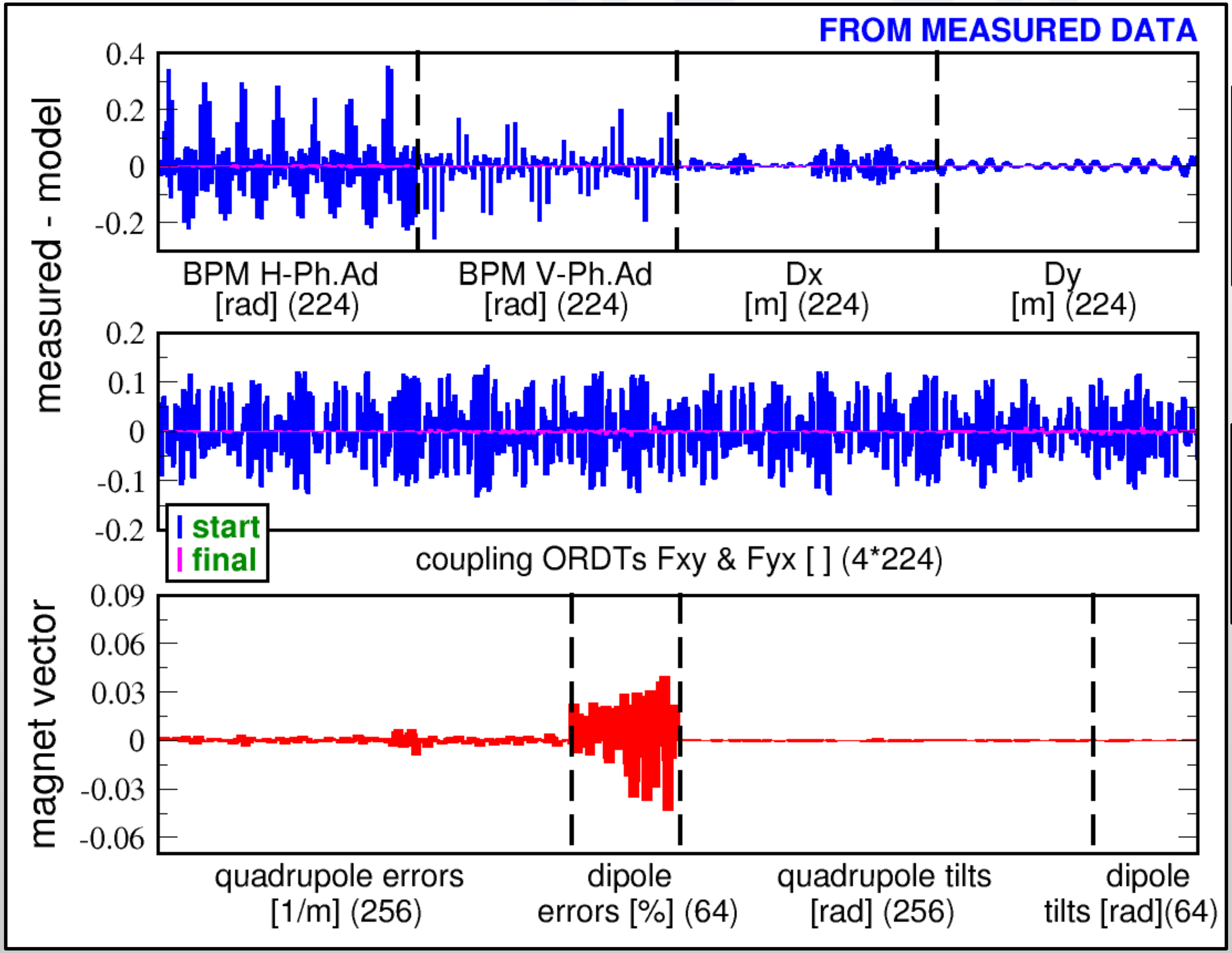
normal block

$$\begin{pmatrix} \delta\Delta\vec{\phi}_x \\ \delta\Delta\vec{\phi}_y \\ \delta\vec{D}_x \end{pmatrix} = P_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

skew block

$$\begin{pmatrix} \delta\vec{F}_{xy} \\ \delta\vec{F}_{yx} \\ \delta\vec{D}_y \end{pmatrix} = P_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

MDT 29/09/2015: TbT measurement and fit #2 (normal 1st, skew 2nd)



normal block

$$\begin{pmatrix} \delta\Delta\vec{\phi}_x \\ \delta\Delta\vec{\phi}_y \\ \delta\vec{D}_x \end{pmatrix} = P_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix}$$

skew block

$$\begin{pmatrix} \delta\vec{F}_{xy} \\ \delta\vec{F}_{yx} \\ \delta\vec{D}_y \end{pmatrix} = P_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

fitted model depends highly on nr. of eigen-values in SVD and weights between Ph-Ad$_{xy}$ D$_{xy}$ & F$_{xy,yx}$

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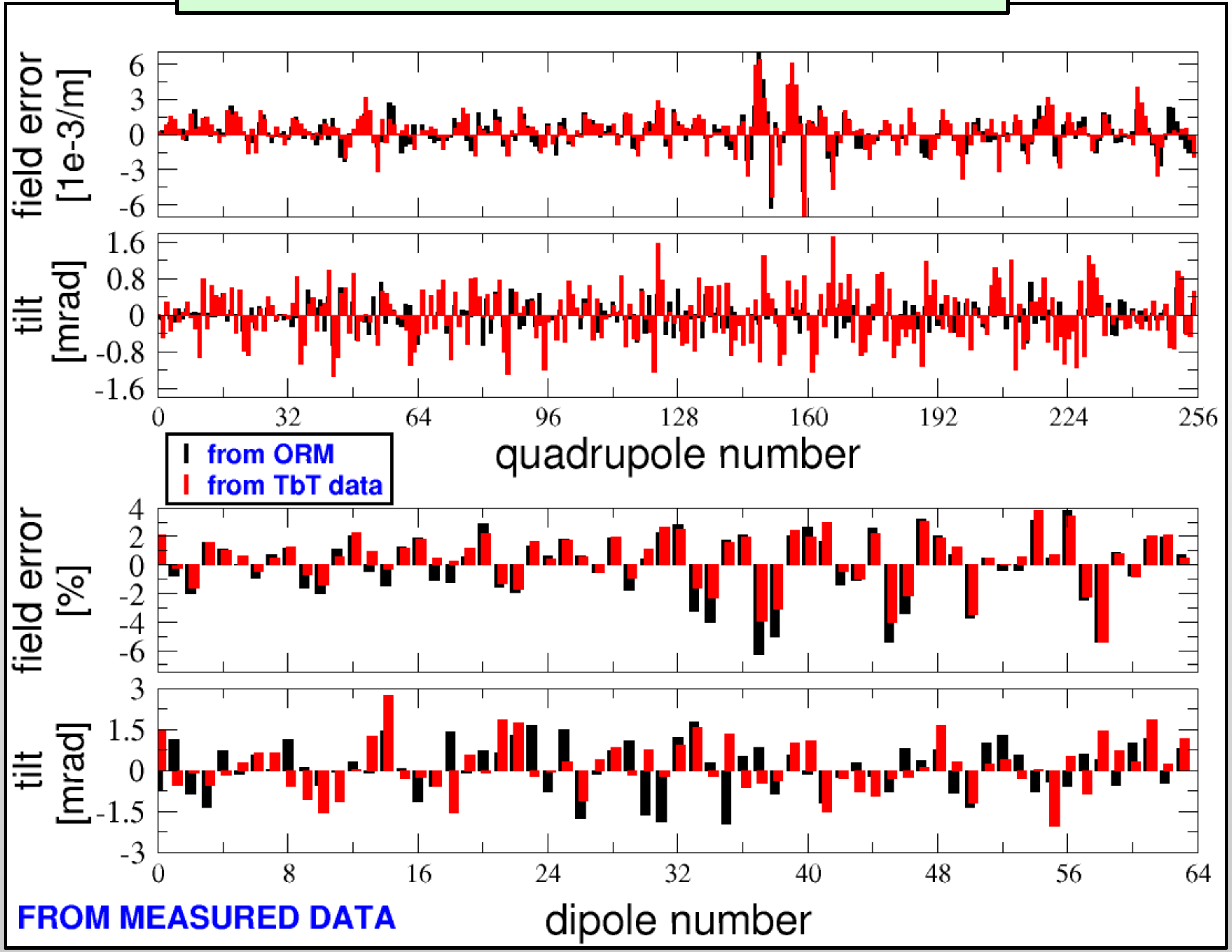
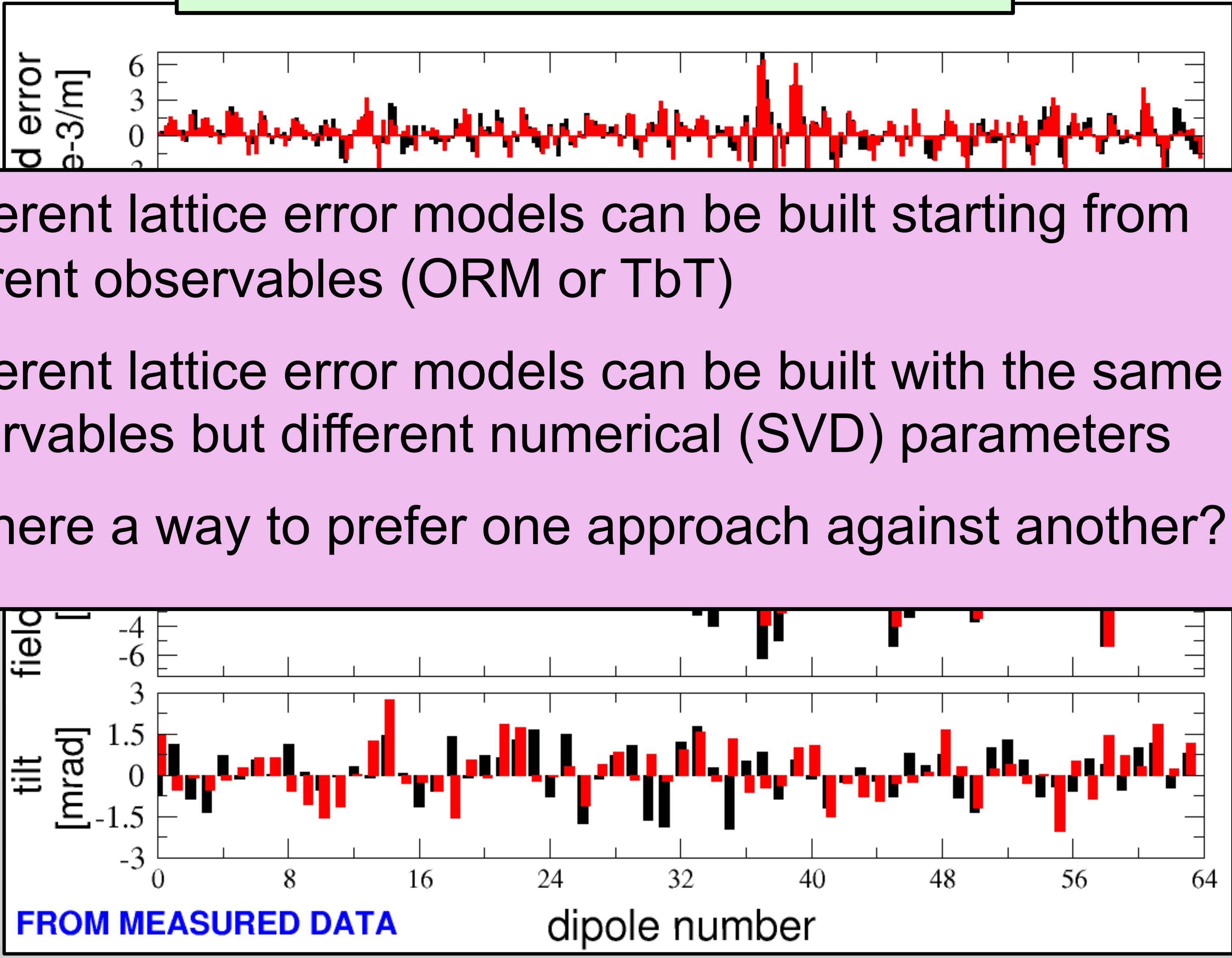
examples of inferred linear models



linear magnetic model: comparisons

examples of inferred linear models



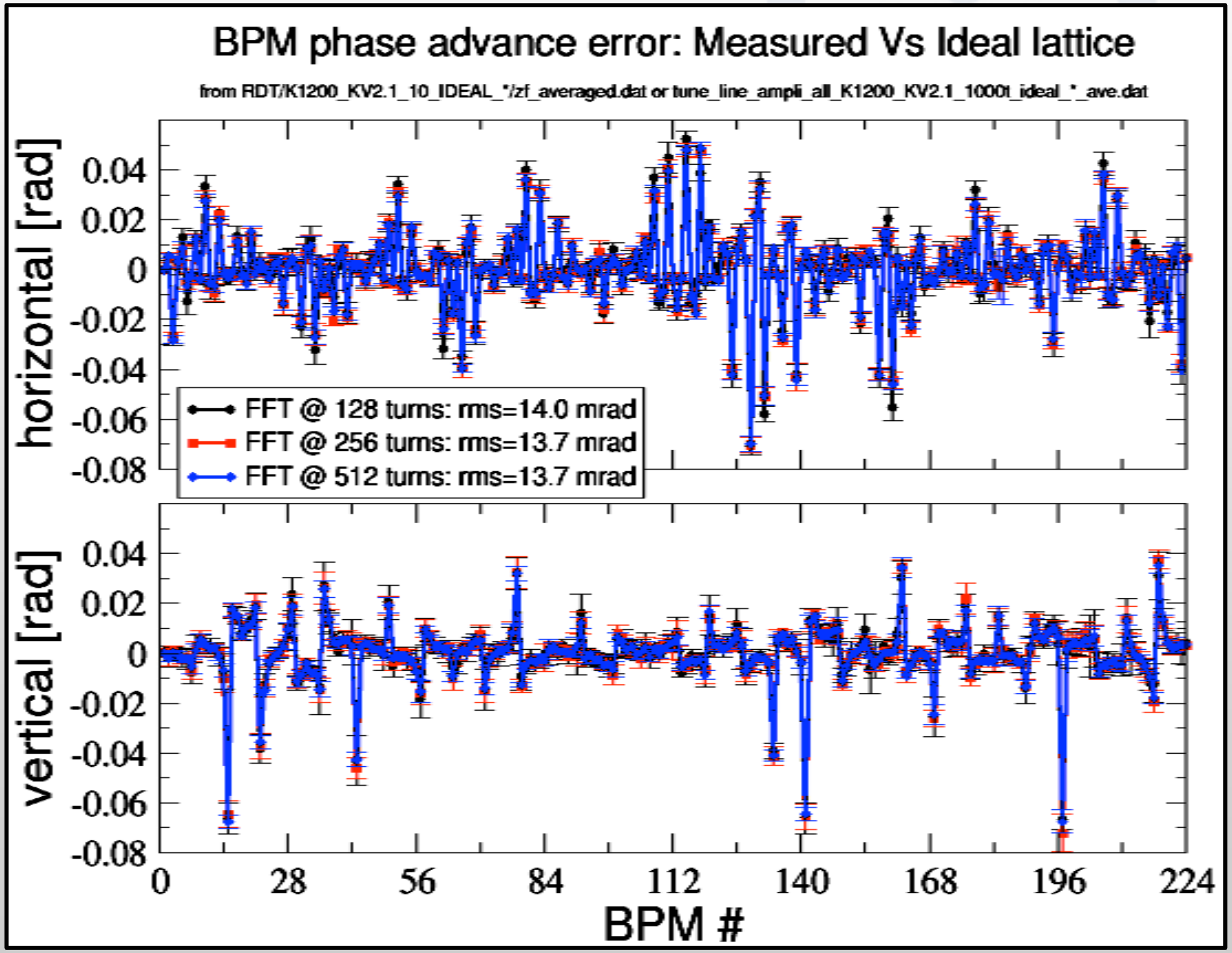
• different lattice error models can be built starting from different observables (ORM or TbT)

• different lattice error models can be built with the same observables but different numerical (SVD) parameters

• is there a way to prefer one approach against another?

Is there a way to prefer one approach against another?

1. Start with the observables



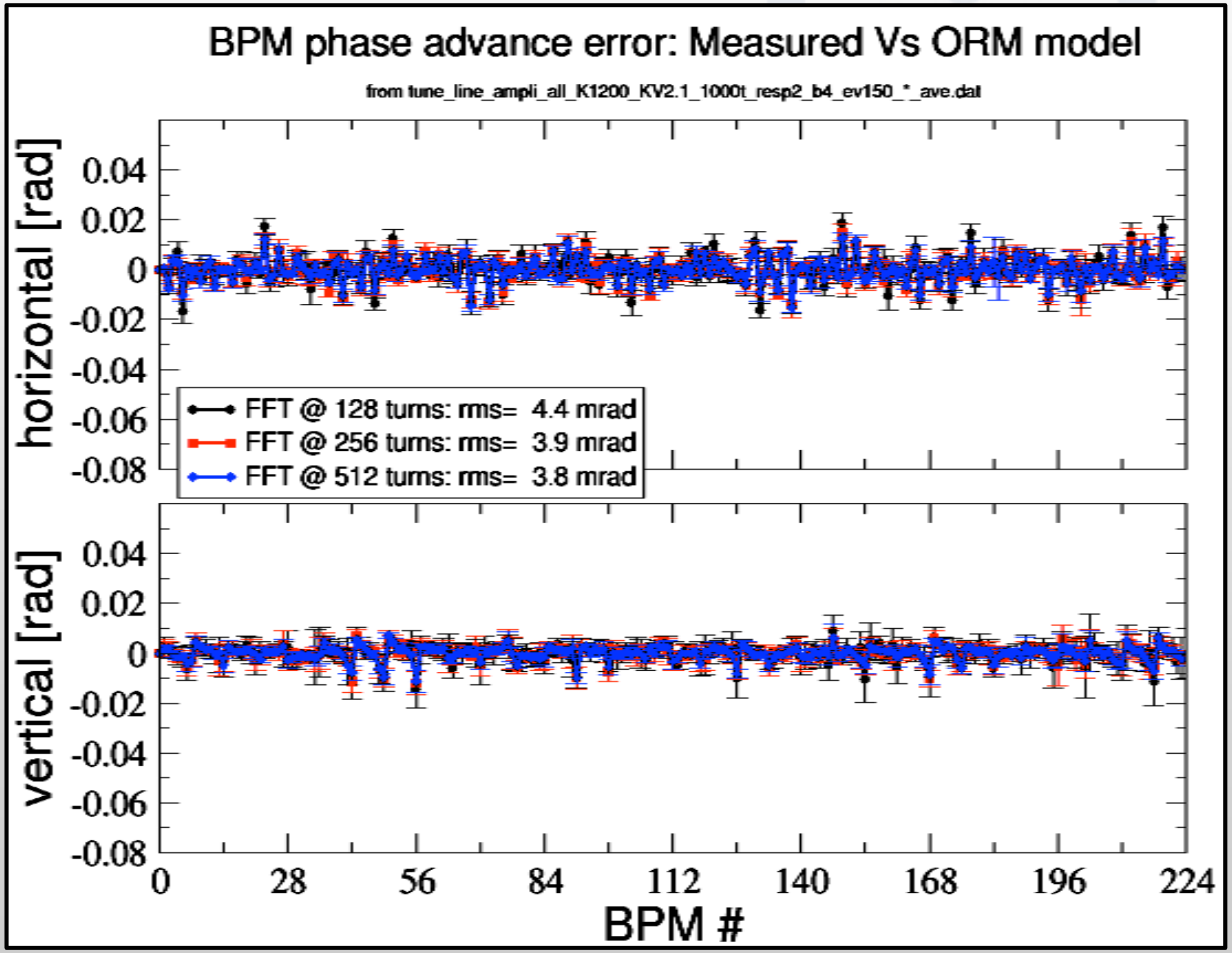
Initial residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
820	27	356	15	14

linear magnetic model: comparisons

Is there a way to prefer one approach against another?

1. Start with the observables



Initial residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
820	27	356	15	14

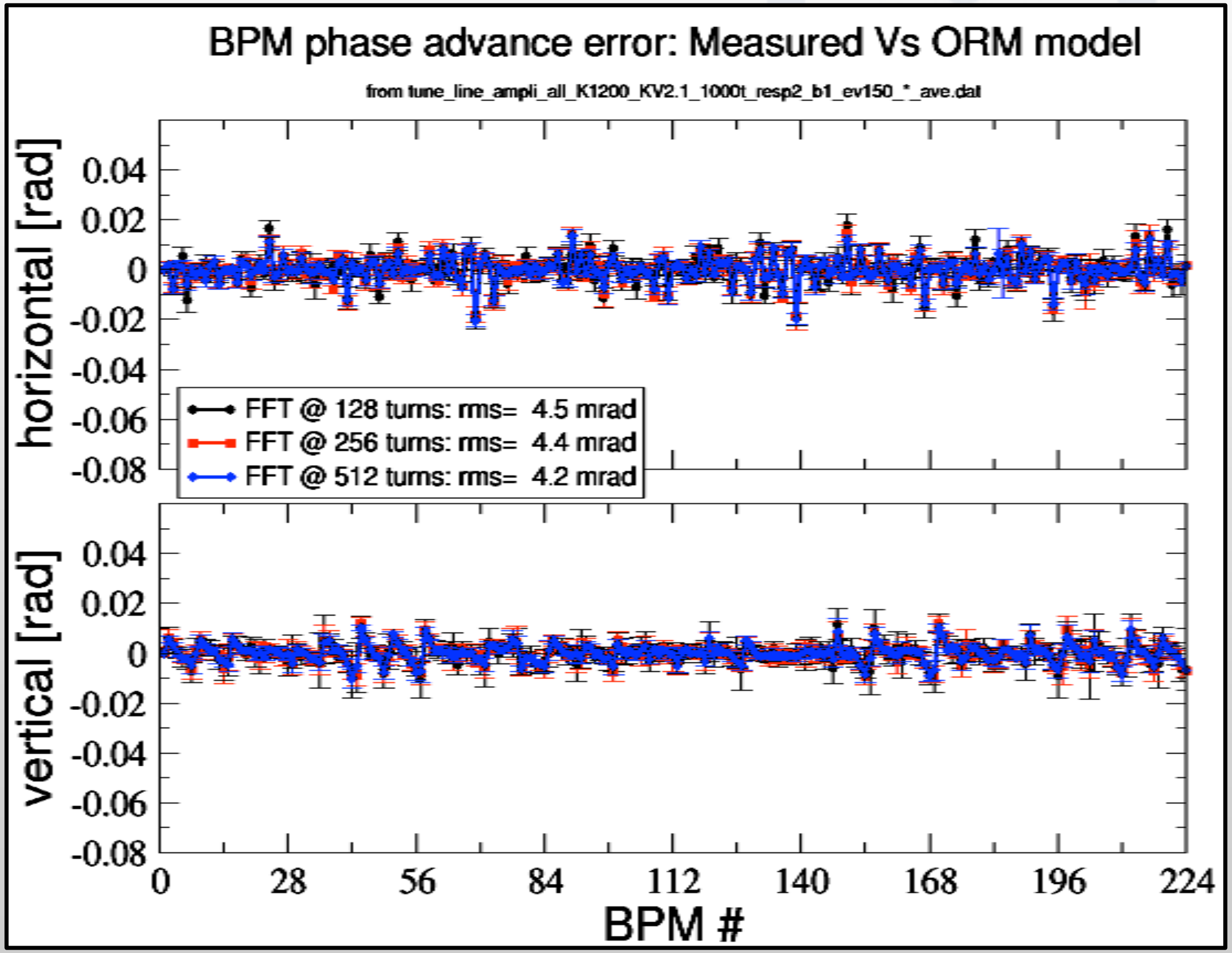
Final residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
110	3.1	35	0.3	3.8

ORM fit **TbT fit**

Is there a way to prefer one approach against another?

1. Start with the observables



Initial residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
820	27	356	15	14

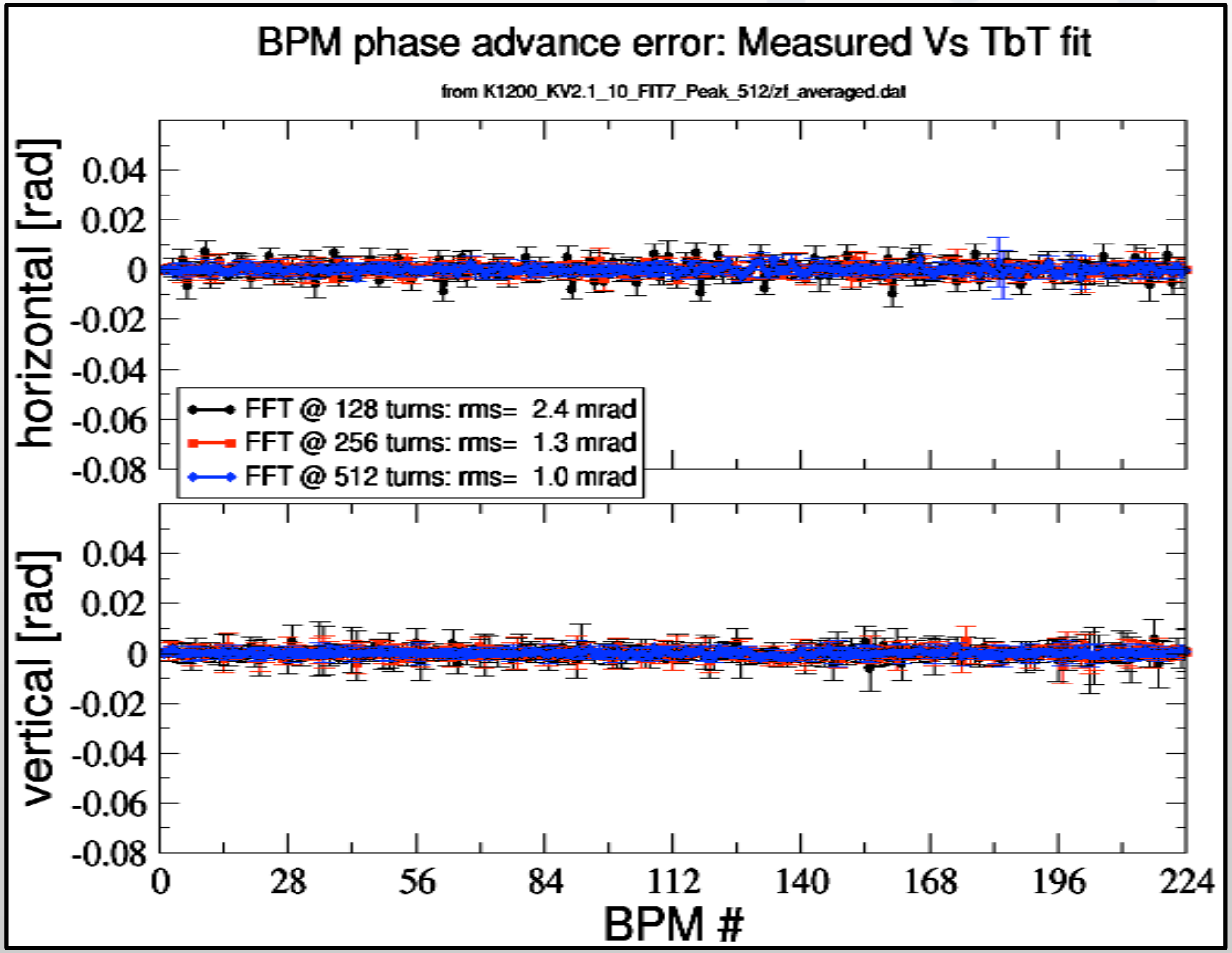
Final residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
110	3.1	35	0.3	3.8
80	3.3	35	0.2	4.2

ORM fit **TbT fit**

Is there a way to prefer one approach against another?

1. Start with the observables



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R_n	D_x	R_s	D_y	Ph. Ad.
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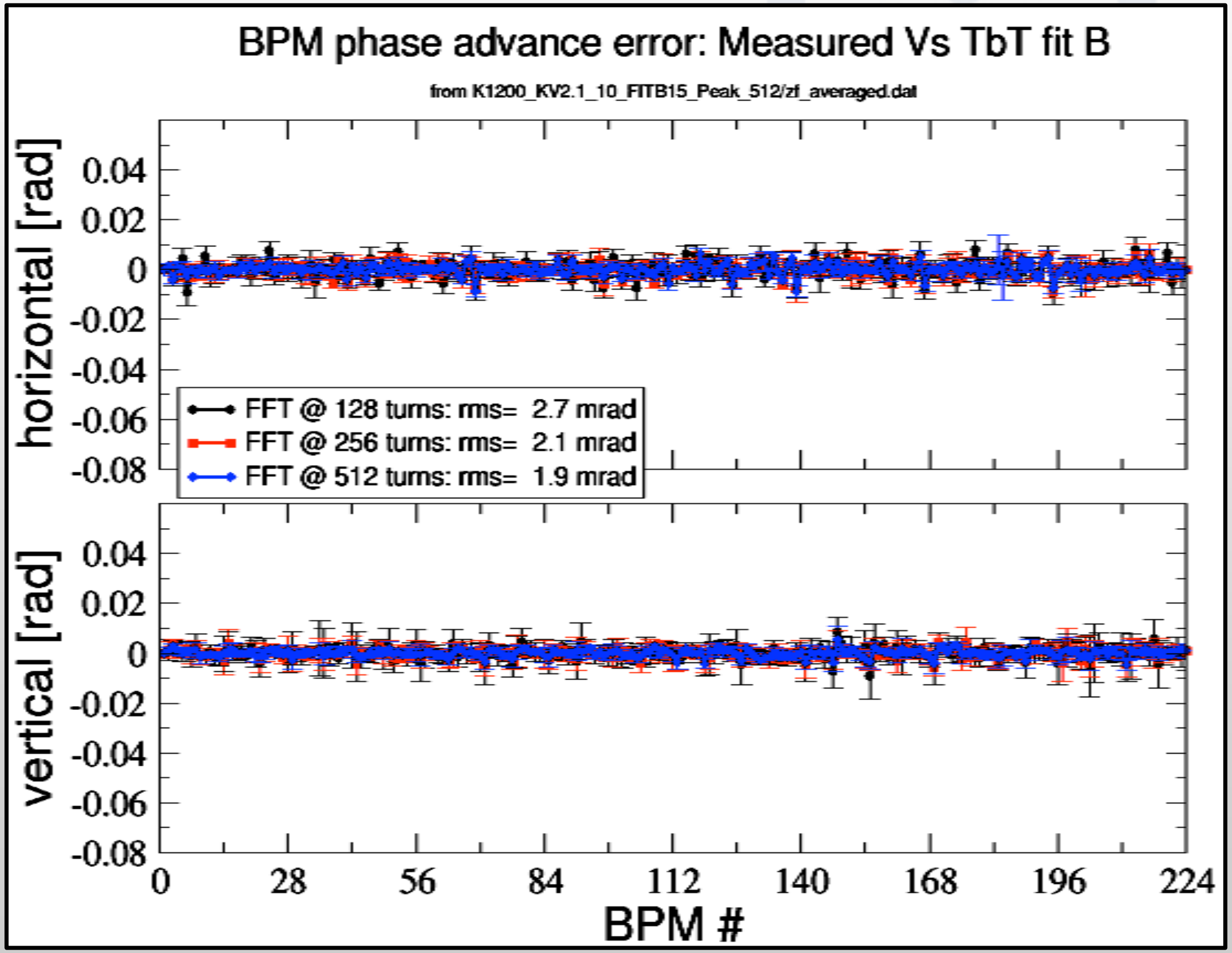
80	3.3	35	0.2	4.2
150	3.6	42	0.5	1.0

ORM fit **TbT fit**

Is there a way to prefer one approach against another?

1. Start with the observables



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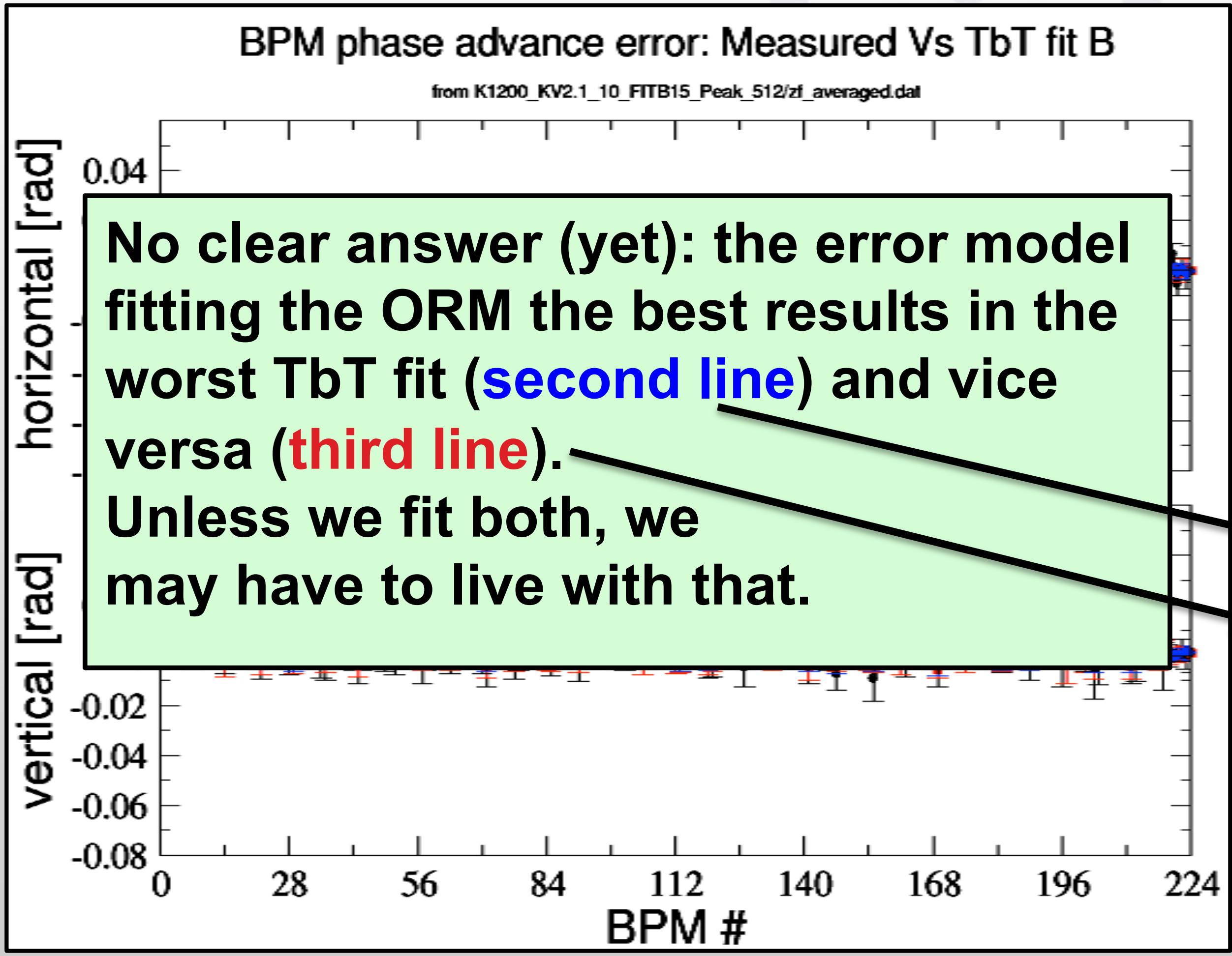
150	3.6	42	0.5	1.0
140	3.6	44	0.4	1.9

ORM fit **TbT fit**

linear magnetic model: comparisons

Is there a way to prefer one approach against another?

1. Start with the observables



No clear answer (yet): the error model fitting the ORM the best results in the worst TbT fit (second line) and vice versa (third line). Unless we fit both, we may have to live with that.

Initial residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
820	27	356	15	14

Final residuals [10^{-3}]:

R_n	D_x	R_s	D_y	Ph. Ad.
110	3.1	35	0.3	3.8
80	3.3	35	0.2	4.2
150	3.6	42	0.5	1.0
140	3.6	44	0.4	1.9

=worst = best

ORM fit TbT fit

linear magnetic model: comparisons

Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating

Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating

β from BPM Ph. Adv. & trans. matrices

$$\beta_{x,1}^{(meas)} = \frac{\left(\frac{1}{\tan\Delta\phi_{x,21}^{(meas)}} - \frac{1}{\tan\Delta\phi_{x,31}^{(meas)}}\right)}{\frac{m_{11}}{m_{12}} - \frac{n_{11}}{n_{12}}}$$

$$M_{xx}(1\rightarrow 2) = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \;,\; N_{xx}(1\rightarrow 3) = \begin{pmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{pmatrix}$$

$$\Delta\phi_{x,21}^{(meas)} = \phi_{2,H(1,0)} - \phi_{1,H(1,0)}$$

- BPM calibration independent
- model dependent (transfer matrices)
- BPM ph.Adv. cannot be ~nπ/2 (tan->∞)

β from tune line amplitudes @ BPMs

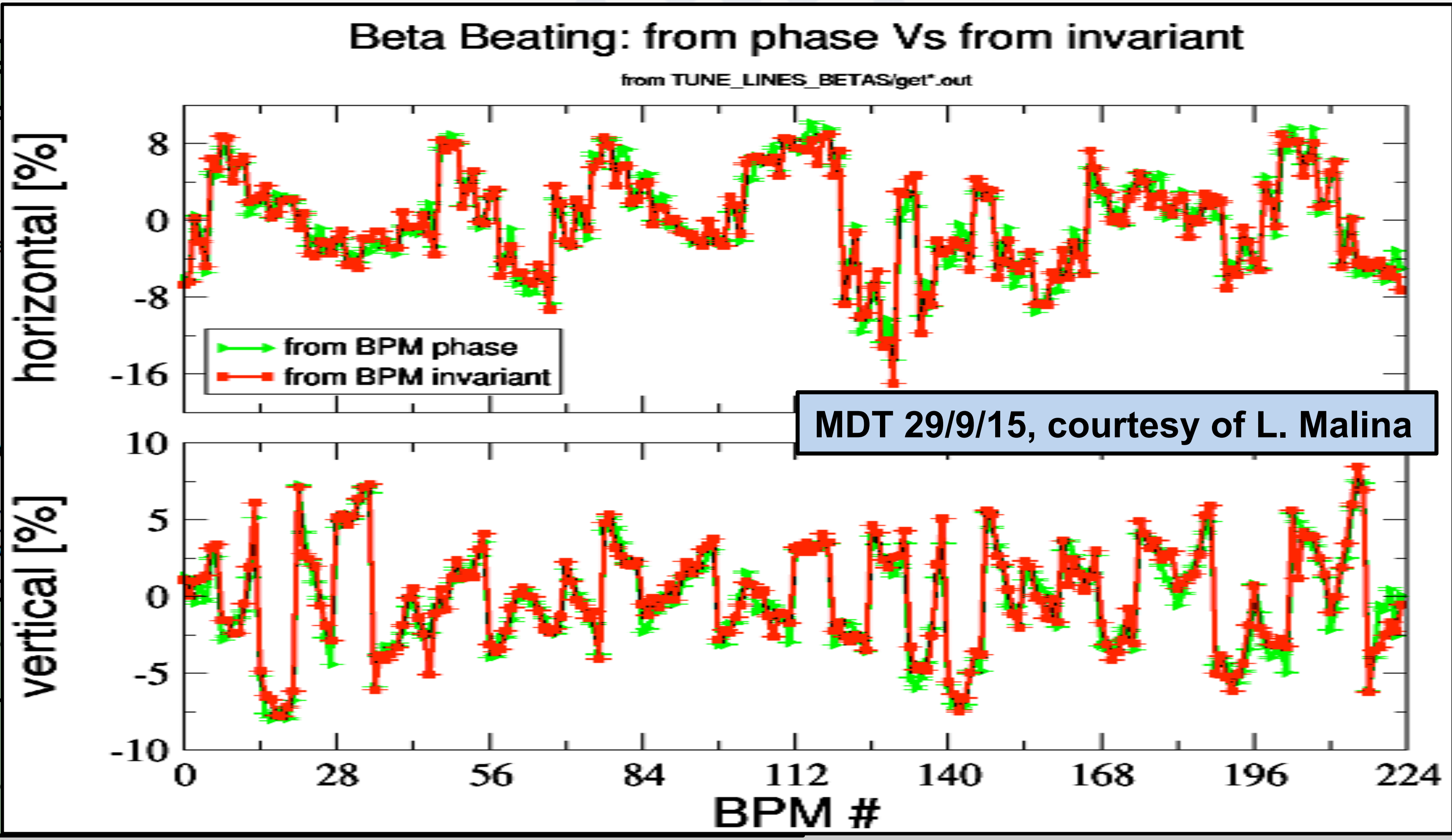
$$\beta_{x,1}^{(meas)} = \left(\frac{|H_1(1,0)|}{\langle |H(1,0)|\rangle}\right)^2 \beta_{x,1}^{(ideal)} \quad , \quad \left[\frac{\vec{x}_1^{(TbT)}}{\sqrt{\beta_{x,1}^{(ideal)}}}\right]$$

$$\beta_{y,1}^{(meas)} = \left(\frac{|V_1(0,1)|}{\langle |V(0,1)|\rangle}\right)^2 \beta_{y,1}^{(ideal)} \quad , \quad \left[\frac{\vec{x}_1^{(TbT)}}{\sqrt{\beta_{x,1}^{(ideal)}}}\right]$$

- BPM calibration dependent
- less model dependent (β only)
- no need of BPM synchroniz.

Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating



MDT 29/9/15, courtesy of L. Malina

Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating

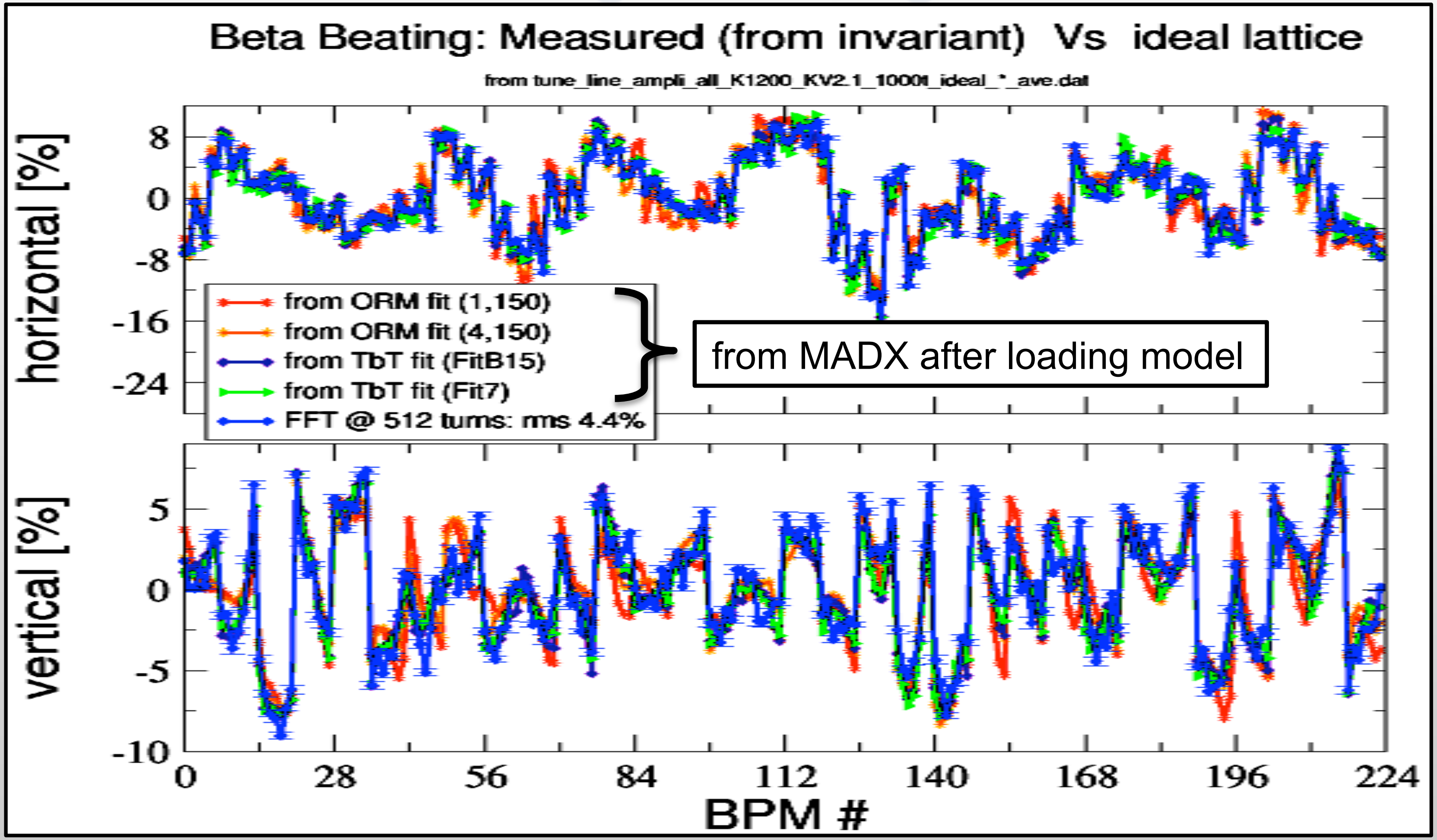
β from tune line amplitudes @ BPMs

$$\beta_{x,1}^{(meas)}\ beat = \frac{\beta_{x,1}^{(meas)} - \beta_{x,1}^{(ideal)}}{\beta_{x,1}^{(ideal)}} = \left(\frac{|H_1(1,0)|}{\langle |H(1,0)| \rangle}\right)^2 - 1$$

$$\beta_{y,1}^{(meas)}\ beat = \frac{\beta_{y,1}^{(meas)} - \beta_{y,1}^{(ideal)}}{\beta_{y,1}^{(ideal)}} = \left(\frac{|V_1(0,1)|}{\langle |V(0,1)| \rangle}\right)^2 - 1$$

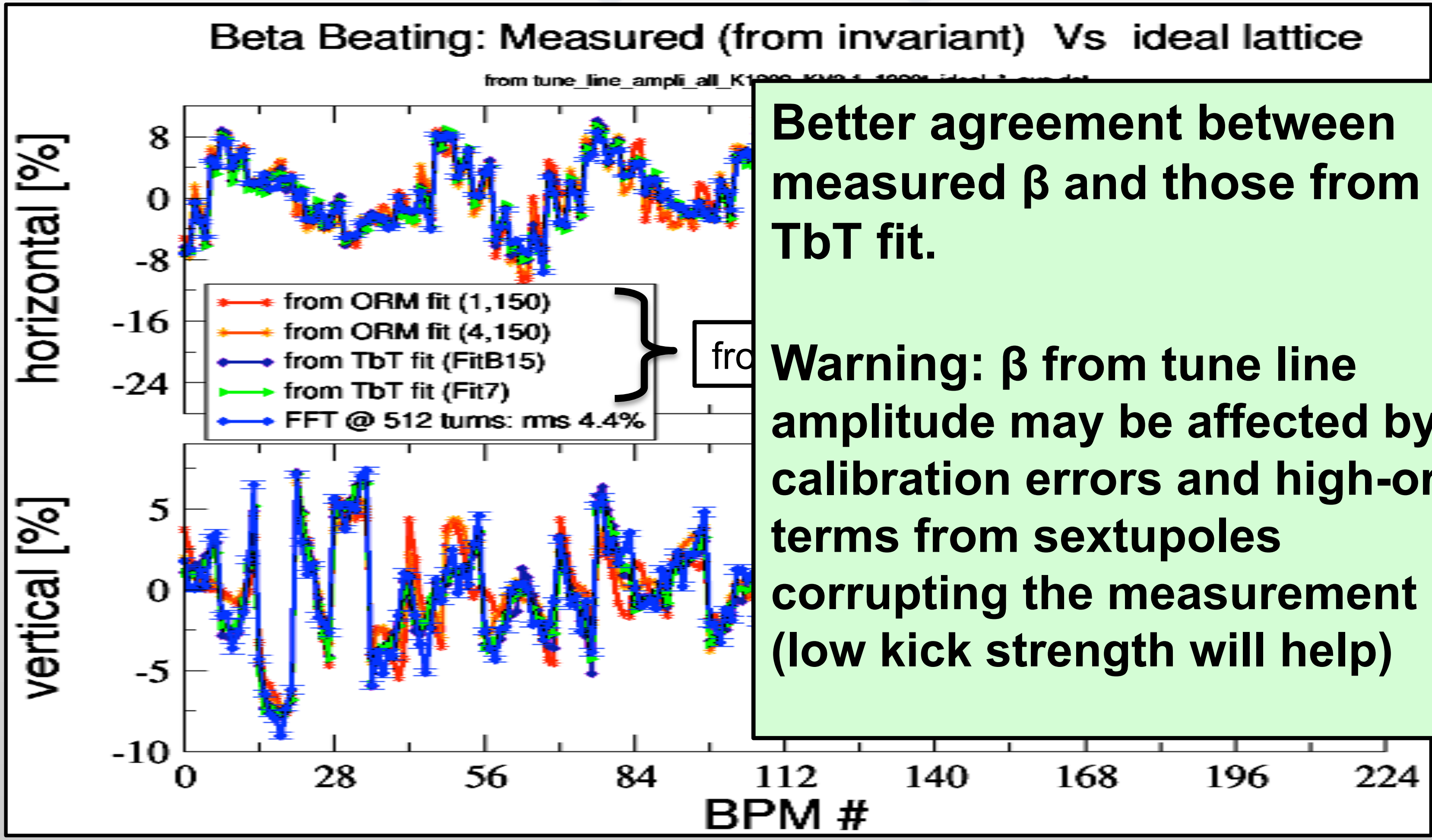
Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating



Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating

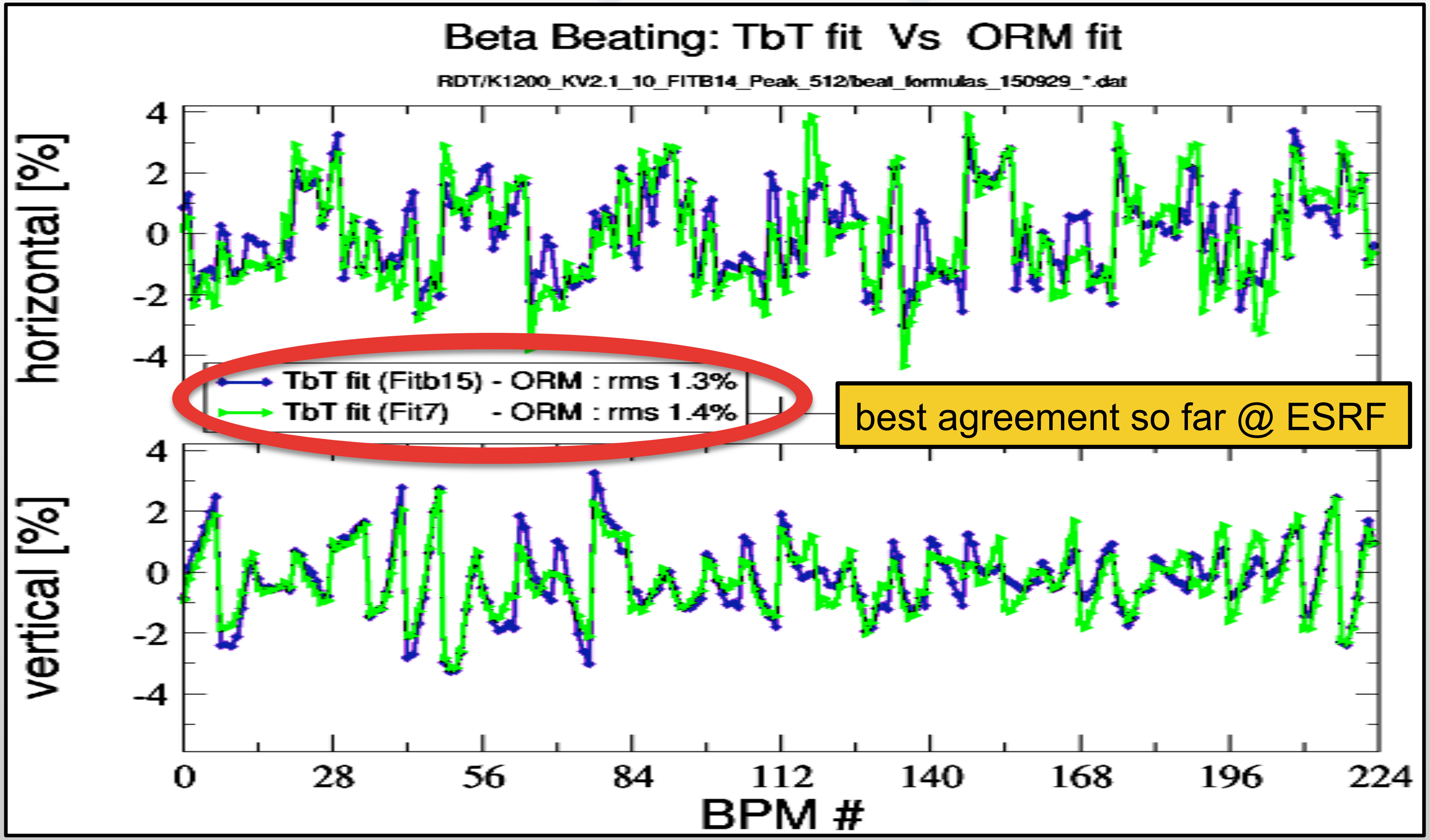


Better agreement between measured β and those from the TbT fit.

Warning: β from tune line amplitude may be affected by calibration errors and high-order terms from sextupoles corrupting the measurement (low kick strength will help)

Is there a way to prefer one approach against another?

2. Continue with the observables: beta-beating



best agreement so far @ ESRF

Is there a way to prefer one approach against another?

3. End with practical considerations (@ ESRF)

- ORM measurement requires ~20’ + ~5’ for fit and computation of correction
- TbT measurement are quicker (~1’) but requires BPM switch from slow to TbT (MAF) acquisition mode, back and forth (~20’)
- In TbT mode we cannot correct the orbit: impossible to check the effectiveness of a correction without going back to the slow acquisition mode: very time consuming
- Quality of TbT analysis will dependent on the sextupole setting (i.e. filling mode): modes with higher chroma and detuning => poorer quality (greater decoherence, lower spectr. resol.). ORM fit is independent upon the modes
- ORM and TbT β-beating deviate of ~1% (rms), well below the measured overal 4% (rms): presently we are limited by the low number of quad correctors (32/256), not by the error model

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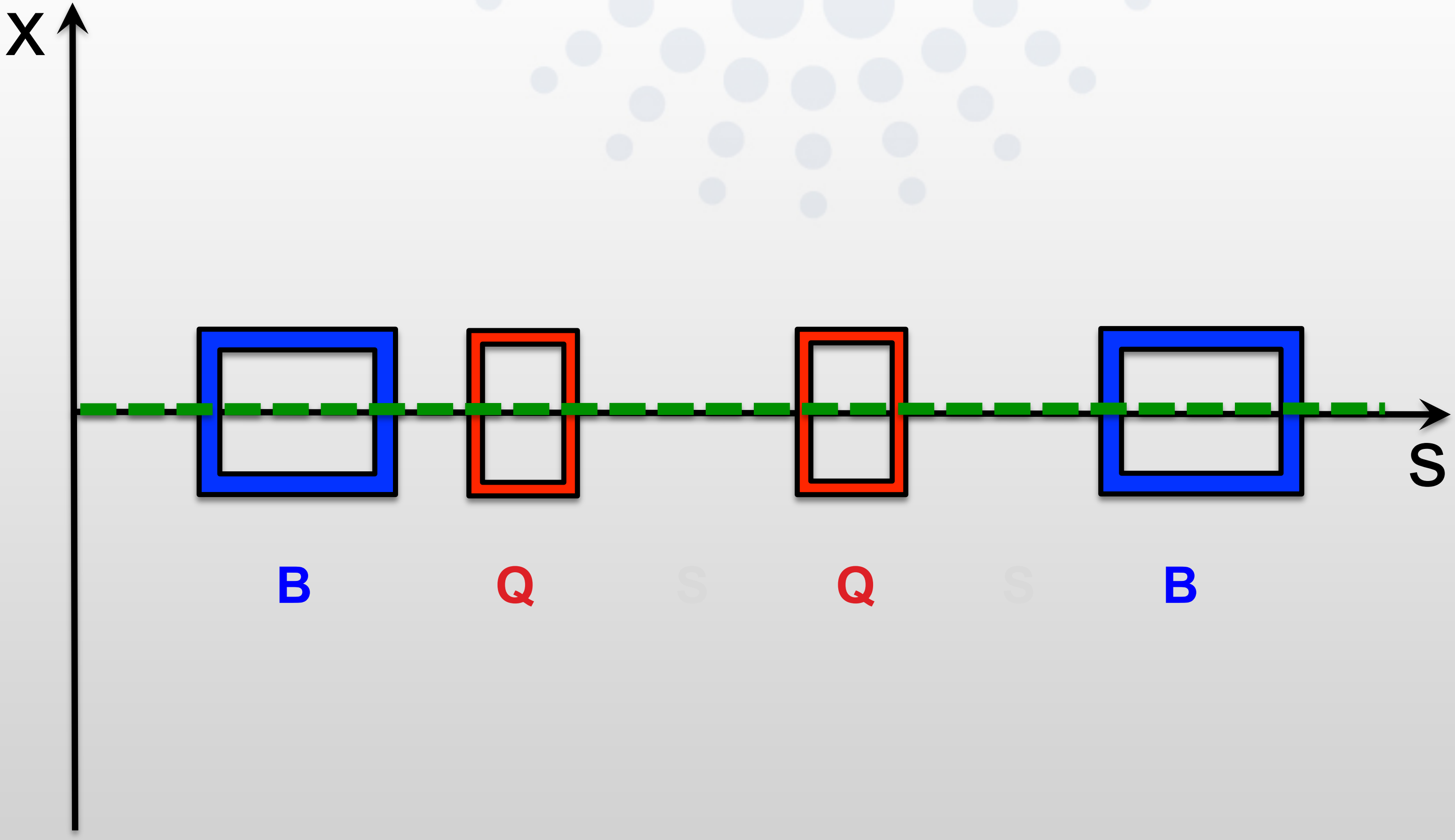
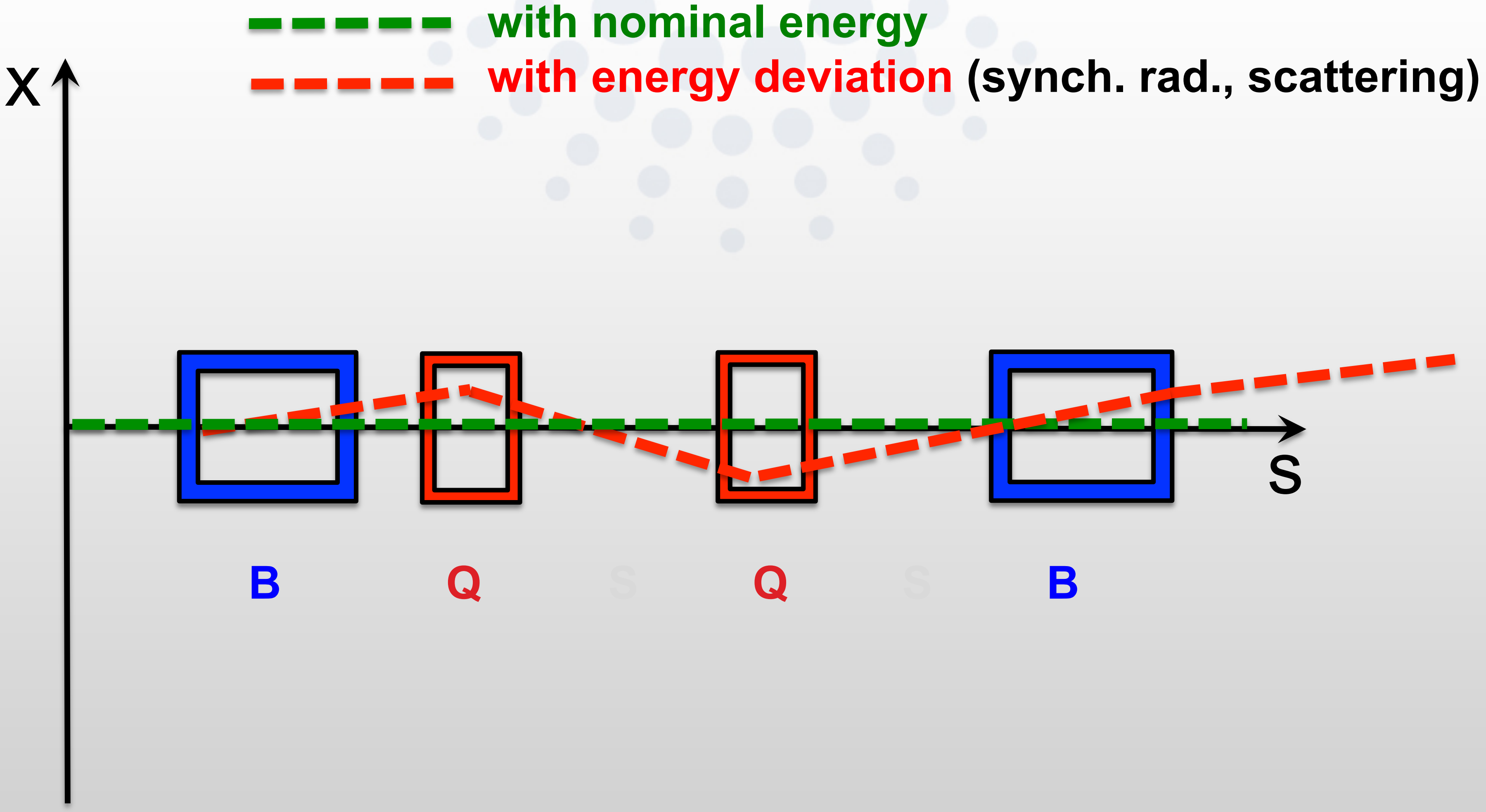
ideal orbit of particle with bends & quads

with nominal energy



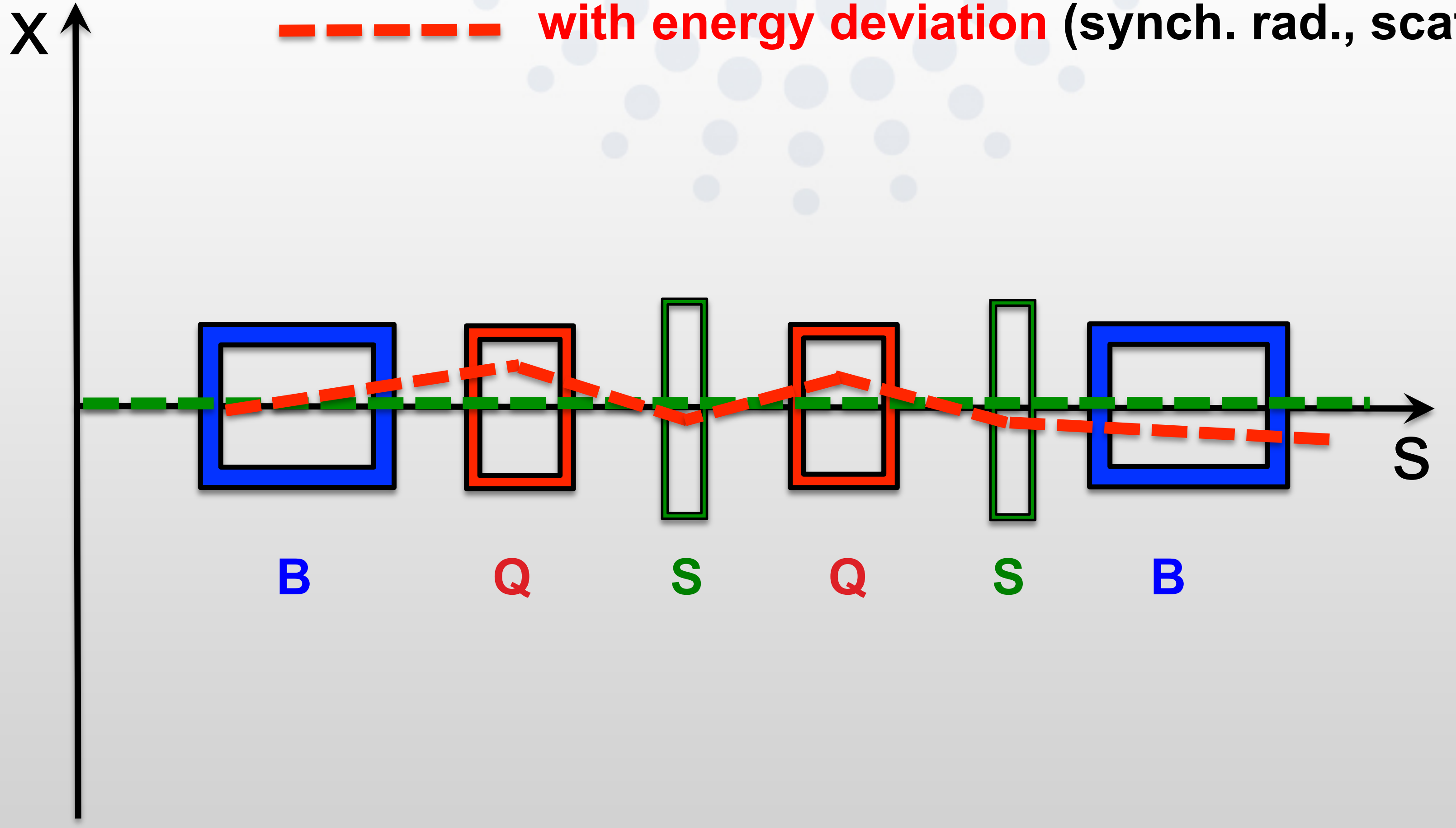
ideal orbit of particle with bends & quads



ideal orbit of particle with bends & quads & sexts

with nominal energy

with energy deviation (synch. rad., scattering)



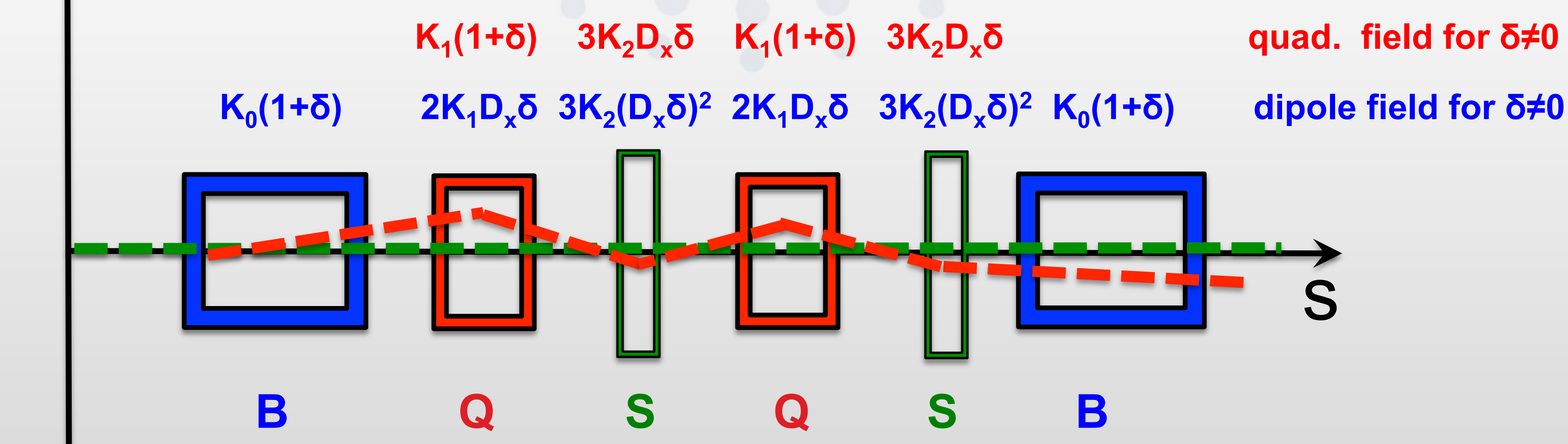
nonlinear magnetic model from orbit BPM data

ideal orbit of particle with bends & quads & sexts

- - - - - - with nominal energy

- - - - - - with energy deviation (synch. rad., scattering)

X



feed-down fields for $\delta \neq 0$ (orbit distortion @ magnet $\Delta x = D_x\delta$):

quad: $K_1x^2 \rightarrow K_1(x+\Delta x)^2 = K_1(x+D_x\delta)^2 = K_1x^2 + (2K_1D_x\delta)x$ Q->Q+B

sext: $K_2x^3 \rightarrow K_2(x+\Delta x)^3 = K_2x^3 + (3K_2Dx\delta)x^2 + [3K_2(Dx\delta)^2]x$ S->S+Q+B

nonlinear magnetic model from orbit BPM data

- off energy additional focusing is provided by sextupoles
- by measuring the ORM off energy information on sextupoles can be extracted

- off energy additional focusing is provided by sextupoles
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approach Nr. 1

on momentum δ=0:

$$\delta O_{xx} = O_{xx}^{(meas)} - O_{xx}^{(ideal)}$$
$$\delta O_{yy} = O_{yy}^{(meas)} - O_{yy}^{(ideal)}$$
$$\delta D_{x} = D_{x}^{(meas)} - D_{x}^{(ideal)}$$

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta=0} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta=0} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

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approach Nr. 1

on momentum δ=0:

$$\delta O_{xx} = O_{xx}^{(meas)} - O_{xx}^{(ideal)}$$
$$\delta O_{yy} = O_{yy}^{(meas)} - O_{yy}^{(ideal)}$$
$$\delta D_{x} = D_{x}^{(meas)} - D_{x}^{(ideal)}$$

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta=0} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta=0} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

off momentum δ≠0:

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta\neq 0} = M'_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \\ \delta\vec{K}_2^{(sext)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta\neq 0} = M'_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \\ \vec{\theta}^{(sext)} \end{pmatrix}$$

- off energy additional focusing is provided by sextupoles
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approach Nr. 1

on momentum δ=0:

$$\delta O_{xx} = O_{xx}^{(meas)} - O_{xx}^{(ideal)}$$
$$\delta O_{yy} = O_{yy}^{(meas)} - O_{yy}^{(ideal)}$$
$$\delta D_{x} = D_{x}^{(meas)} - D_{x}^{(ideal)}$$

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta=0} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta=0} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

off momentum δ≠0 including linear error model, to be pseudo-inverted:

$$\begin{pmatrix} \delta\vec{O}^{(err)} \\ \delta\vec{D}^{(err)} \end{pmatrix}_{\delta\neq 0} = M'_{(err)} \begin{pmatrix} \delta\vec{K}_2^{(sext)} \\ \vec{\theta}^{(sext)} \end{pmatrix}$$

nonlinear magnetic model from orbit BPM data

- off energy additional focusing is provided by sextupoles
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approach Nr. 2

on momentum δ=0:

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta=0} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta=0} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}_{\delta=0}^{(fit)}$$

- off energy additional focusing is provided by sextupoles
- by measuring the ORM off energy information on sextupoles can be extracted

approach Nr. 2

on momentum δ=0:

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta=0} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta=0} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix} \Rightarrow \begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}_{\delta=0}^{(fit)}$$

off momentum δ≠0 :

$$\begin{pmatrix} \delta\vec{O}_{xx} \\ \delta\vec{O}_{yy} \\ \delta\vec{D}_{x} \end{pmatrix}_{\delta\neq0} = M_{normal} \begin{pmatrix} \delta\vec{K}_1^{(quad)} \\ \delta\vec{K}_0^{(bend)} \end{pmatrix} \qquad \begin{pmatrix} \delta\vec{O}_{xy} \\ \delta\vec{O}_{yx} \\ \delta\vec{D}_{y} \end{pmatrix}_{\delta\neq0} = M_{skew} \begin{pmatrix} \vec{\theta}^{(quad)} \\ \vec{\theta}^{(bend)} \end{pmatrix} \Rightarrow \begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}_{\delta\neq0}^{(fit)}$$

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approach Nr. 2

on momentum δ=0:

$$\begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}^{(fit)}_{\delta=0}$$

off momentum δ≠0 :

$$\begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}^{(fit)}_{\delta\neq0}$$

$$\begin{pmatrix} \partial\vec{\beta}/\partial\delta \\ \partial\vec{D}/\partial\delta \\ \partial\vec{F}_{xy}/\partial\delta \end{pmatrix}^{(fit)} \Rightarrow \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(fit)} - \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(model)} = S \begin{pmatrix} \delta\vec{K}_2^{(sext)} \\ \vec{\theta}^{(sext)} \end{pmatrix}$$

to be pseudo-inverted

chromatic terms

- off energy additional focusing is provided by sextupoles
- by measuring the ORM off energy information on sextupoles can be extracted

approach Nr. 2

being tested @ ESRF

on momentum δ=0:

$$\begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}^{(fit)}_{\delta=0}$$

off momentum δ≠0 :

$$\begin{pmatrix} \vec{\beta} \\ \vec{D} \\ \vec{F}_{xy} \end{pmatrix}^{(fit)}_{\delta\neq0}$$

$$\begin{pmatrix} \partial\vec{\beta}/\partial\delta \\ \partial\vec{D}/\partial\delta \\ \partial\vec{F}_{xy}/\partial\delta \end{pmatrix}^{(fit)} \Rightarrow \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(fit)} - \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(model)} = S \begin{pmatrix} \delta\vec{K}_2^{(sext)} \\ \vec{\theta}^{(sext)} \end{pmatrix}$$

to be pseudo-inverted

chromatic terms

nonlinear magnetic model from orbit BPM data

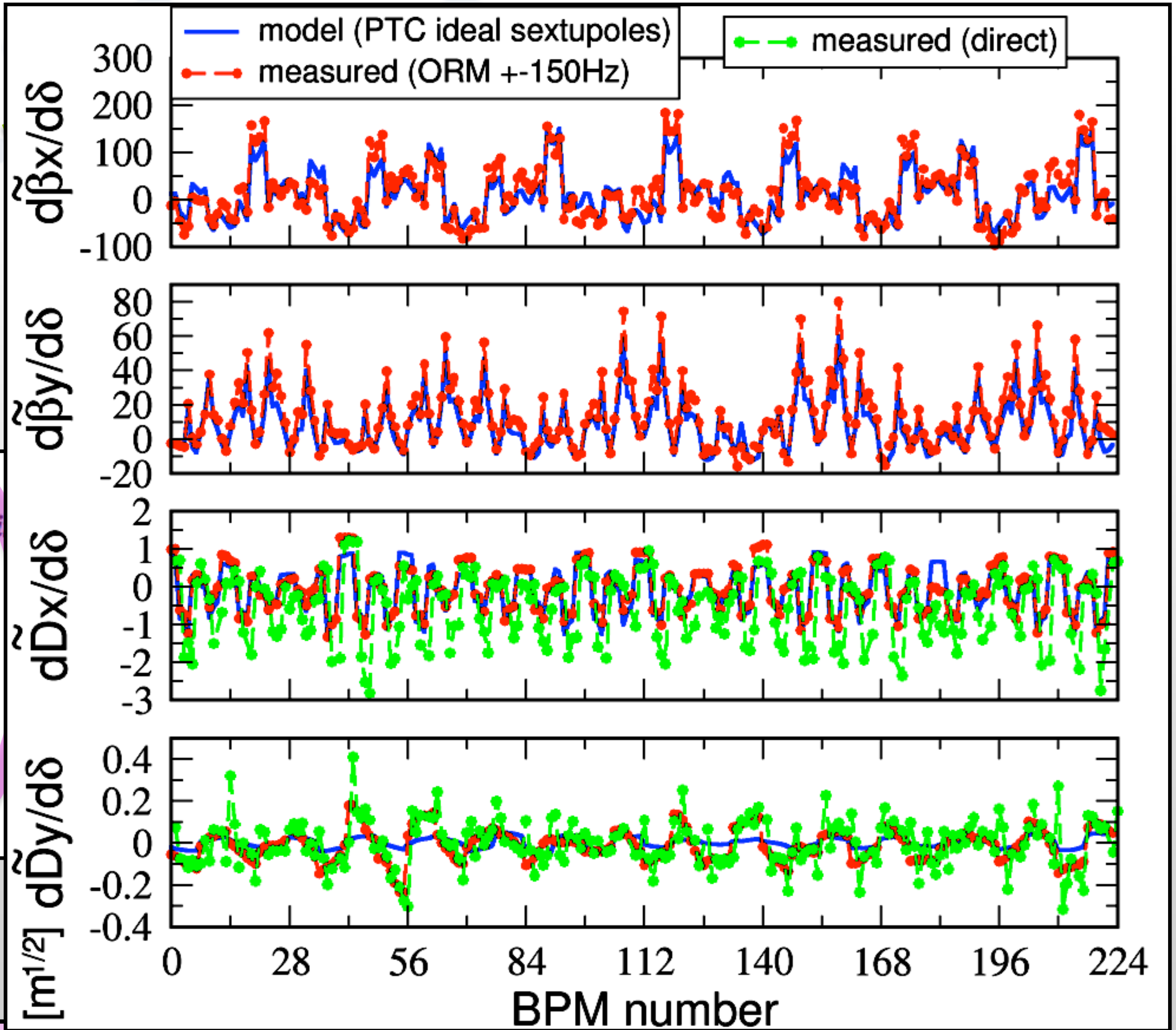
from MADX-PTC
or
analytic formulas

$$
\begin{pmatrix} \partial\vec{\beta}/\partial\delta \\ \partial\vec{D}/\partial\delta \\ \partial\vec{F}_{xy}/\partial\delta \end{pmatrix}^{(fit)} \Rightarrow \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(fit)} - \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(model)} = S \begin{pmatrix} \delta\vec{K}_2^{(sext)} \\ \vec{\theta}^{(sext)} \end{pmatrix}
$$

from 2 ORM measurements & fits

from MADX-PTC
or
analytic formulas

$$\begin{pmatrix} \partial\vec{\beta}/\partial\delta \\ \partial\vec{D}/\partial\delta \\ \partial\vec{F}_{xy}/\partial\delta \end{pmatrix}^{(fit)} \Rightarrow \begin{pmatrix} \vec{\beta}\,' \\ \vec{D}\,' \\ \vec{F}_{xy}\,' \end{pmatrix}^{(fit)}$$



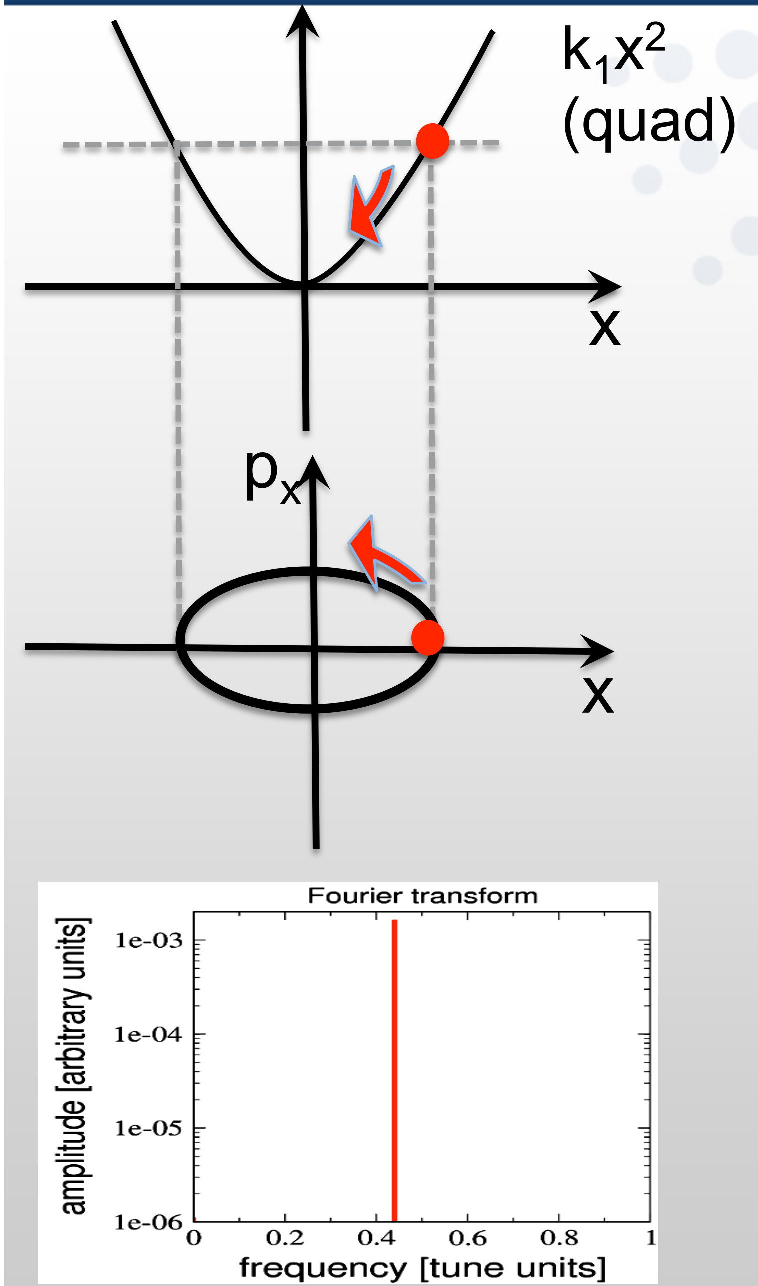
from 2 ORM measurements & fits

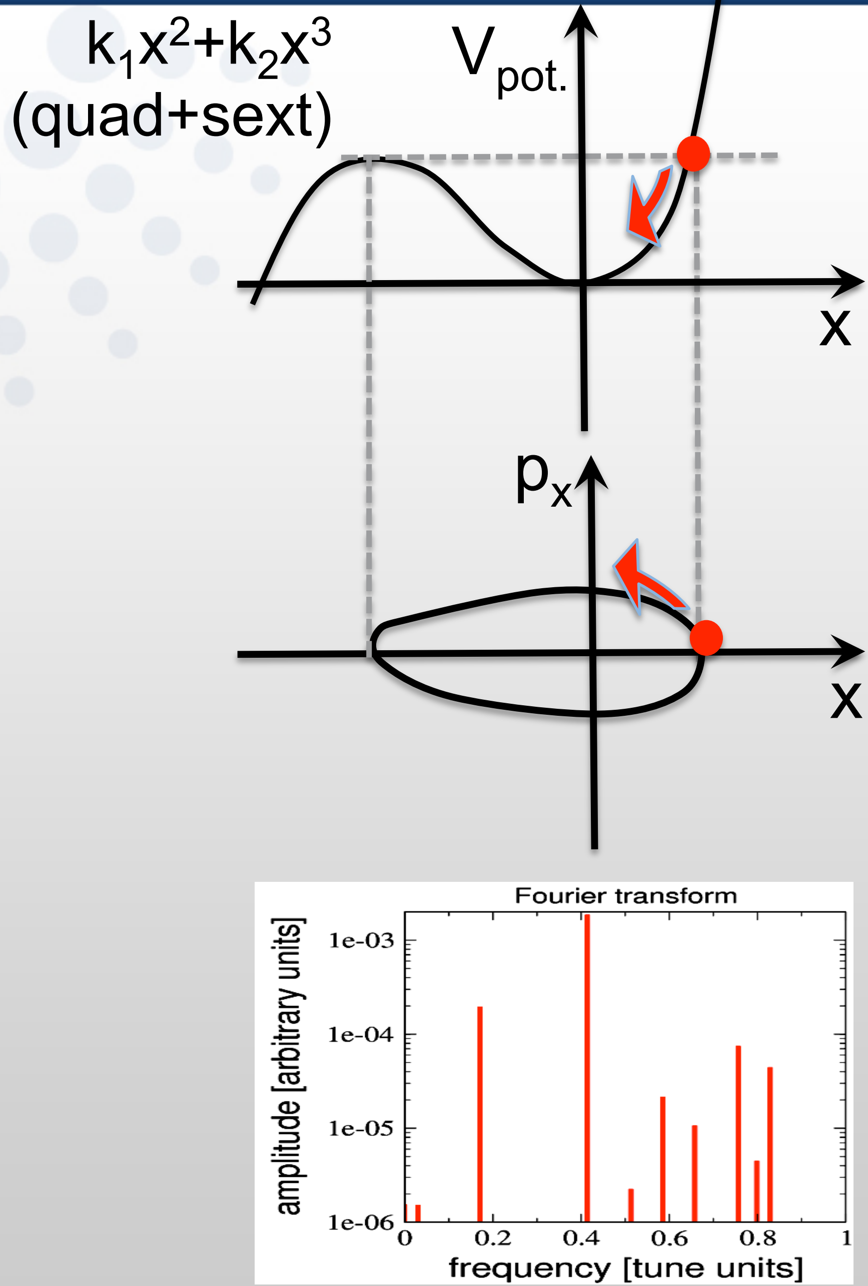
1st meas. @ ESRF 2014

Contents

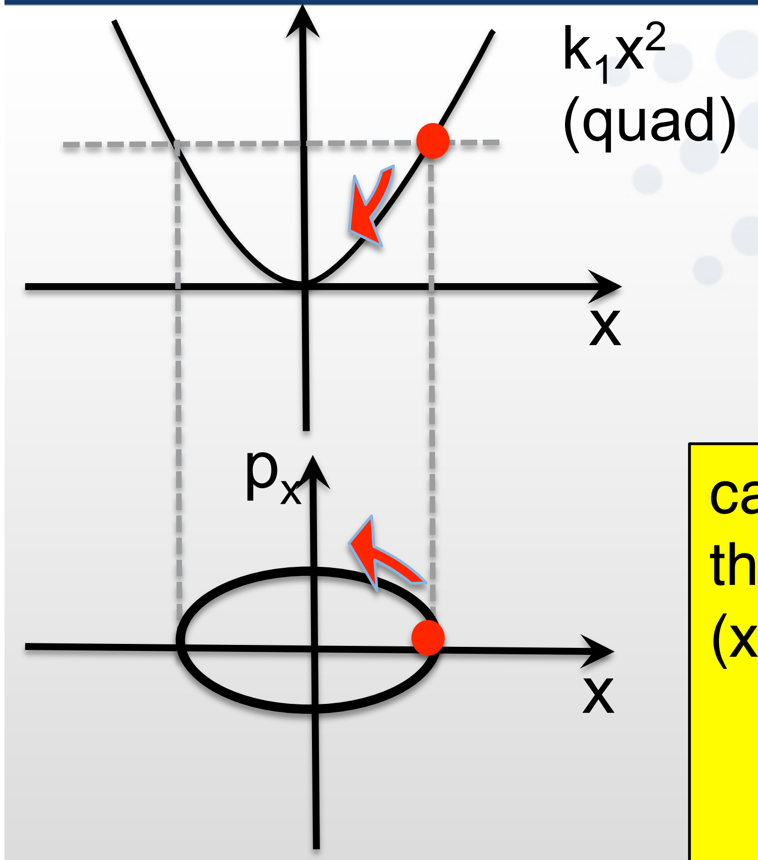
- the physics behind the analysis
- linear magnetic model from orbit BPM data
- linear magnetic model from TbT BPM data
- linear magnetic model: comparisons
- nonlinear magnetic model from orbit BPM data
- nonlinear magnetic model from TbT BPM data

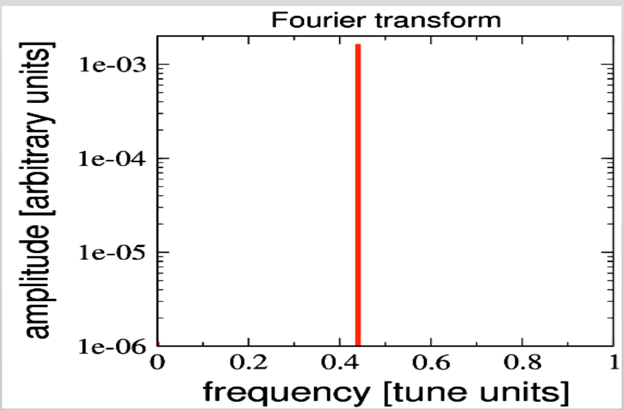
nonlinear magnetic model from TbT BPM data



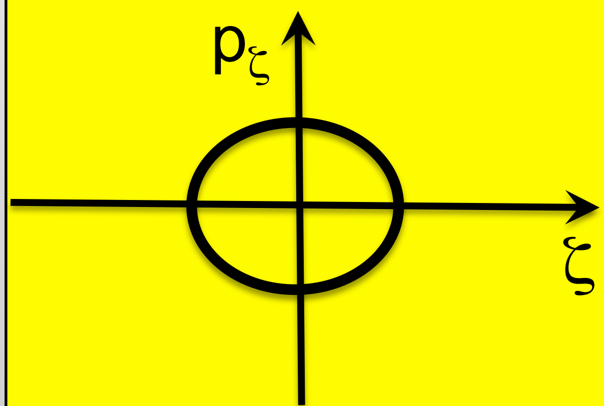


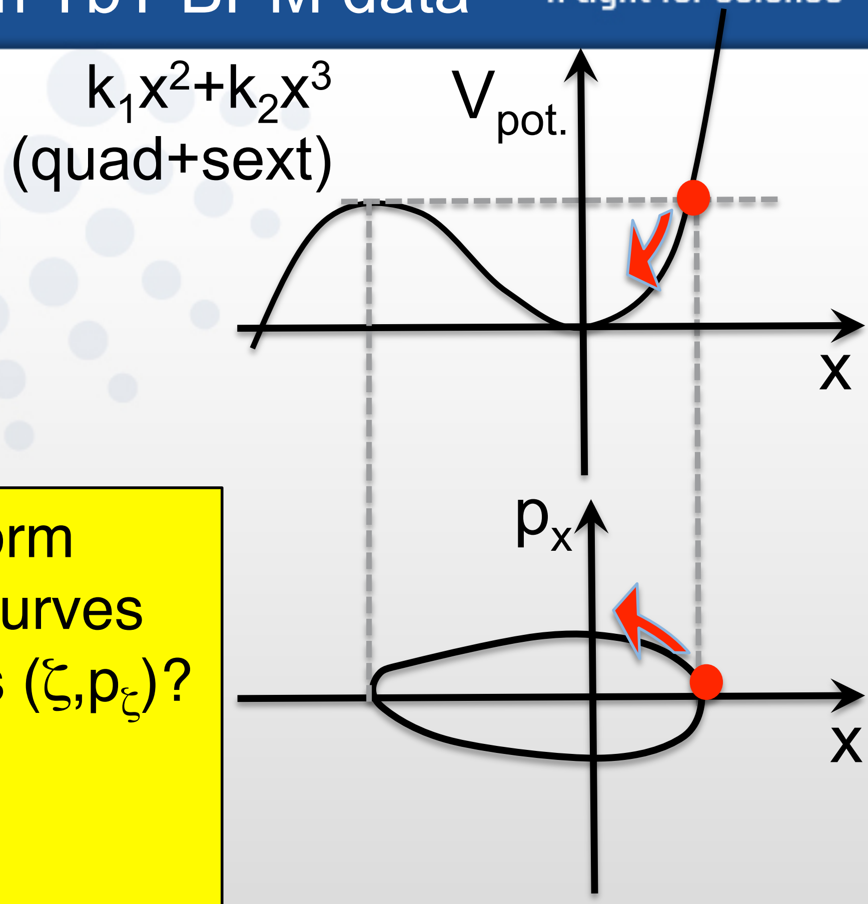
nonlinear magnetic model from TbT BPM data

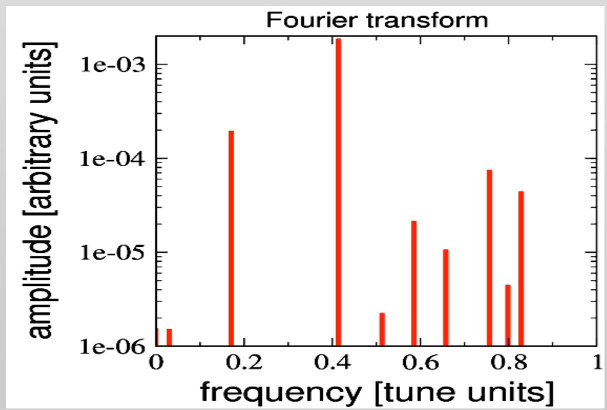




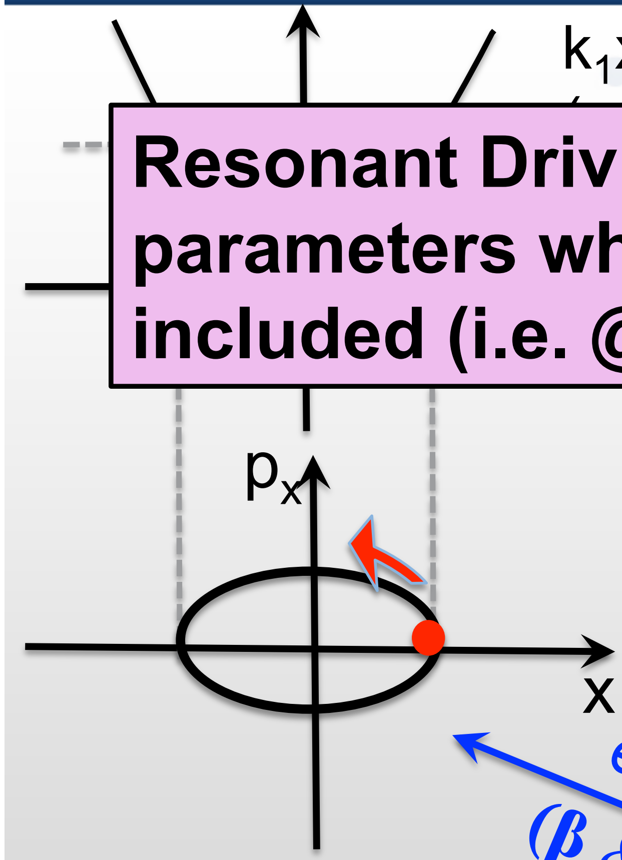
can we transform these closed curves (x,p_x) in circles (ζ,p_ζ)?

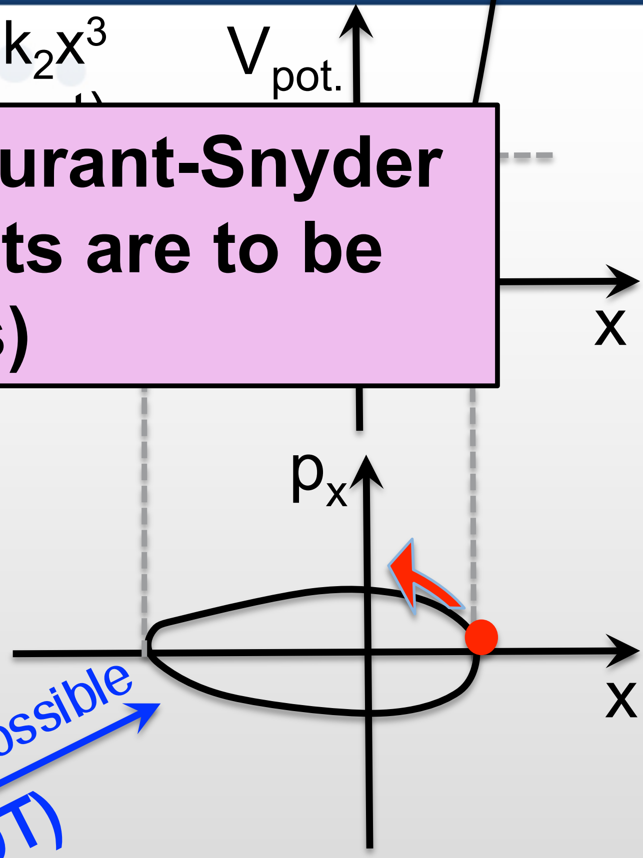




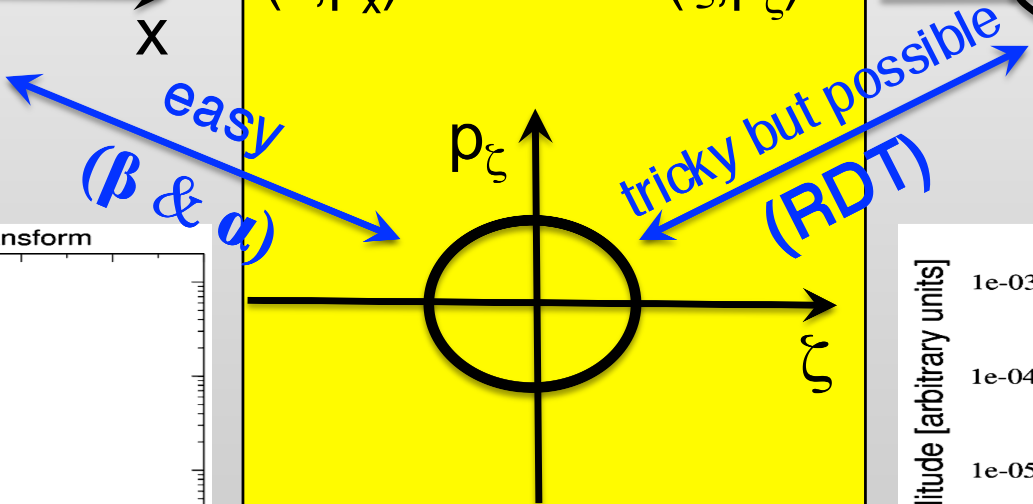


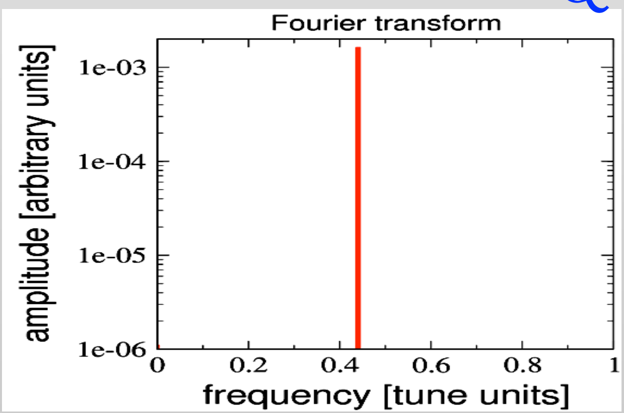
Resonant Driving Terms ⟷ Courant-Snyder parameters when nonlinear magnets are to be included (i.e. @ “large” amplitudes)

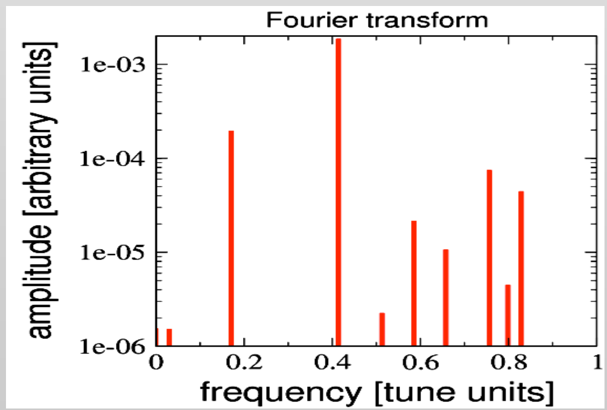




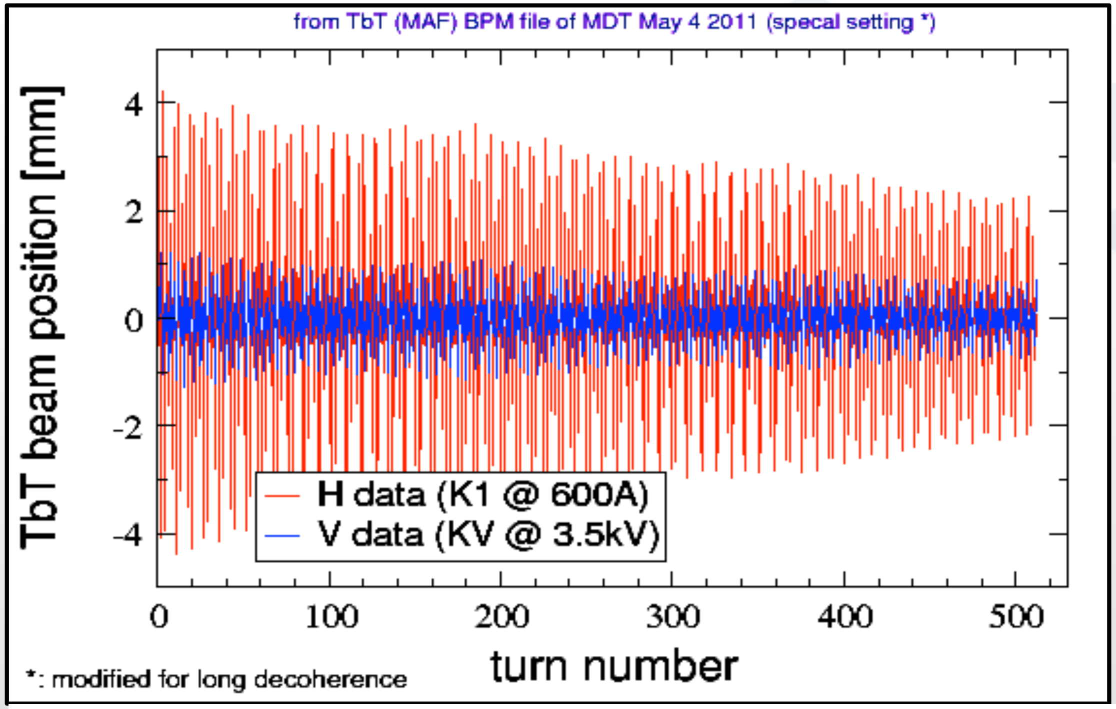
can we transform these closed curves (x,p_x) in circles (ζ,p_ζ)?

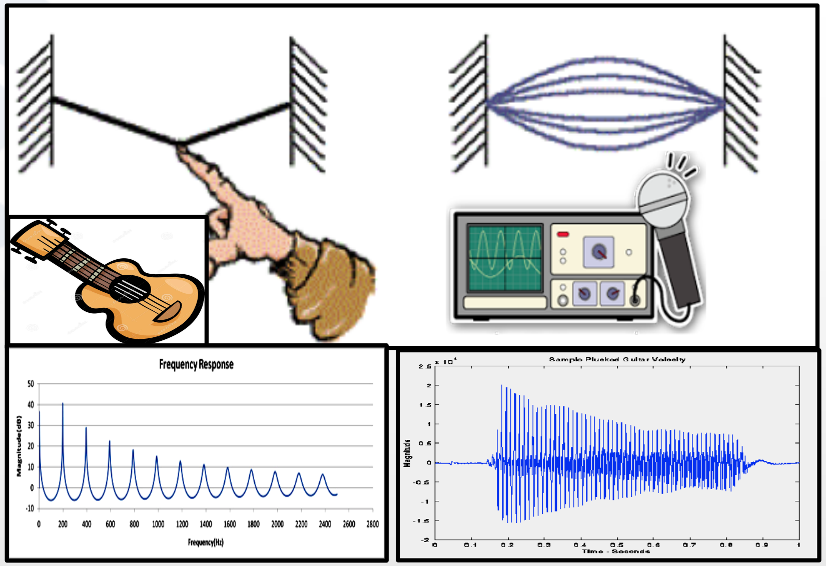


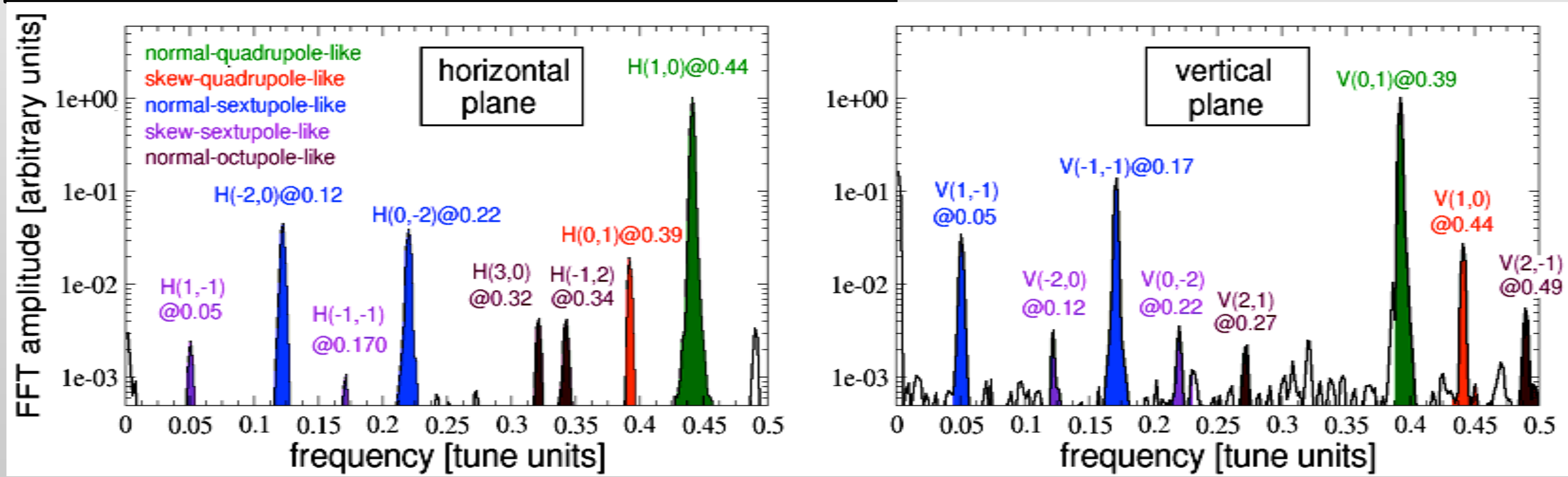




nonlinear magnetic model from TbT BPM data







$|H(1,0)|=\frac{1}{2}(2I_x)^{1/2}$

$|V(0,1)|=\frac{1}{2}(2I_y)^{1/2}$

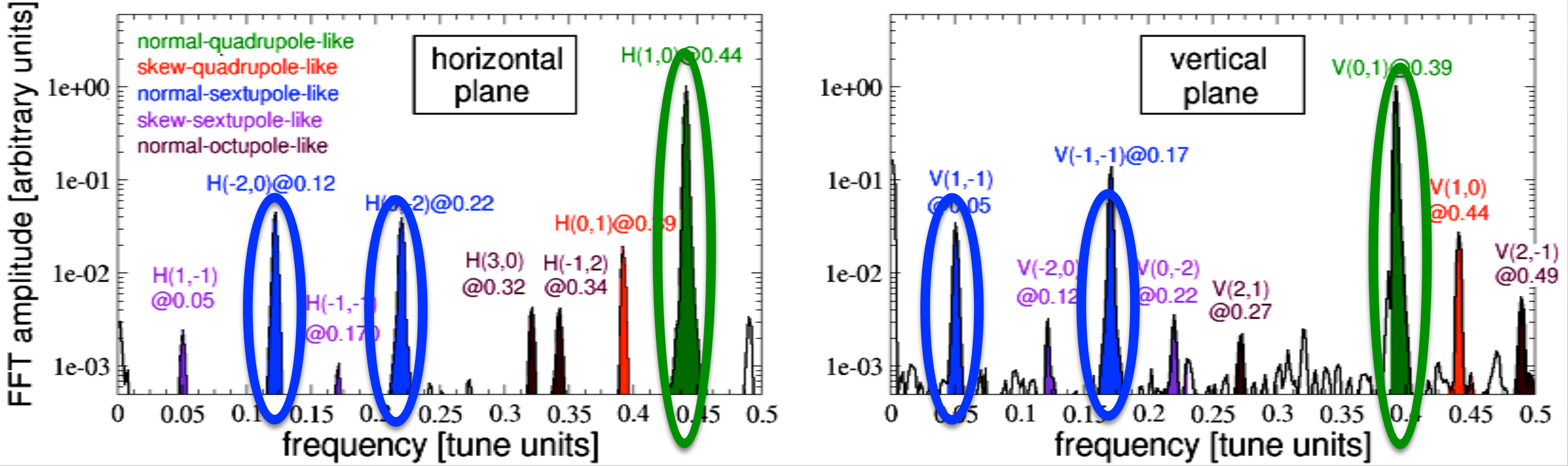
$|H(-2,0)|=(2I_x)\quad|F_{NS3}|$

$|H(0,-2)|=(2I_y)\quad|F_{NS2}|$

$|V(-1,-1)|=(2I_x 2I_y)^{1/2}|F_{NS1}|$

$|V(1,-1)|=(2I_x 2I_y)^{1/2}|F_{NS0}|$

similar relations for phases q: $F=|F|e^{iq}$



from the model

	from linear lattice model	from magnet calibration
F_{NS3} =	$M_3(\beta,\varphi)$ ×	$K_2(\text{sext})$
F_{NS2} =	$M_2(\beta,\varphi)$ ×	$K_2(\text{sext})$
F_{NS1} =	$M_1(\beta,\varphi)$ ×	$K_2(\text{sext})$
F_{NS0} =	$M_0(\beta,\varphi)$ ×	$K_2(\text{sext})$

$$|H(1,0)|=\tfrac{1}{2}(2I_x)^{1/2}$$

$$|V(0,1)|=\tfrac{1}{2}(2I_y)^{1/2}$$

$$|H(-2,0)|=(2I_x)\quad |F_{NS3}|$$

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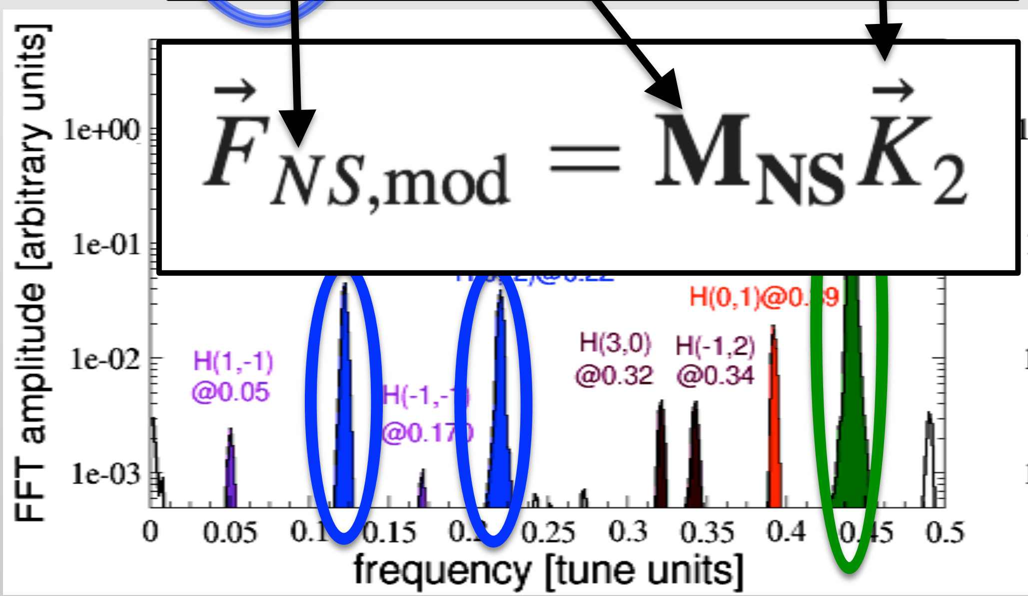
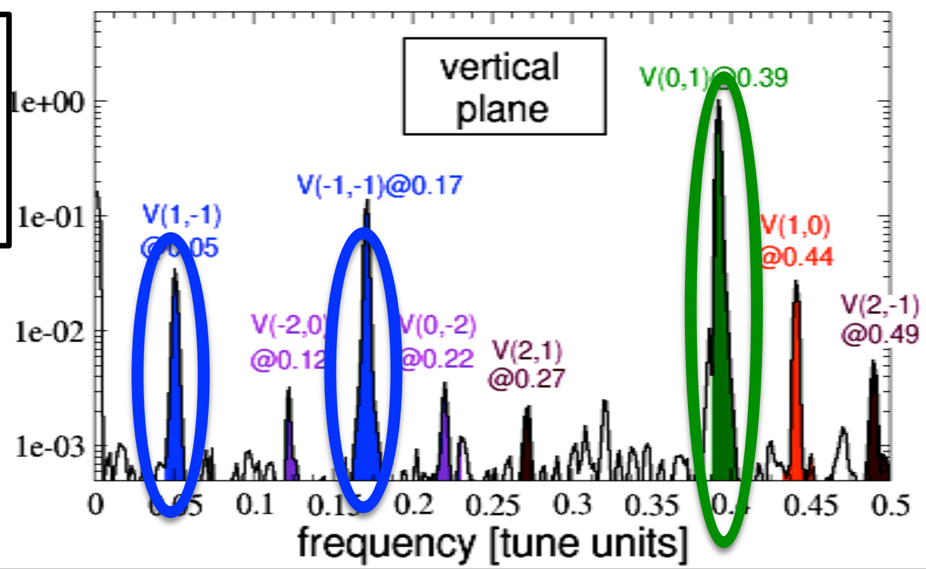
$$|V(-1,-1)|=(2I_x2I_y)^{1/2}|F_{NS1}|$$

$$|V(1,-1)|=(2I_x2I_y)^{1/2}|F_{NS0}|$$

$$\vec{F}_{NS,\text{mod}} = \mathbf{M}_{NS}\vec{K}_2$$





nonlinear magnetic model from TbT BPM data

from the model

	from linear lattice model	from magnet calibration
F_{NS3} =	$M_3(\beta,\varphi)$ ×	$K_2(\text{sext})$
F_{NS2} =	$M_2(\beta,\varphi)$ ×	$K_2(\text{sext})$
F_{NS1} =	$M_1(\beta,\varphi)$ ×	$K_2(\text{sext})$
F_{NS0} =	$M_0(\beta,\varphi)$ ×	$K_2(\text{sext})$

$|H(1,0)|=\frac{1}{2}(2I_x)^{1/2}$

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$|H(-2,0)|=(2I_x)\,|F_{NS3}|$

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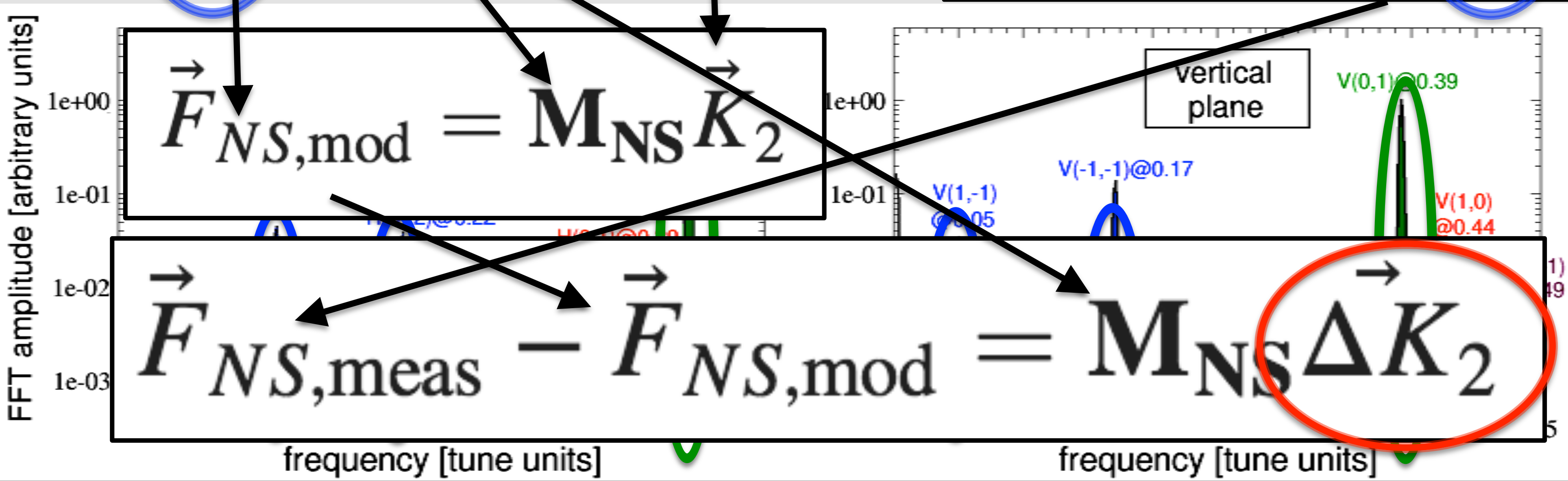
$|V(1,-1)|=(2I_x 2I_y)^{1/2}\,|F_{NS0}|$

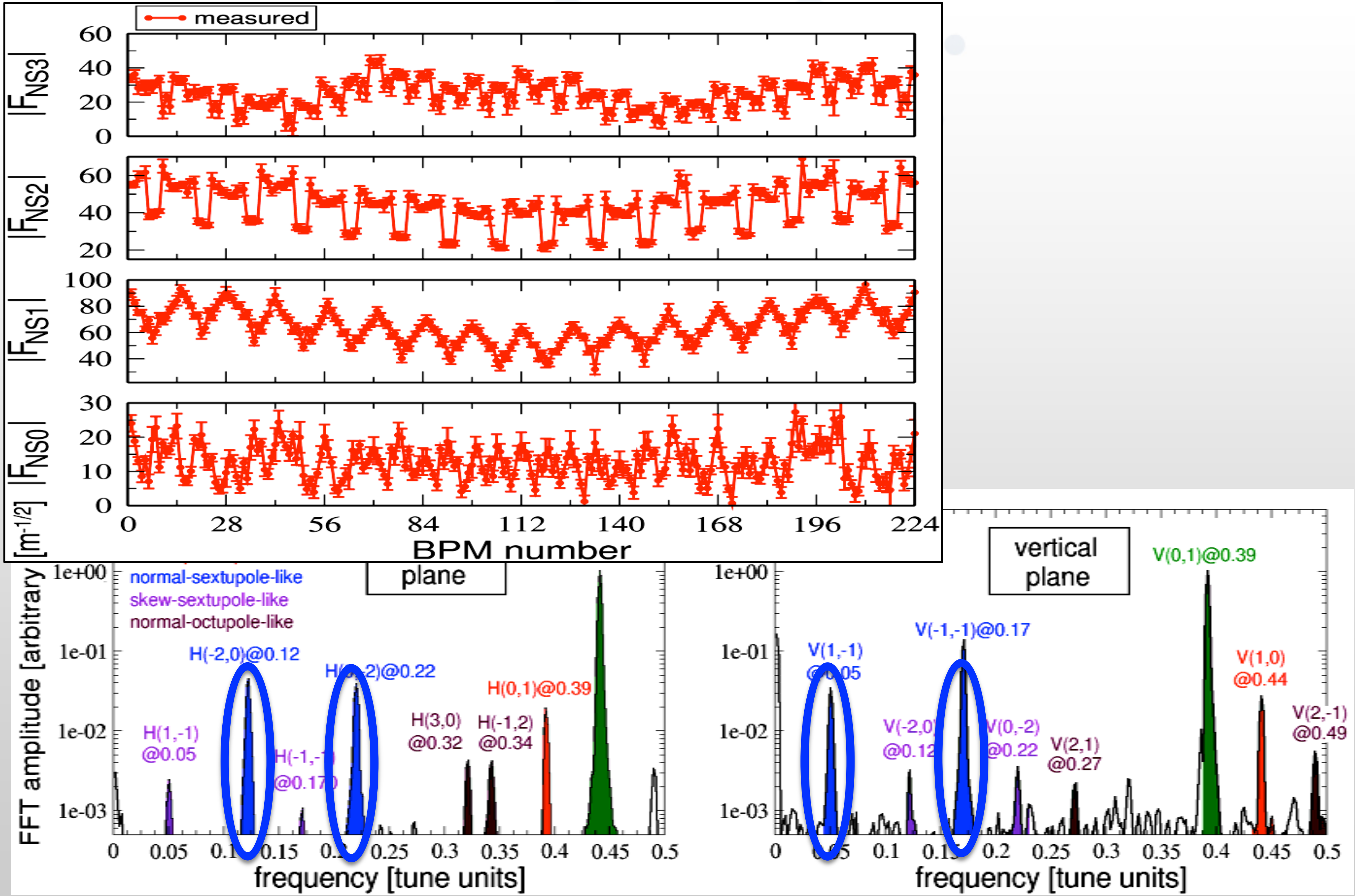


$$\vec{F}_{NS,\mathrm{mod}} = \mathbf{M}_{\mathbf{NS}}\vec{K}_2$$

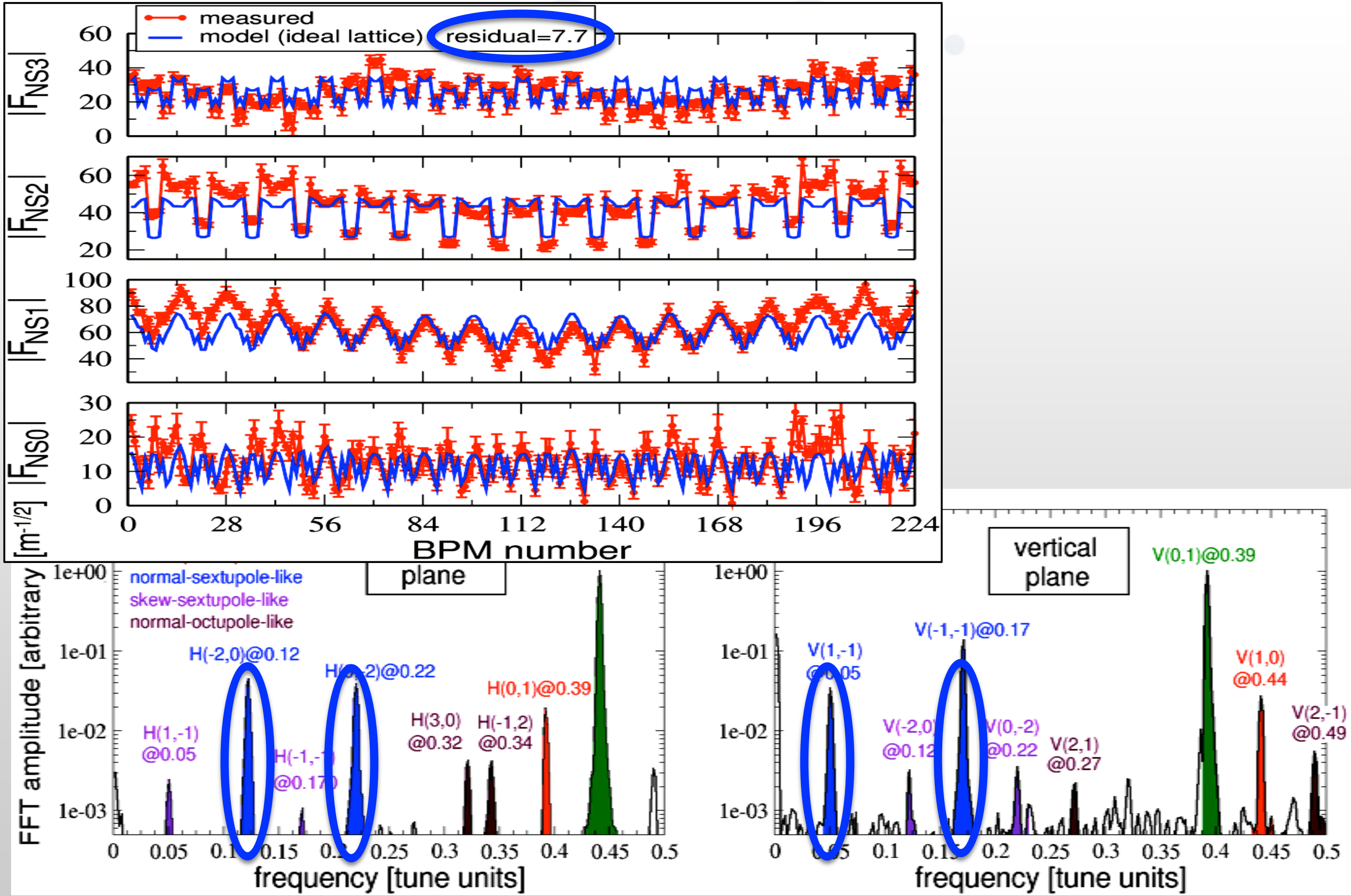
$$\vec{F}_{NS,\mathrm{meas}} - \vec{F}_{NS,\mathrm{mod}} = \mathbf{M}_{\mathbf{NS}}\Delta\vec{K}_2$$

nonlinear magnetic model from TbT BPM data

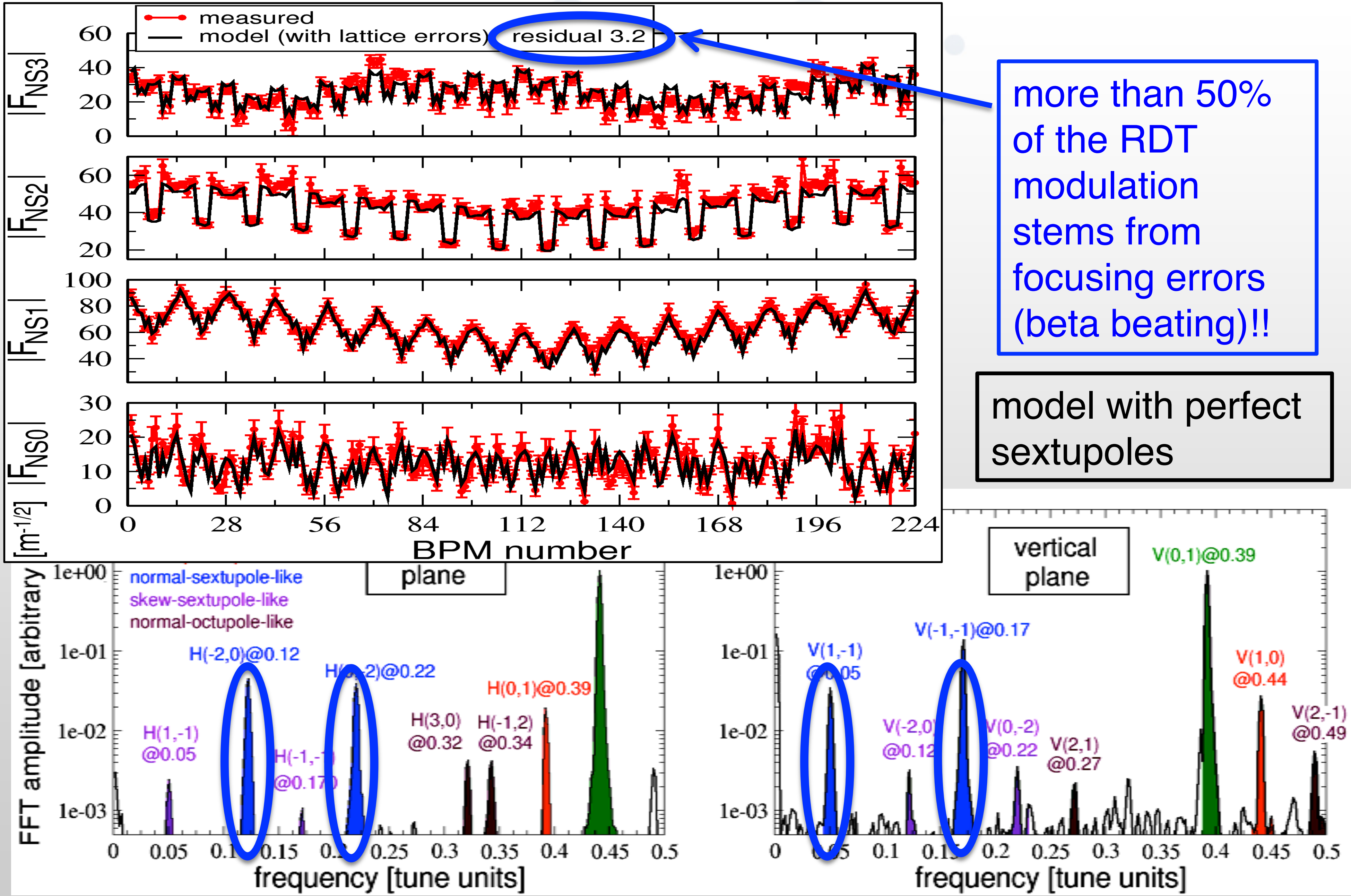
A light for Science



nonlinear magnetic model from TbT BPM data



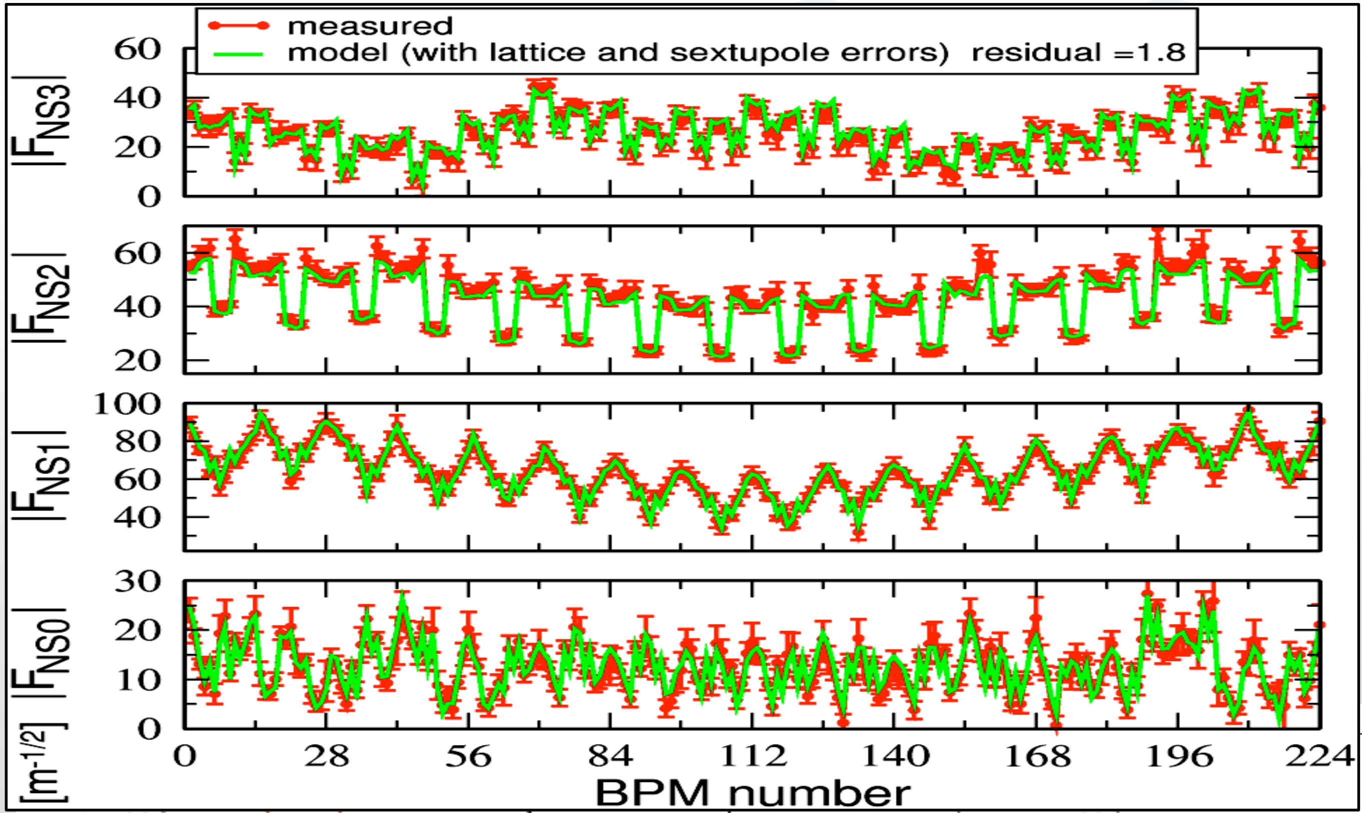
nonlinear magnetic model from TbT BPM data



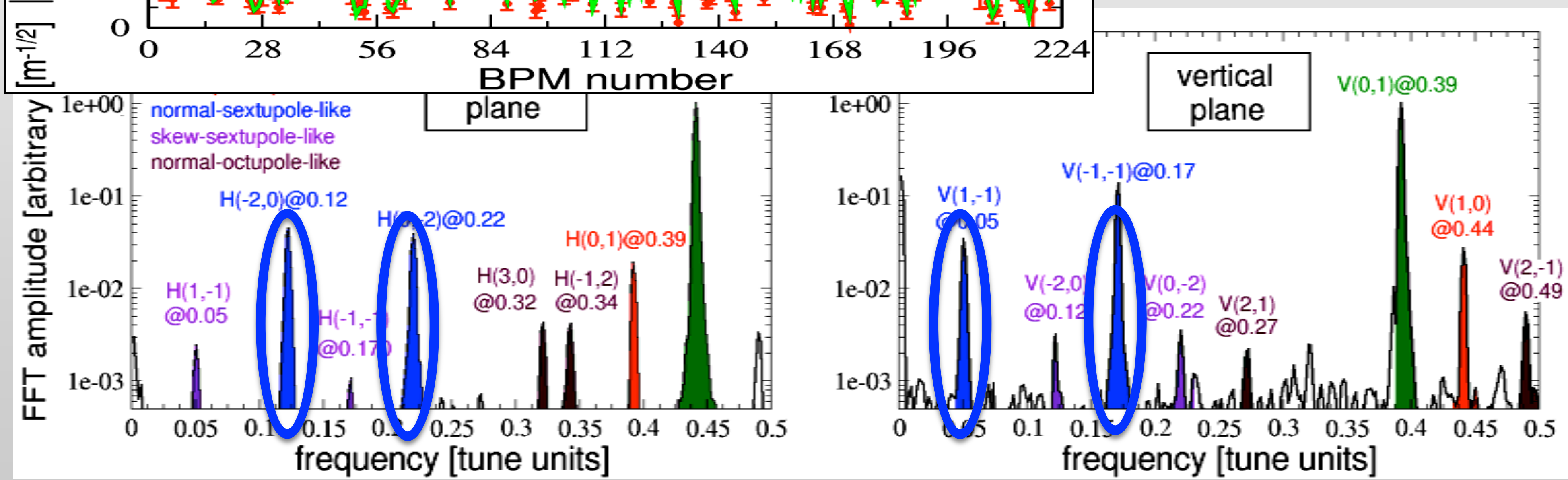
more than 50% of the RDT modulation stems from focusing errors (beta beating)!!

model with perfect sextupoles

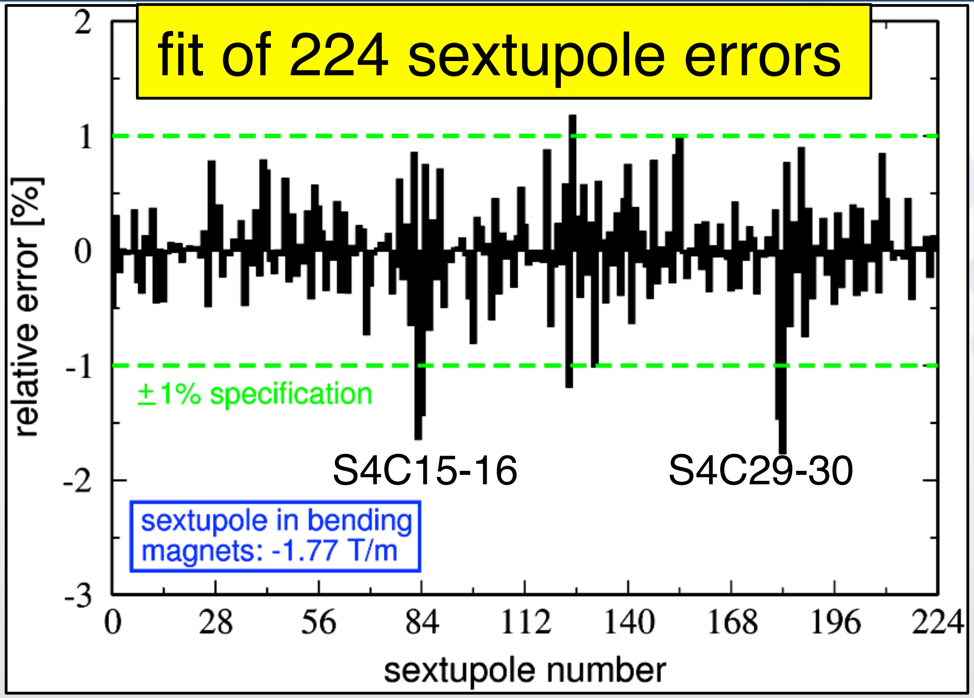
nonlinear magnetic model from TbT BPM data

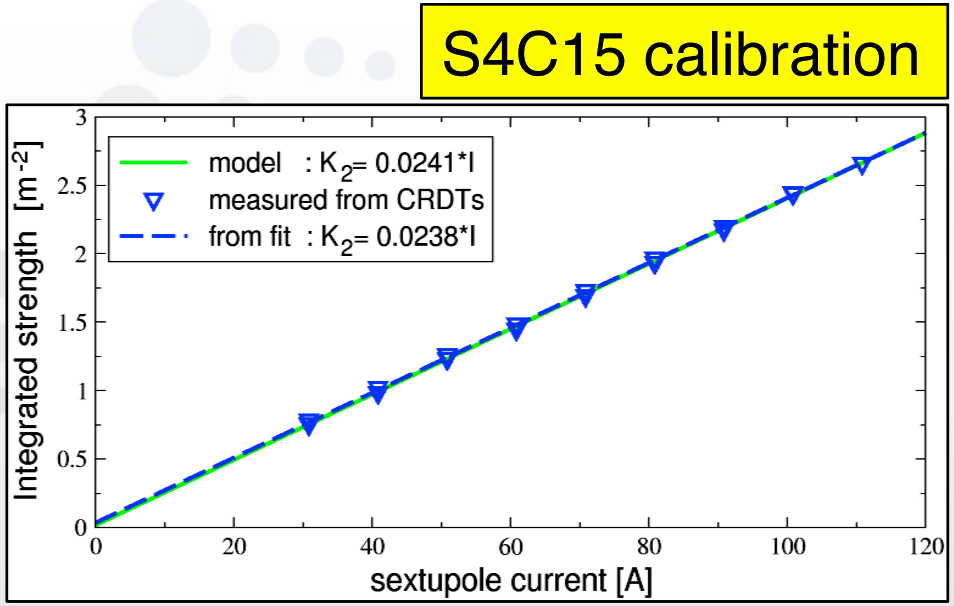


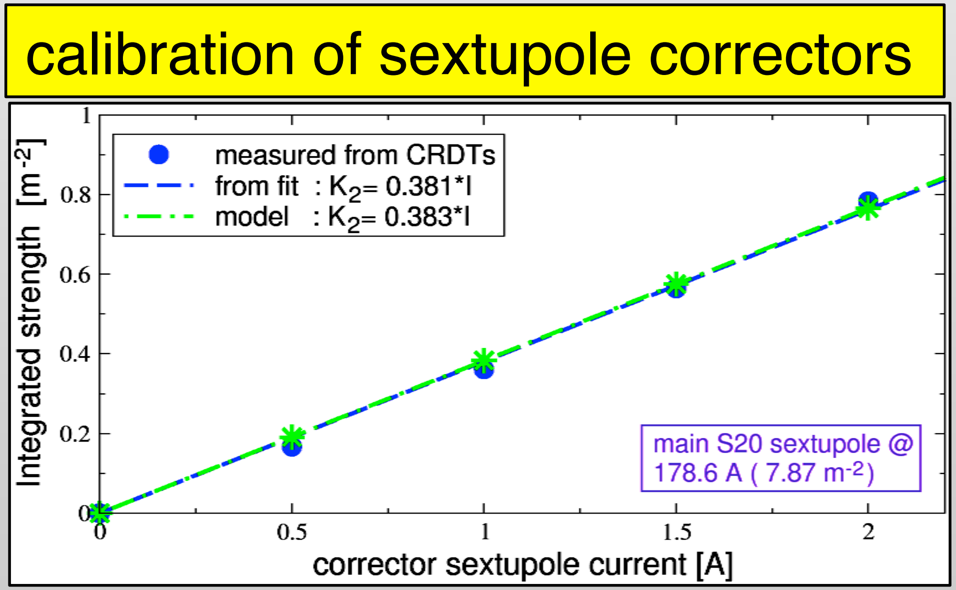
model with fitted sextupole errors



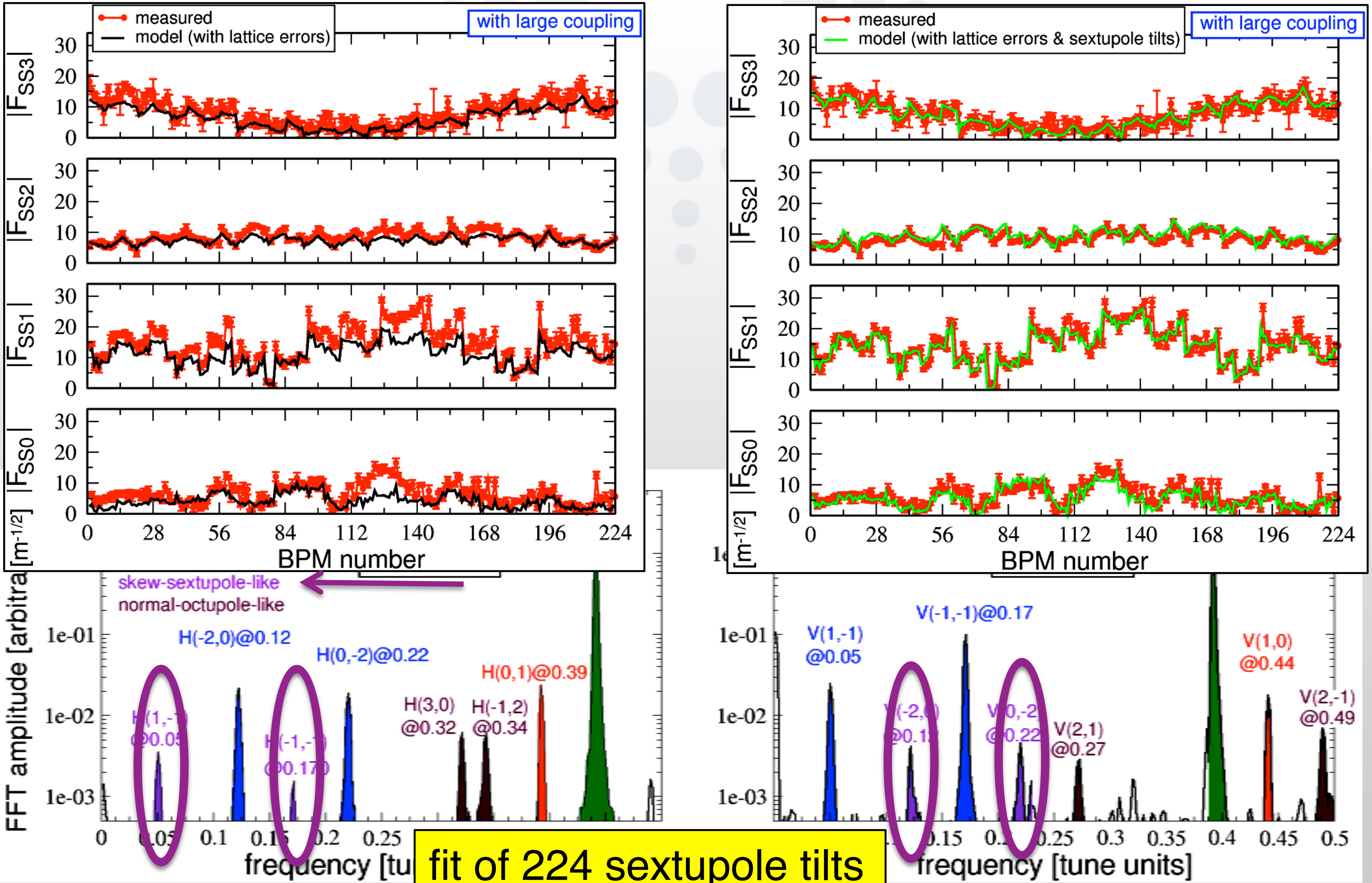
nonlinear magnetic model from TbT BPM data







nonlinear magnetic model from TbT BPM data



fit of 224 sextupole tilts

ORM analysis	TbT analysis
• observables: chromatic terms	• observables: resonant driving terms
• better for lifetime (tbc experimentally)	• better for calibration of nonlinear magnets & DA (tbc experimentally)
• linear system to be solved	• linear system to be solved
• requires at least 2 measurements at δ=0 & δ≠0, or δ=±ε	• requires 1 measurement at δ=0
• works with BPMs in normal orbit mode	• requires BPMs switch to TbT (MAF) mode
• resolution independent upon sextupole setting	• resolution dependent upon sextupole setting (high chroma => low accuracy)
• for octupoles & higher-order multipoles you need several measurements at large δ	• you may characterize octupoles & higher-order multipoles with a single measurement