ESRF

A Light for Science

Experience with resonance driving (and chromatic) terms at ESRF storage ring

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on behalf of the
ASD Beam Dynamics Group

AOC workshop, CERN, 5-6 January 2015

European Synchrotron Radiation Facility

Contents

- from TbT BPM data to resonance driving terms
- from resonance driving terms to magnet strengths
- measuring sextupolar & octupolar fields @ ESRF
- resonance driving terms Vs lifetime => chromatic terms

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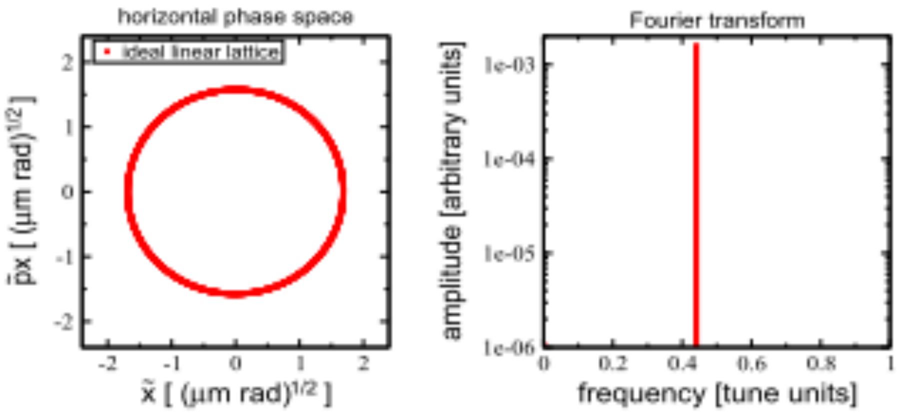
Ideal case: Courant-Snyder phase space is a circle with 1 harmonic H(1,0), i.e. the tune



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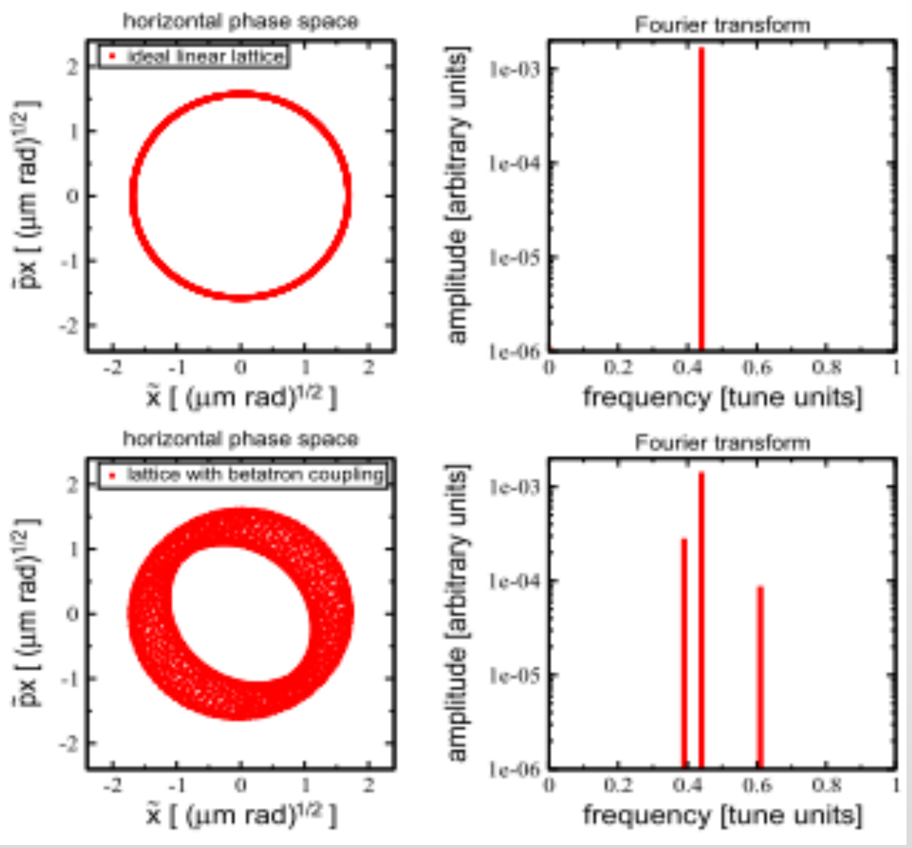
Coupled case: Courant-Snyder phase space contains 3 harmonics H(1,0) & H(0,±1)

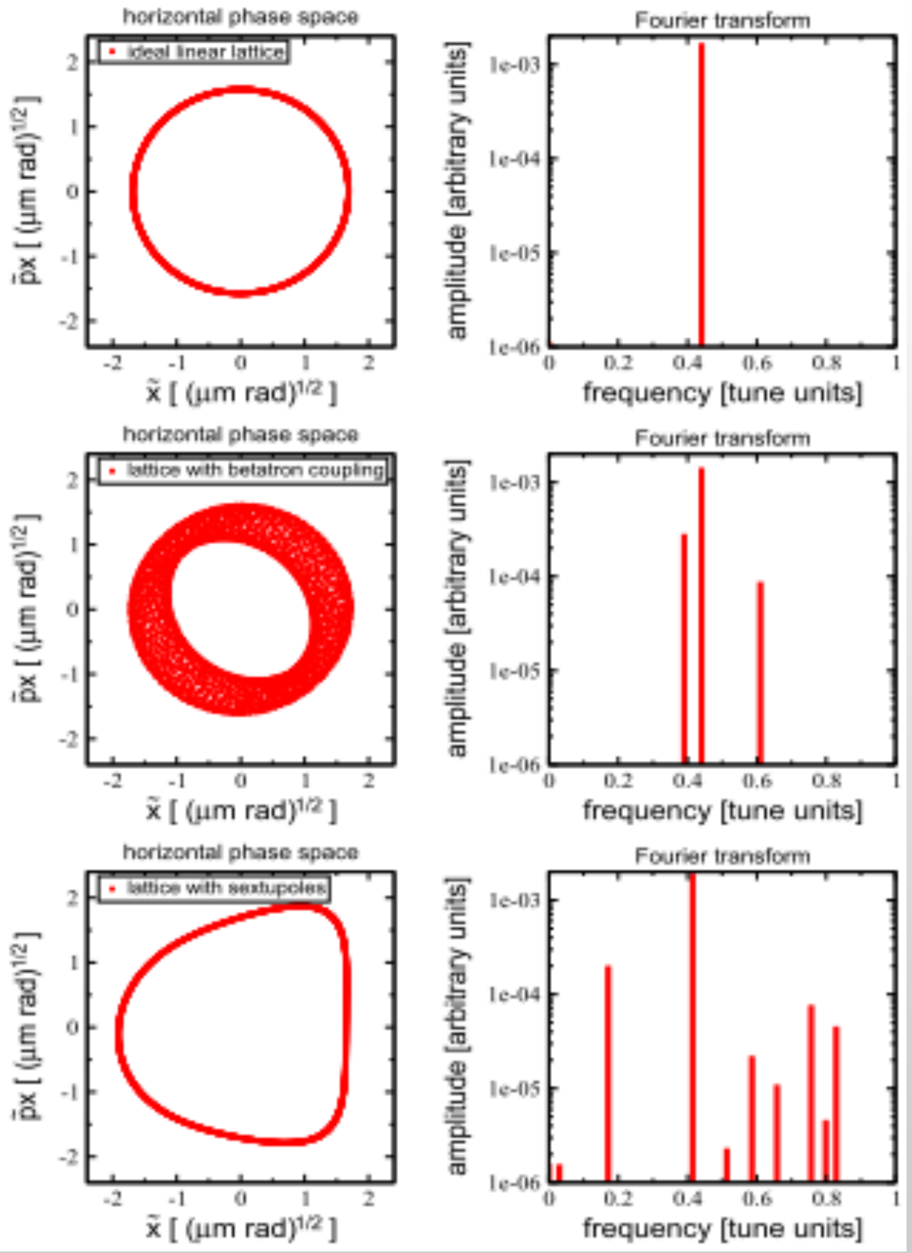


from TbT BPM data to resonance driving terms

Ideal case: Courant-Snyder phase space is a circle with 1 harmonic H(1,0), i.e. the tune

Coupled case: Courant-Snyder phase space contains 3 harmonics H(1,0) & H(0,±1)

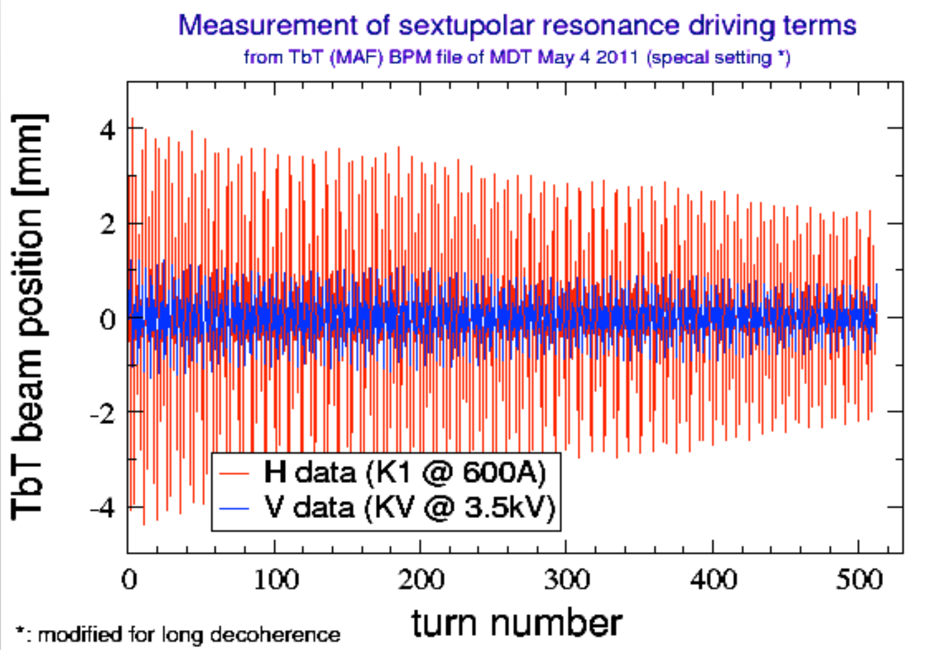
Case with strong sextupoles: Courant-Snyder phase space contains several harmonics H(1,0), H(±2,0), H(0,±2), …

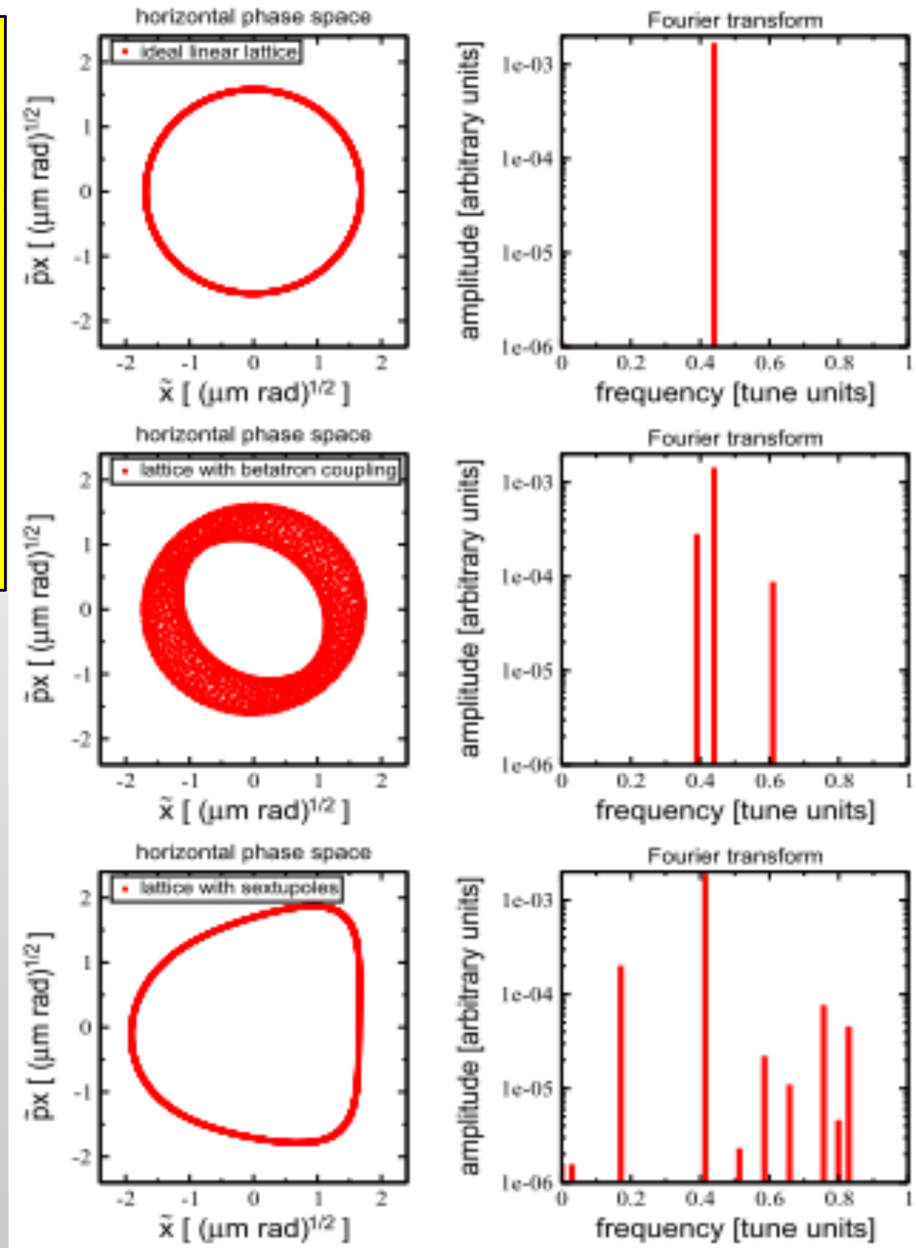


Instead of "measuring" the Courant-Snyder phase space, only its TbT projections are Fourier-analyzed:

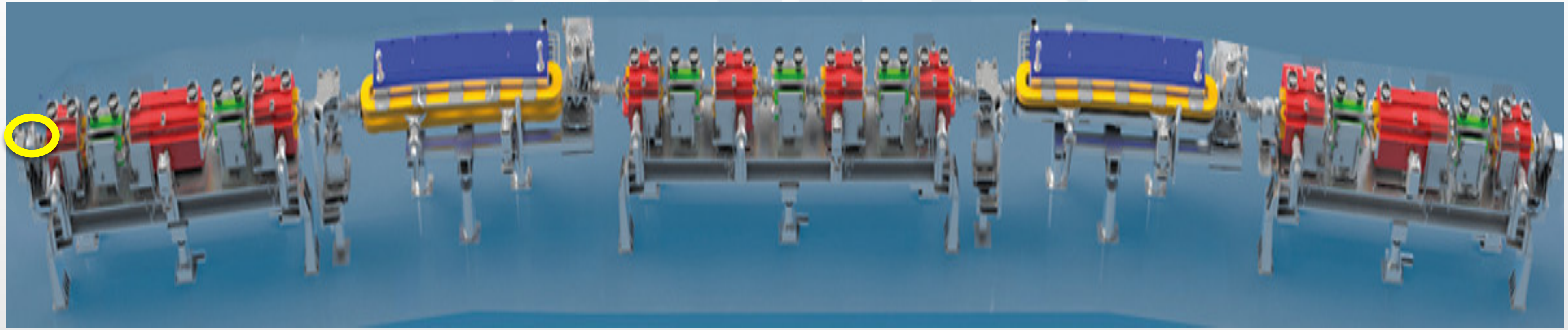
$X(1,\ldots,N)_{BPM} = x(1,\ldots,N)_{BPM} / \beta_x^{1/2}{}_{,BPM}$

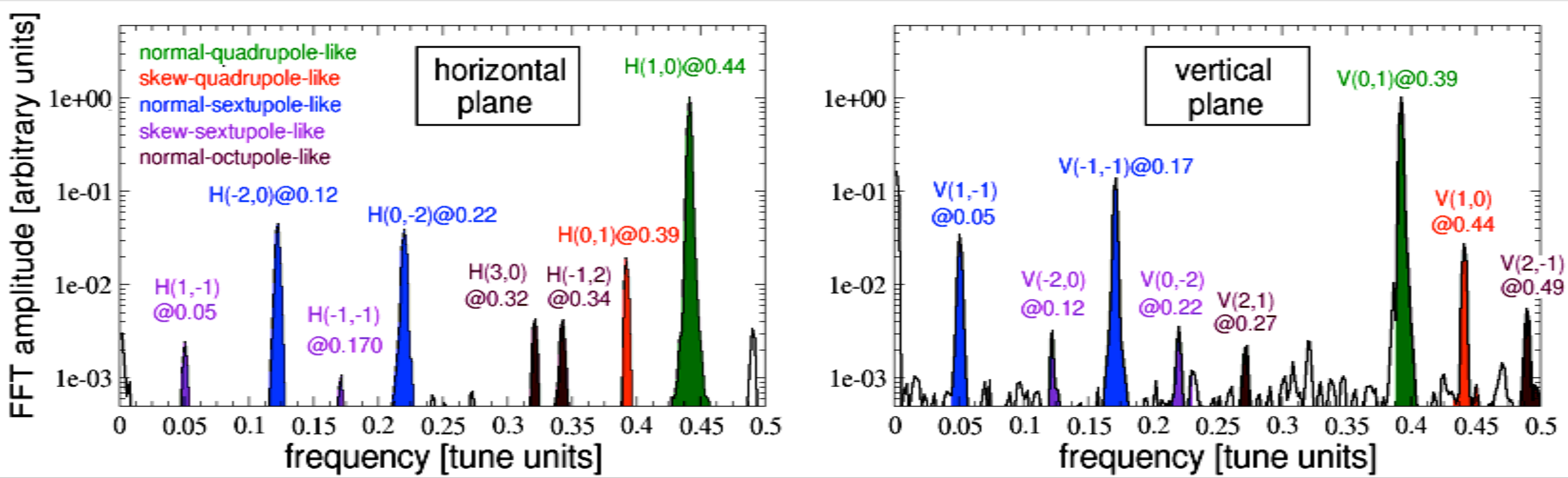
$Y(1,\ldots,N)_{BPM} = y(1,\ldots,N)_{BPM} / \beta_y^{1/2}{}_{,BPM}$





Storage Ring's transverse spectra





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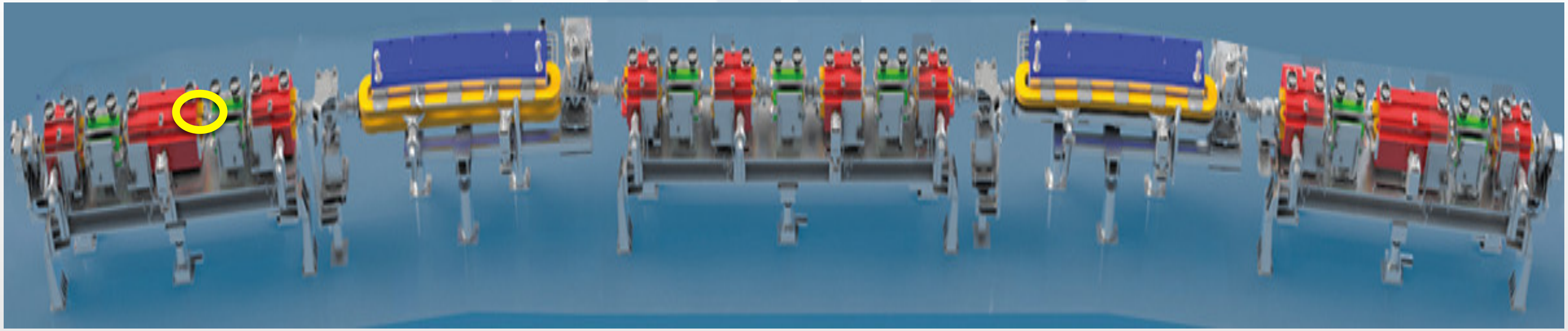

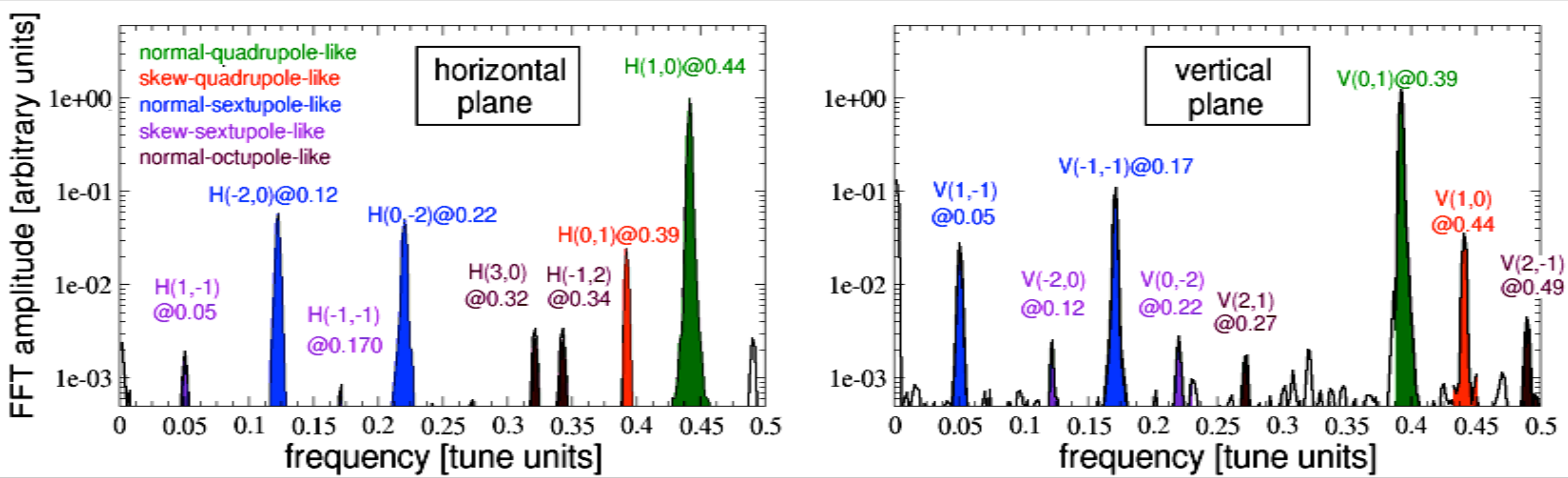

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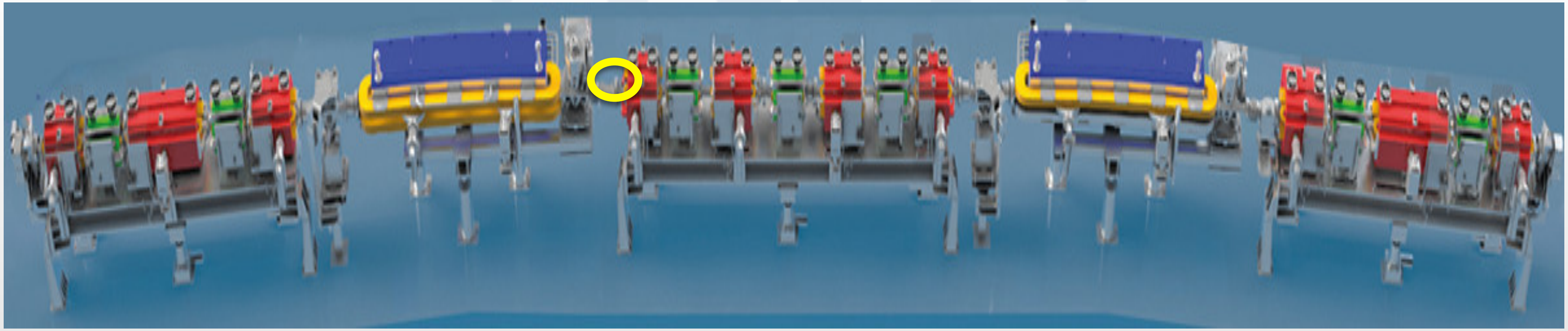

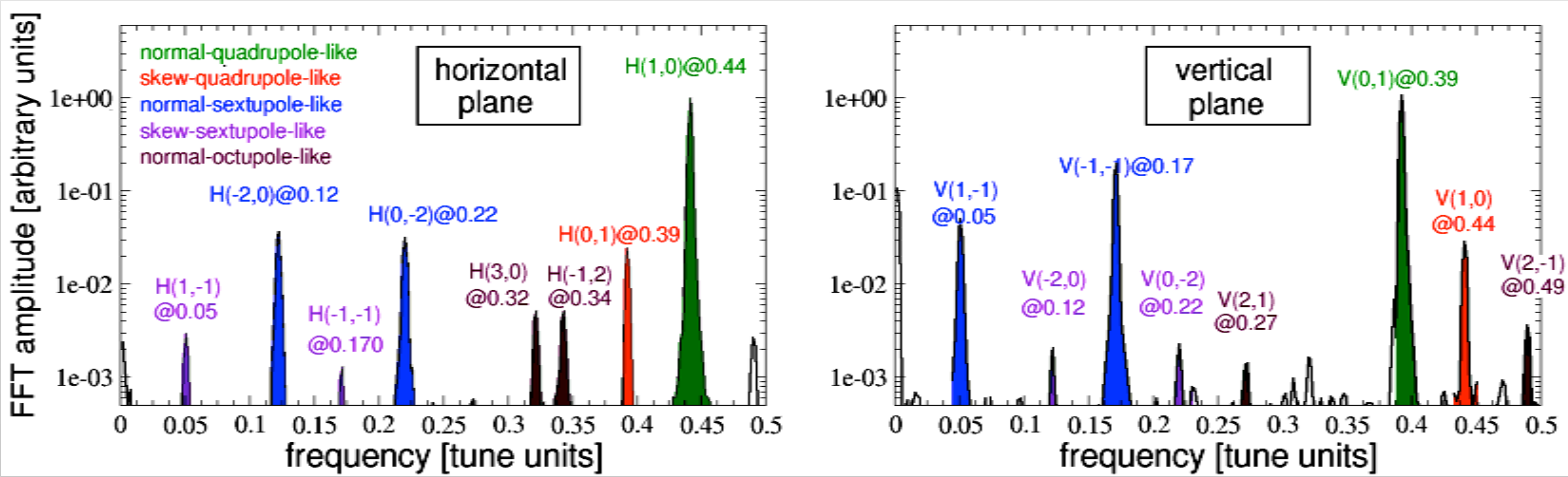

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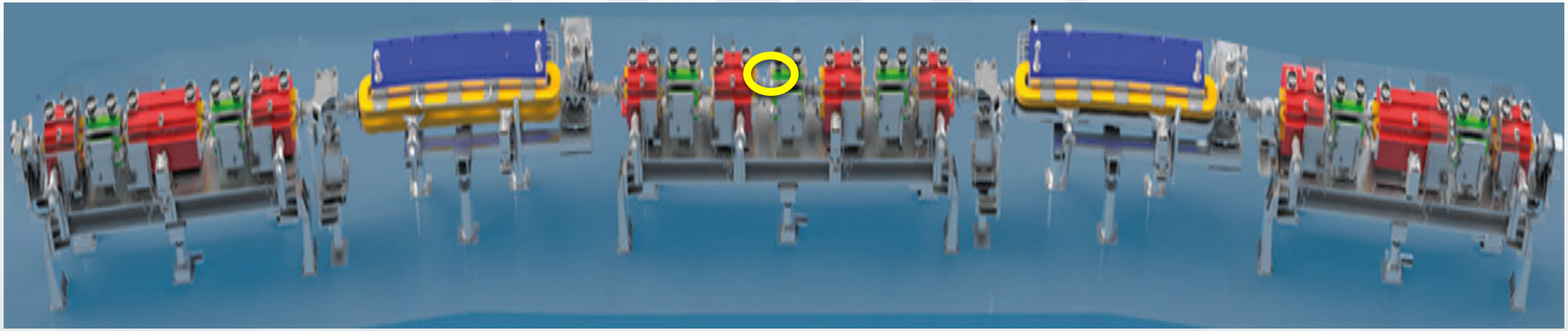

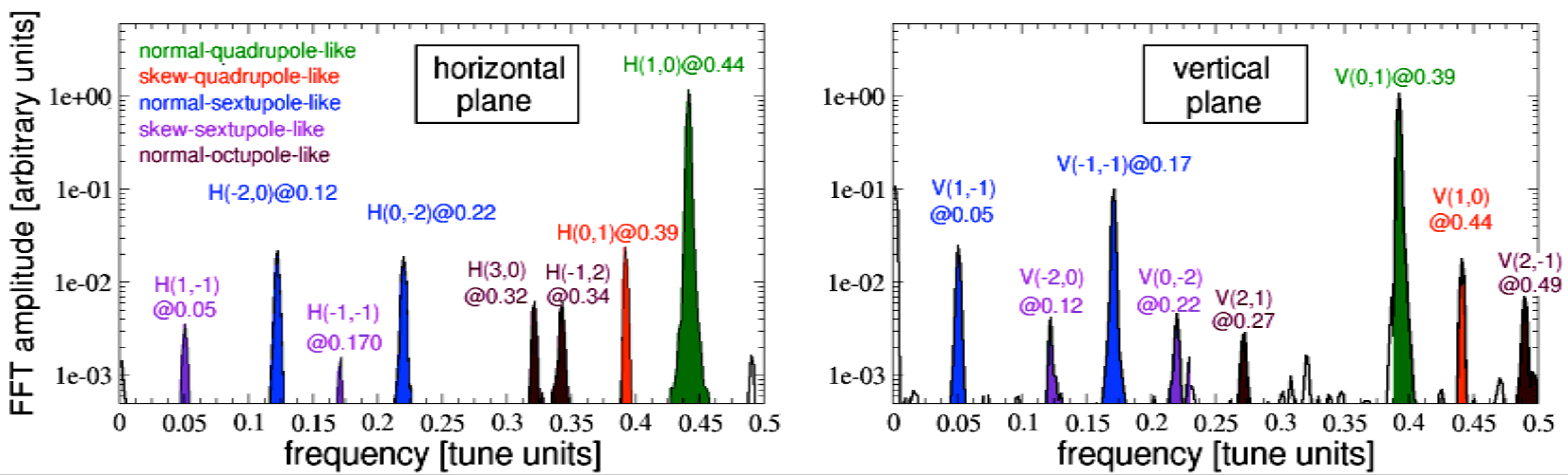

from TbT BPM data to resonance driving terms

$$X(1,\ldots,N)_{BPM} = x(1,\ldots,N)_{BPM} / \beta_{x,BPM}^{1/2}$$
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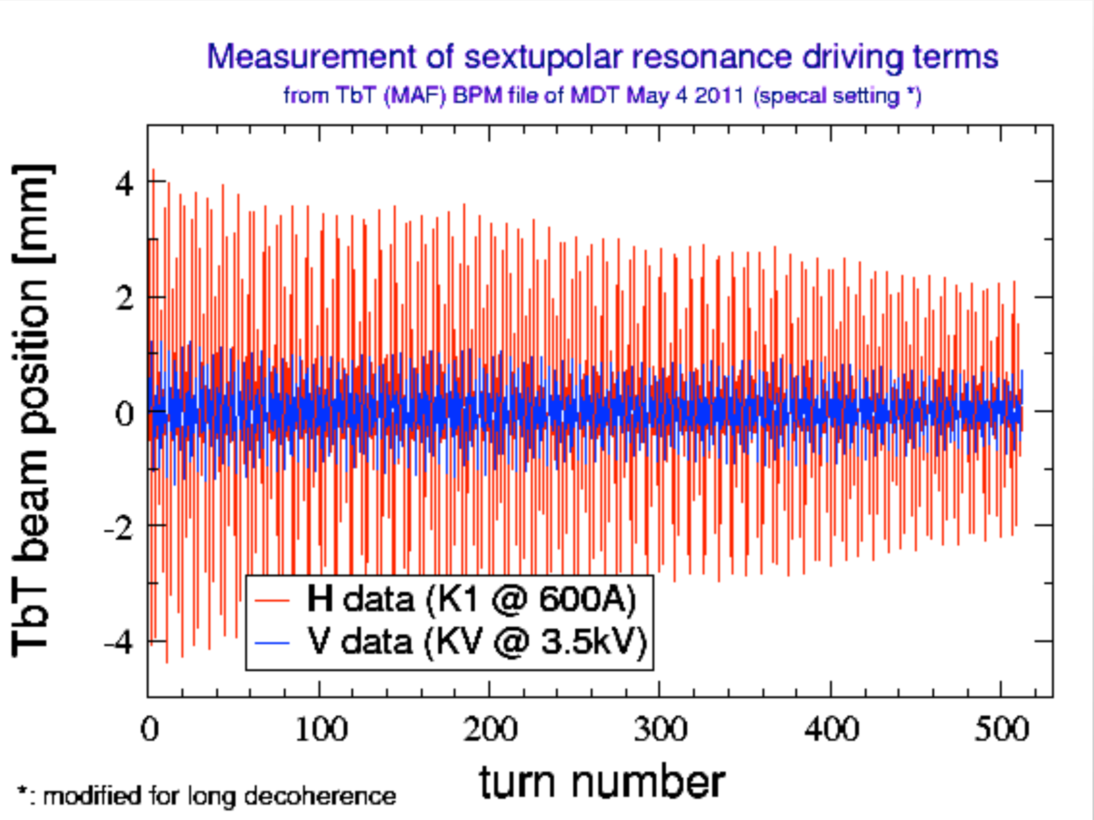

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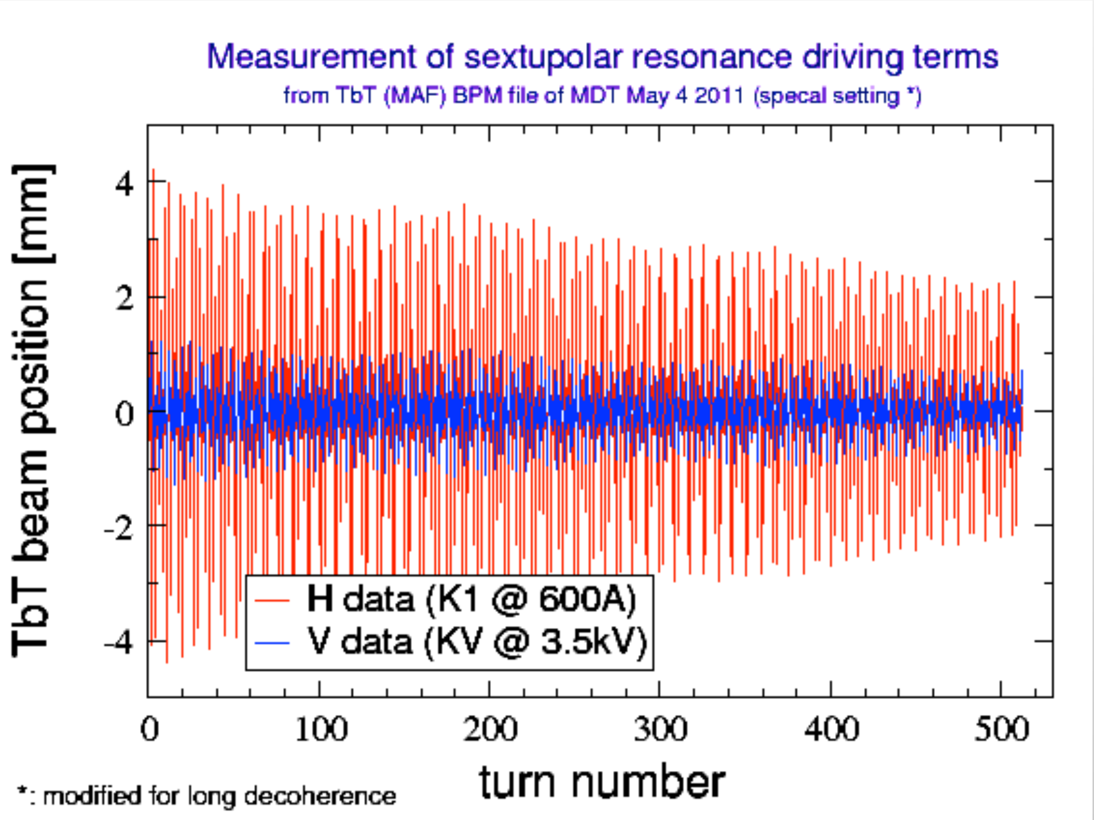

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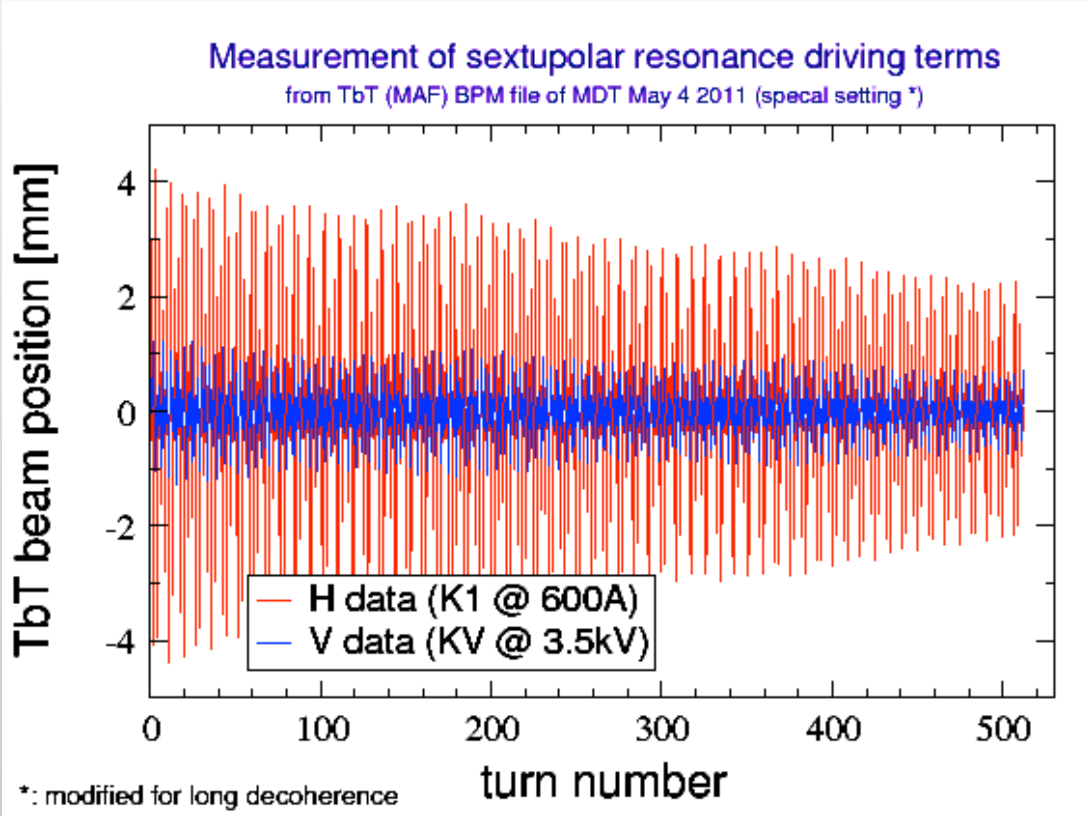
from linear lattice model

from TbT BPM data



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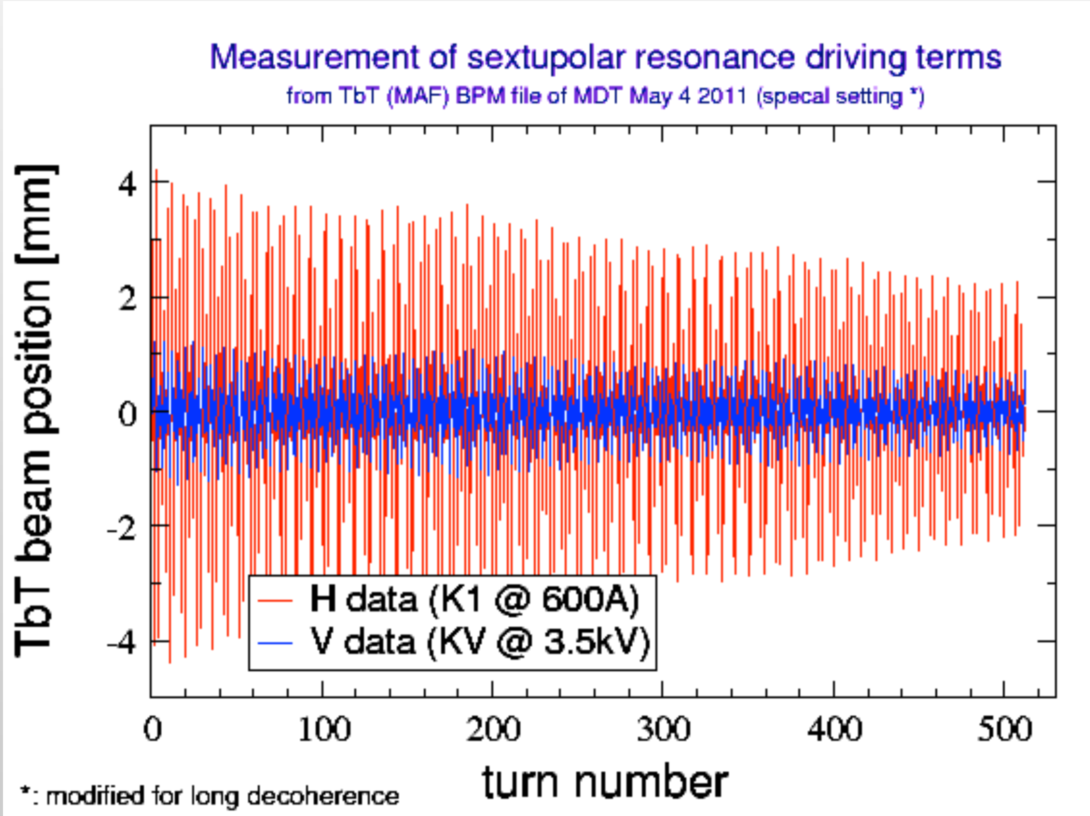
from linear lattice model

Courant-Snyder TbT data for FFT

from TbT BPM data



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Courant-Snyder TbT data for FFT

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

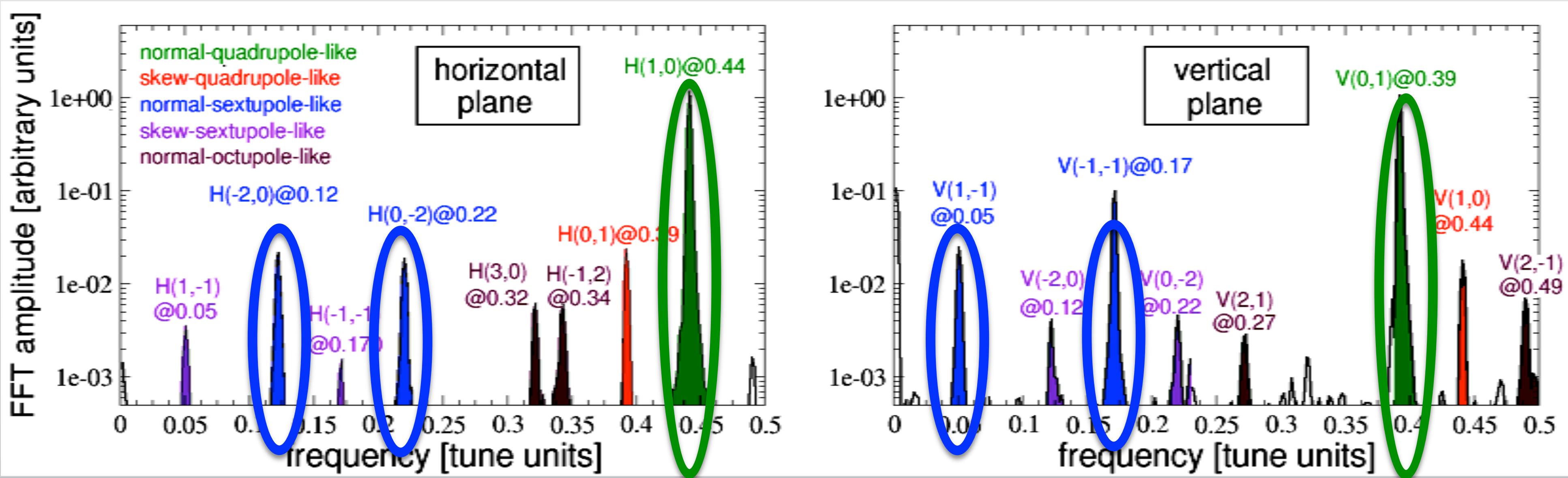
$|V(0,1)| = \tfrac{1}{2}(2I_y)^{1/2}$

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

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

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

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



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Courant-Snyder TbT data for FFT

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

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

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

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

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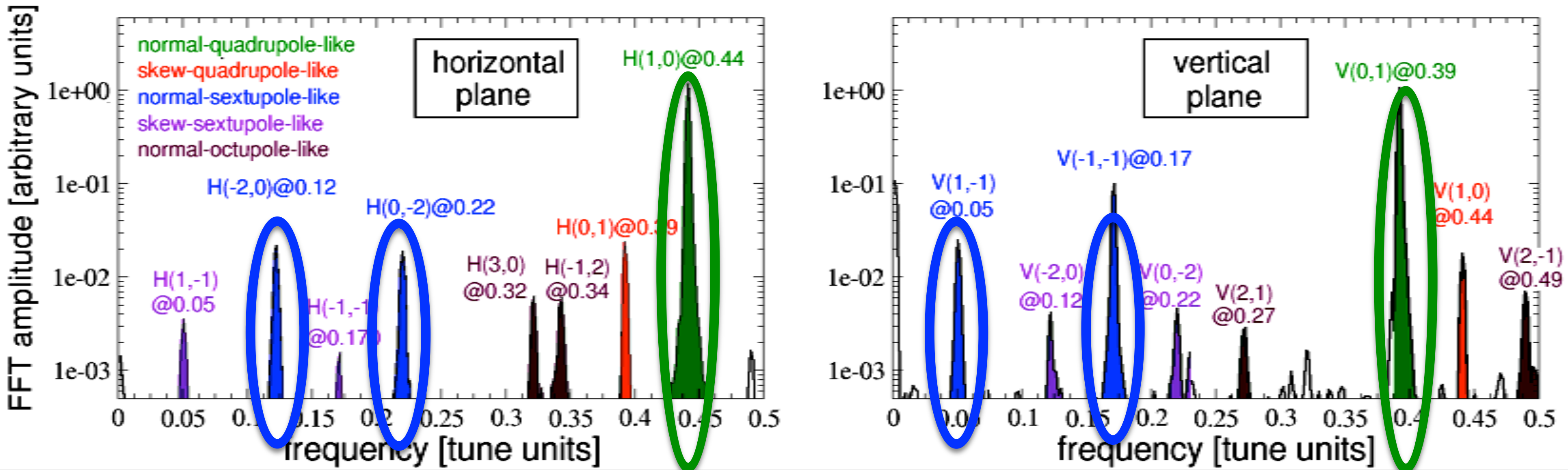

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from RDTs to magnet strengths

from the model

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

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

from measurement

$|H(1,0)|=½(2I_x)^{1/2}$

$|V(0,1)|=½(2I_y)^{1/2}$

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

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$|V(-1,-1)|=(2I_x 2I_y)^{½}|F_{NS1}|$

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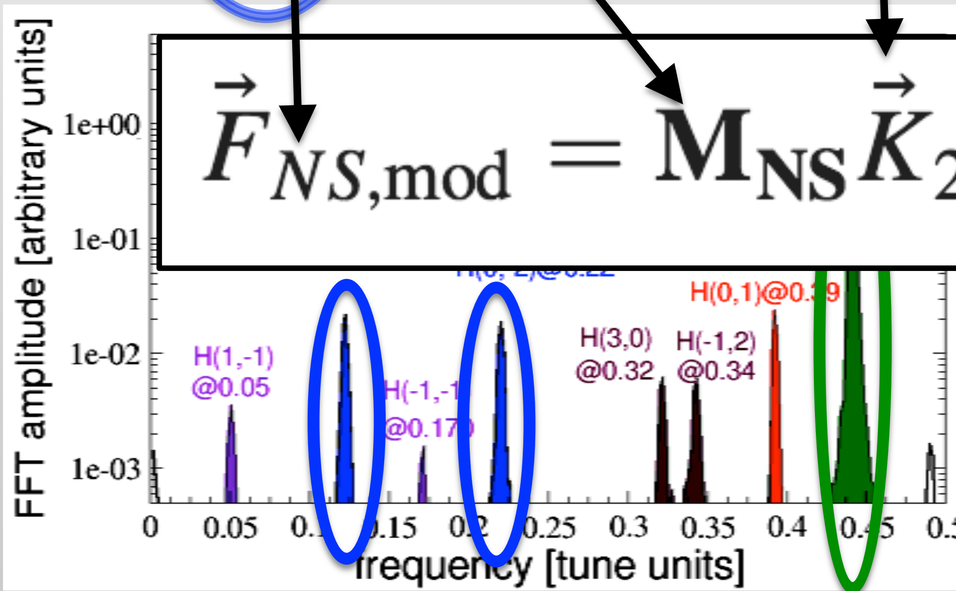

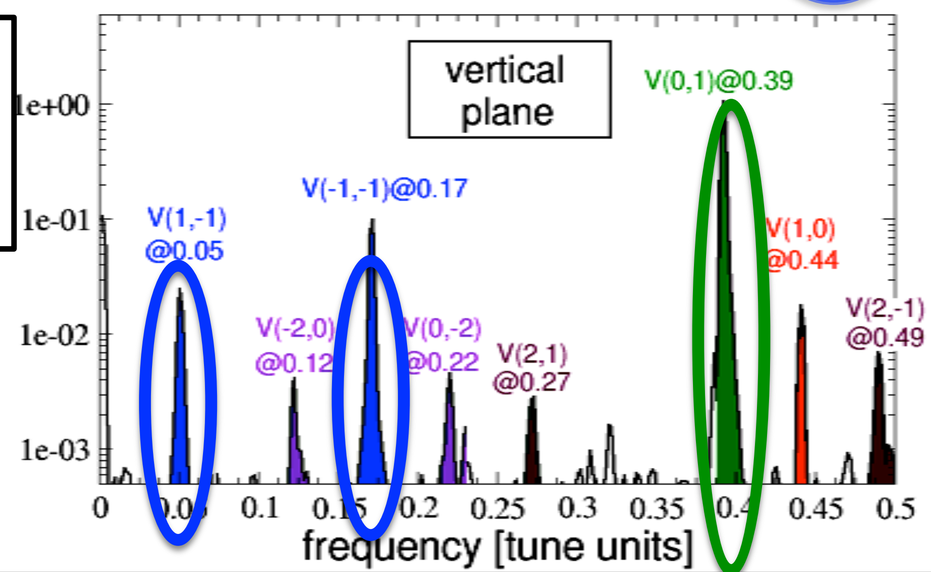

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from measurement

$|H(1,0)|=½(2I_x)^{1/2}$

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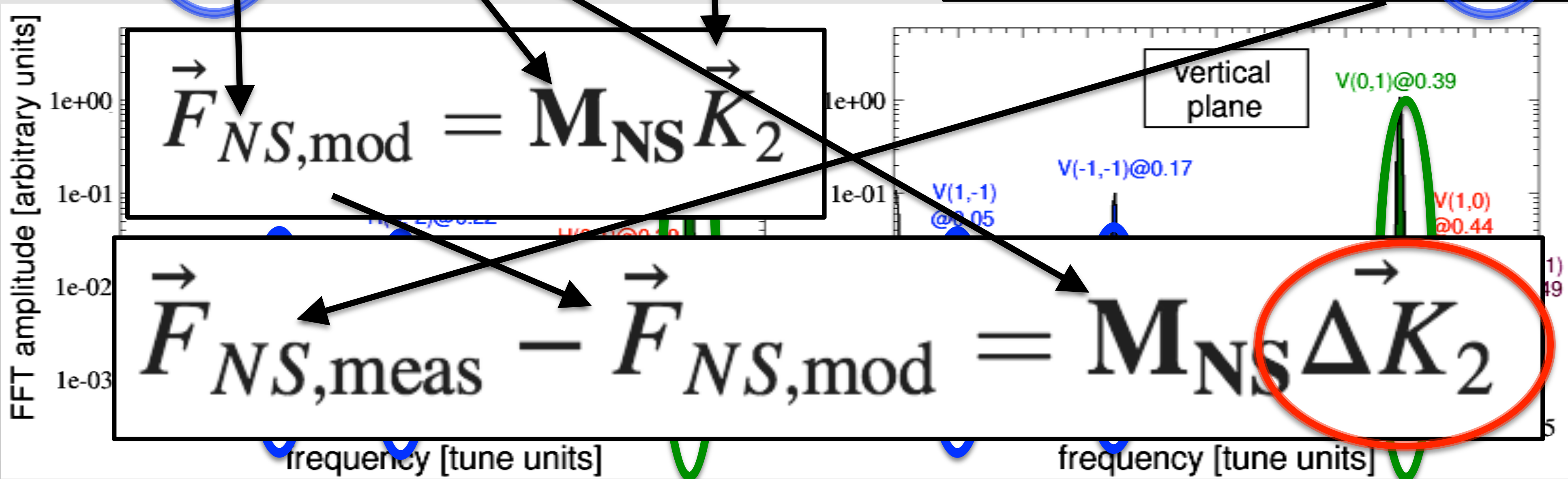
$$\vec{F}_{NS,mod} = \mathbf{M}_{NS}\vec{K}_2$$

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



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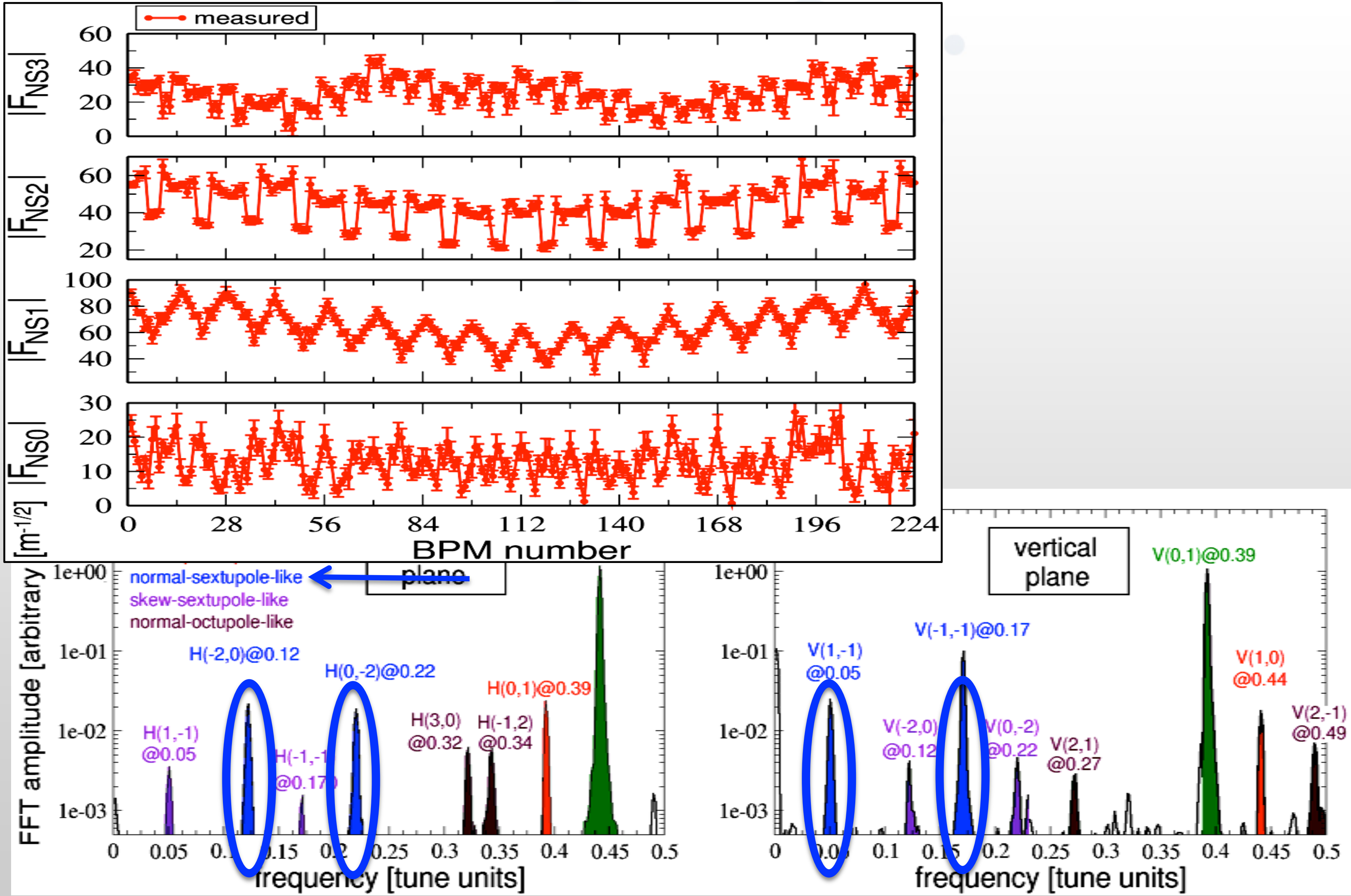
results for sextupole magnets (fields)



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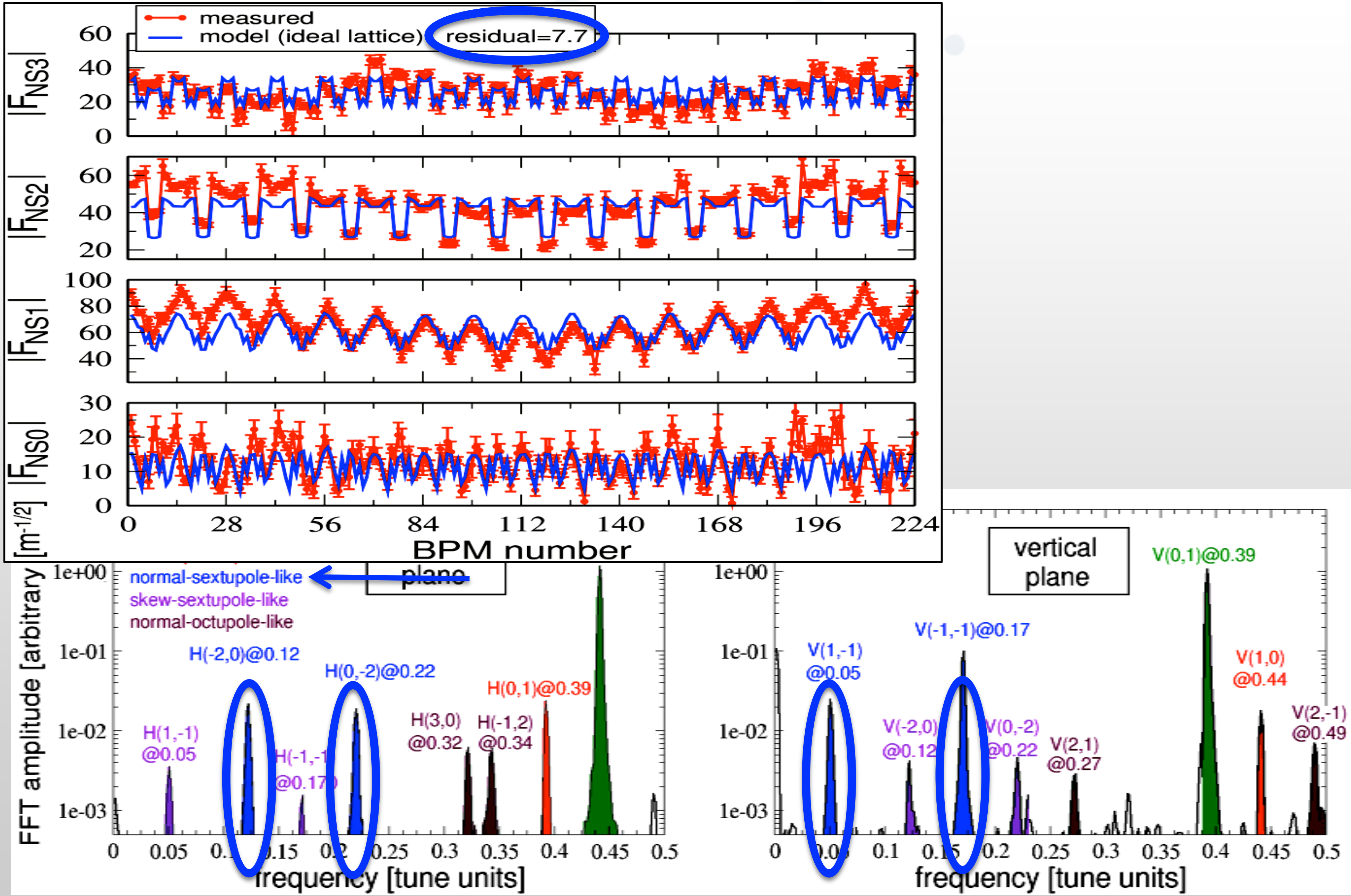

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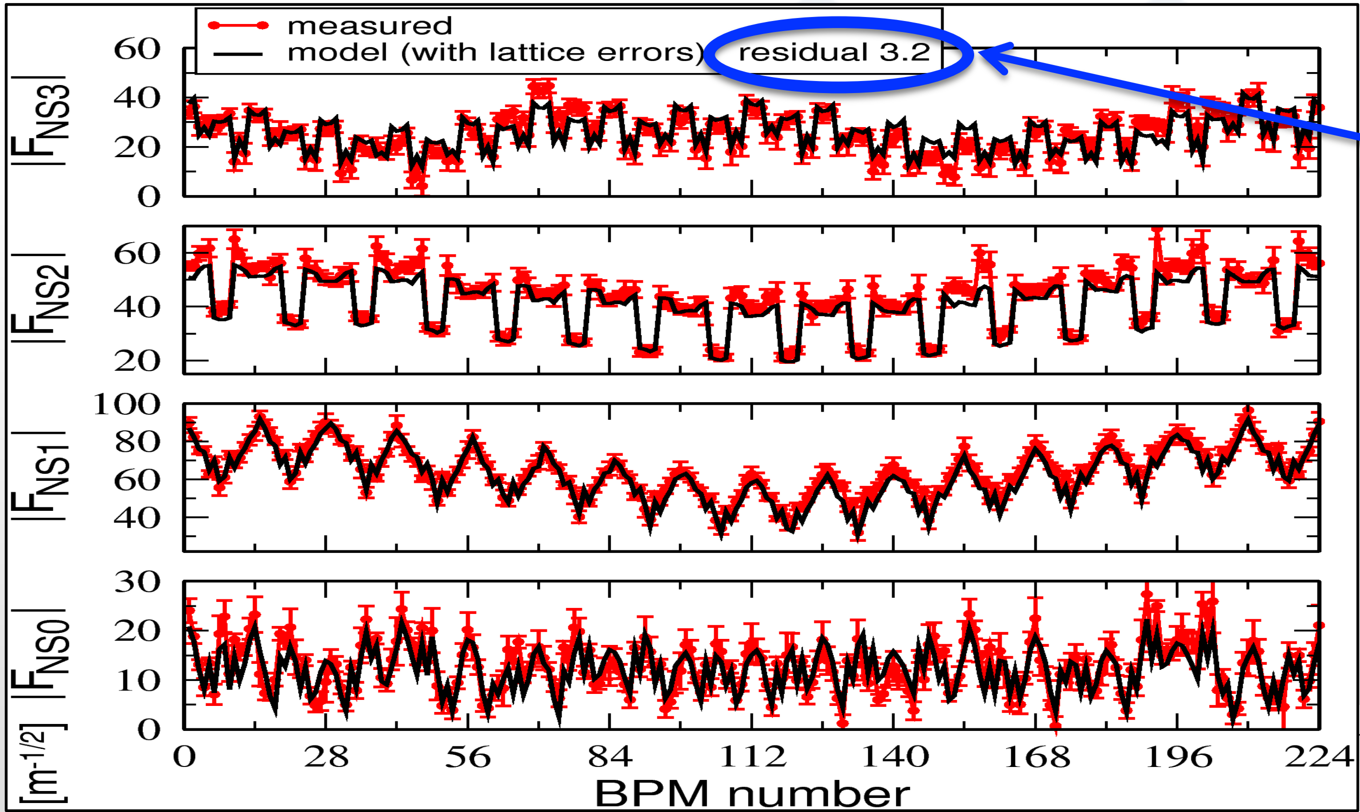
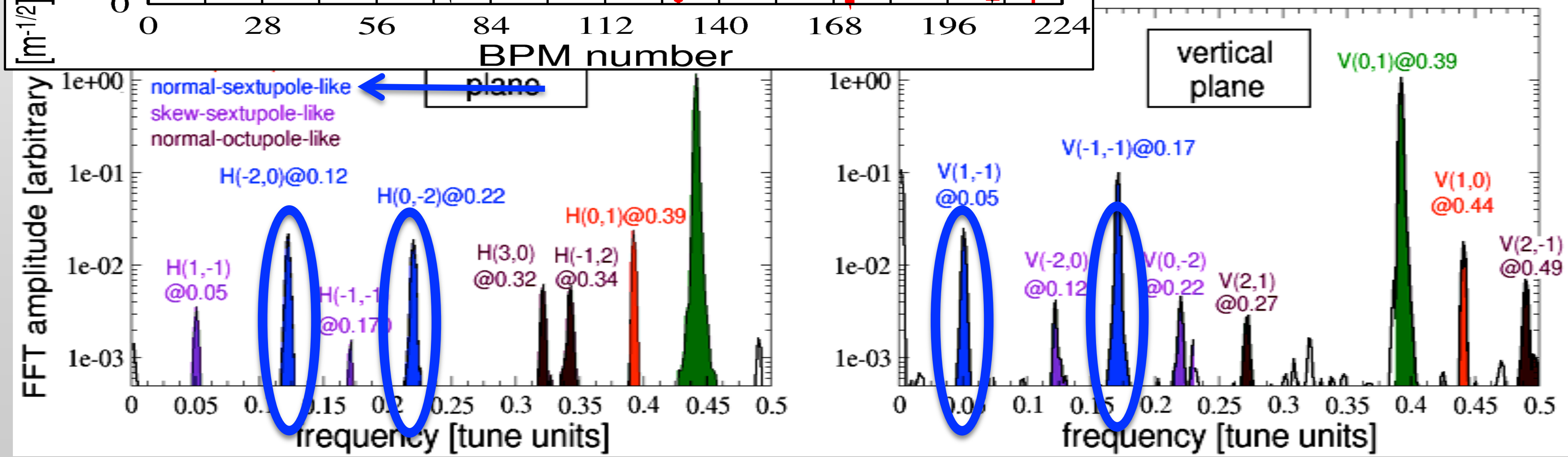


more than 50% of the RDT modulation stems from focusing errors (beta beating)!!

model with perfect sextupoles



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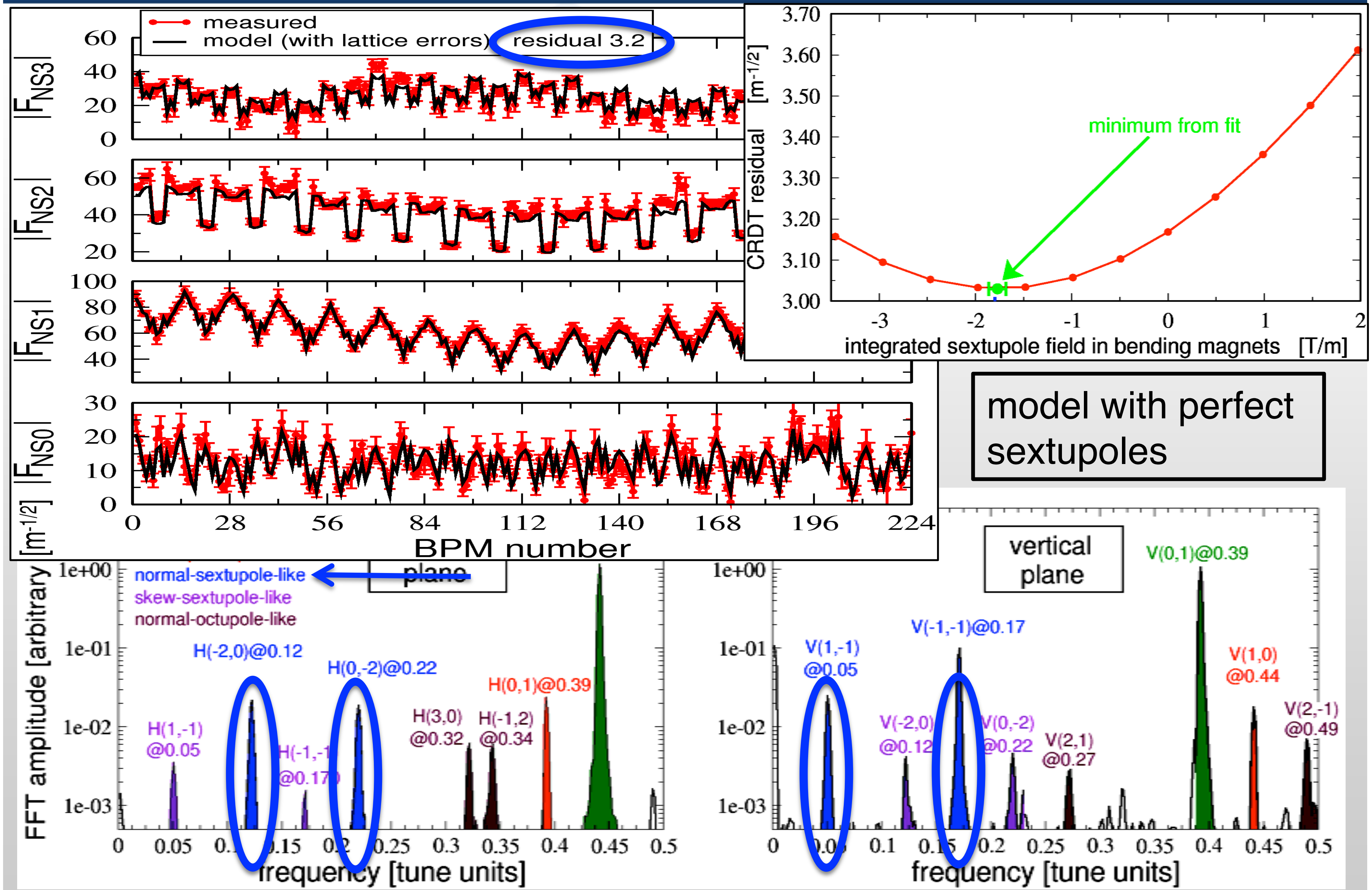

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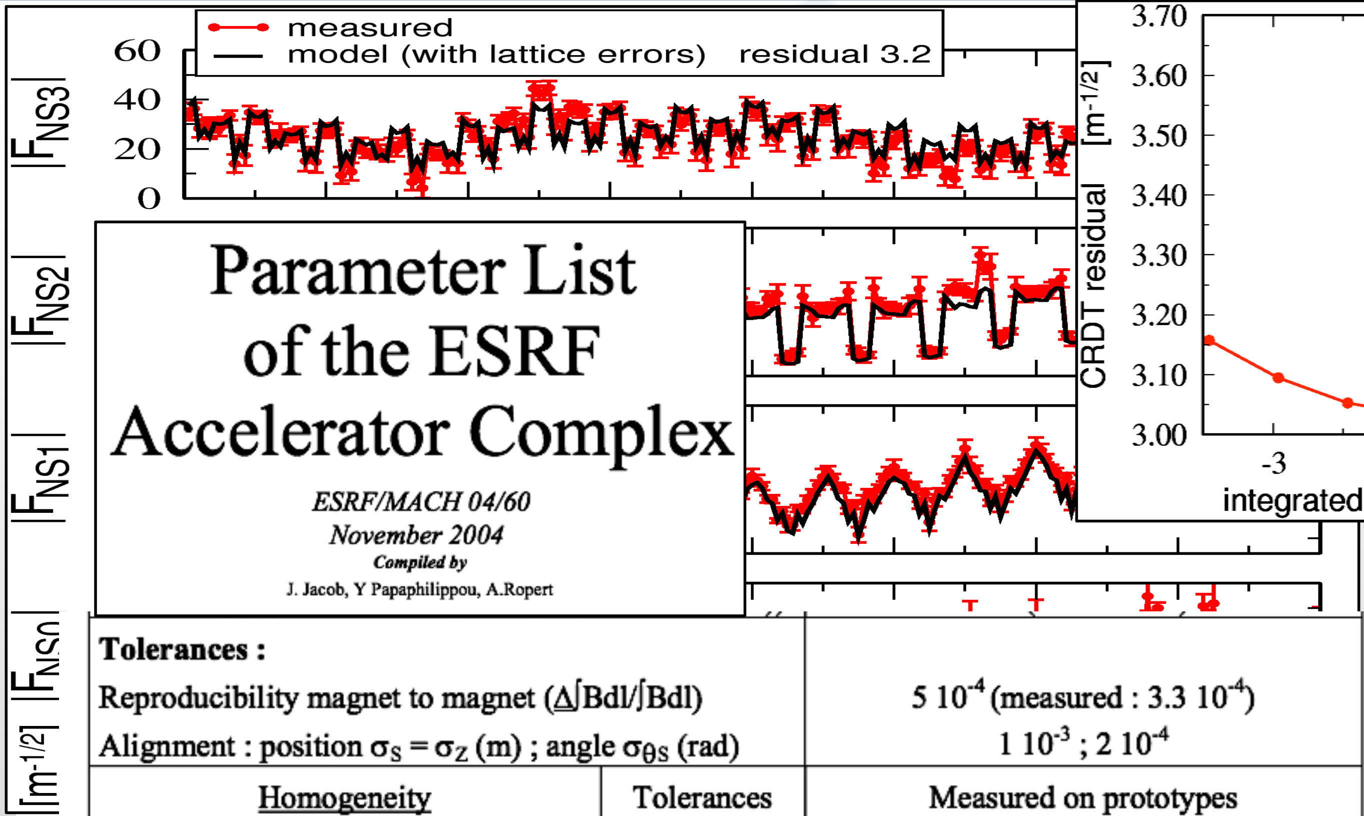


Parameter List of the ESRF Accelerator Complex

ESRF/MACH 04/60

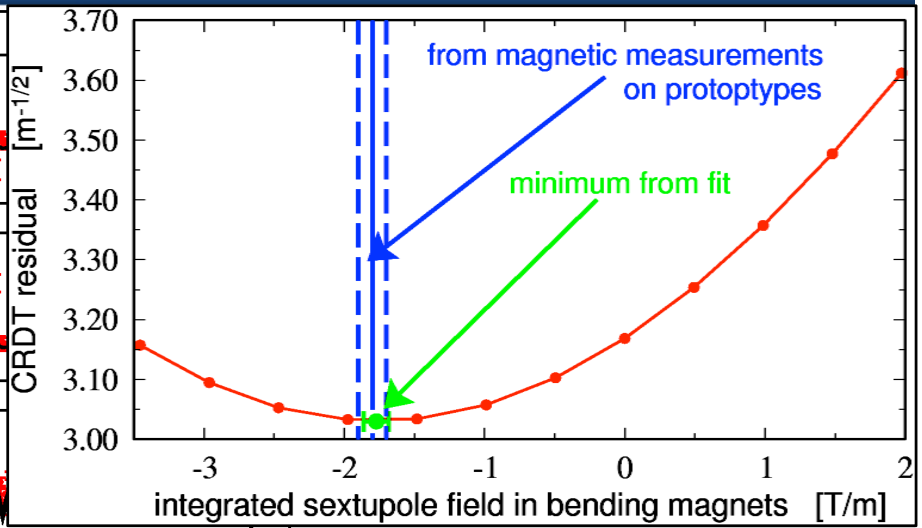
November 2004

Compiled by

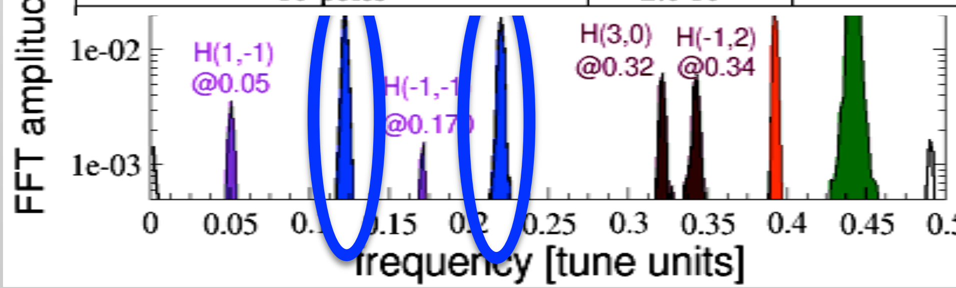
J. Jacob, Y Papaphilippou, A.Ropert

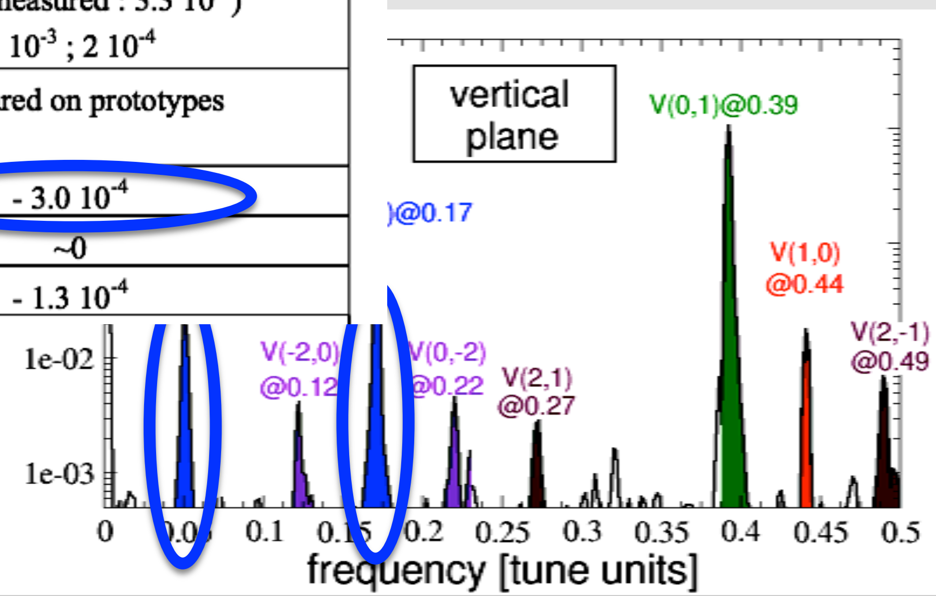
Tolerances :	
Reproducibility magnet to magnet ($\Delta\int Bdl/\int Bdl$)	$5\ 10^{-4}$ (measured : $3.3\ 10^{-4}$)
Alignment : position $\sigma_S = \sigma_Z$ (m) ; angle $\sigma_{\theta S}$ (rad)	$1\ 10^{-3}$; $2\ 10^{-4}$

Homogeneity ($\int\Delta Bdl / \int Bdl$) @ x = 25 mm:	Tolerances	Measured on prototypes
6-poles	$5.0\ 10^{-3}$	$-3.0\ 10^{-4}$
8-poles	$7.0\ 10^{-4}$	~0
10-poles	$2.0\ 10^{-3}$	$-1.3\ 10^{-4}$



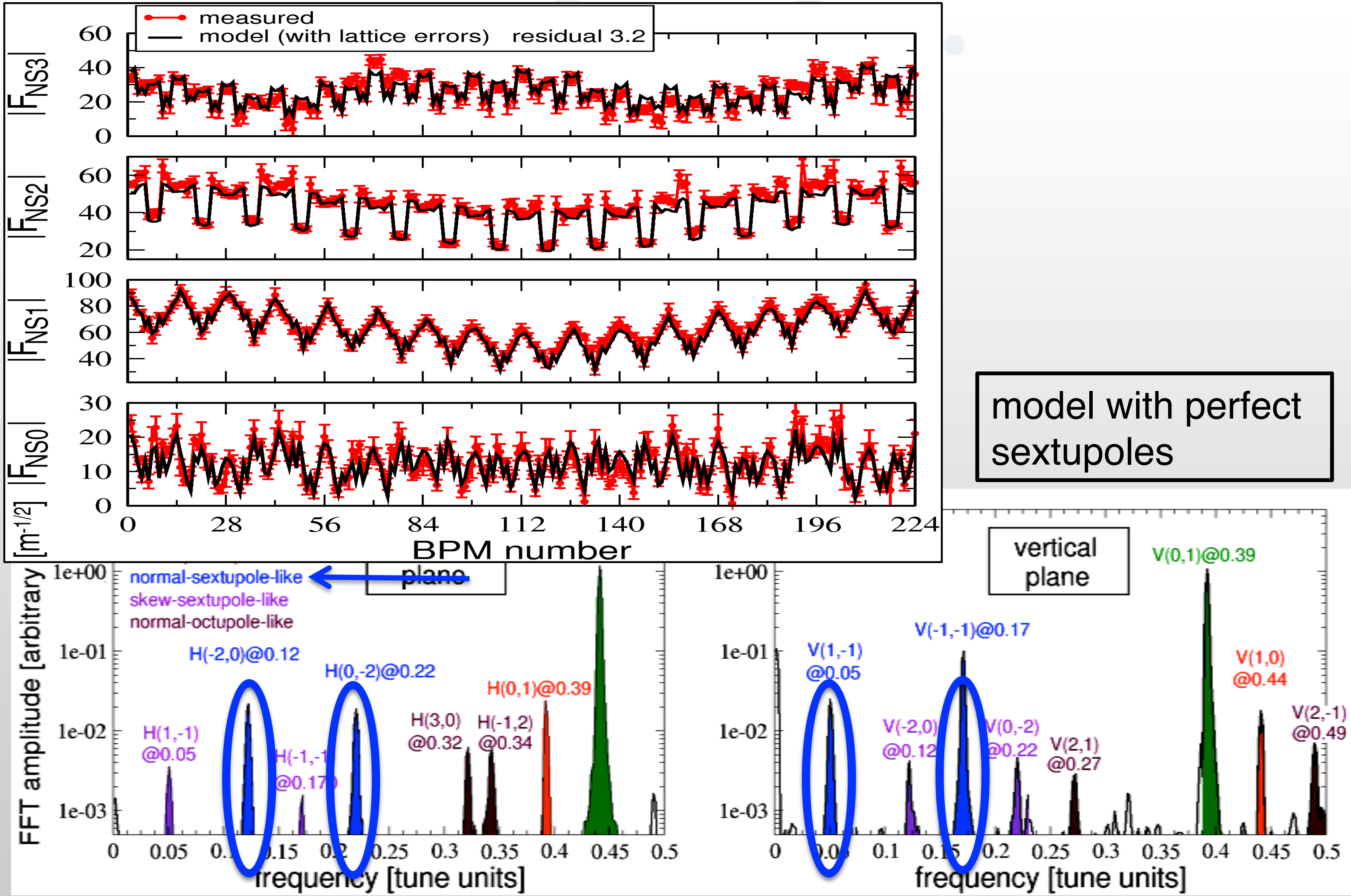
model with perfect sextupoles





results for sextupole magnets (fields)

A Light for Science



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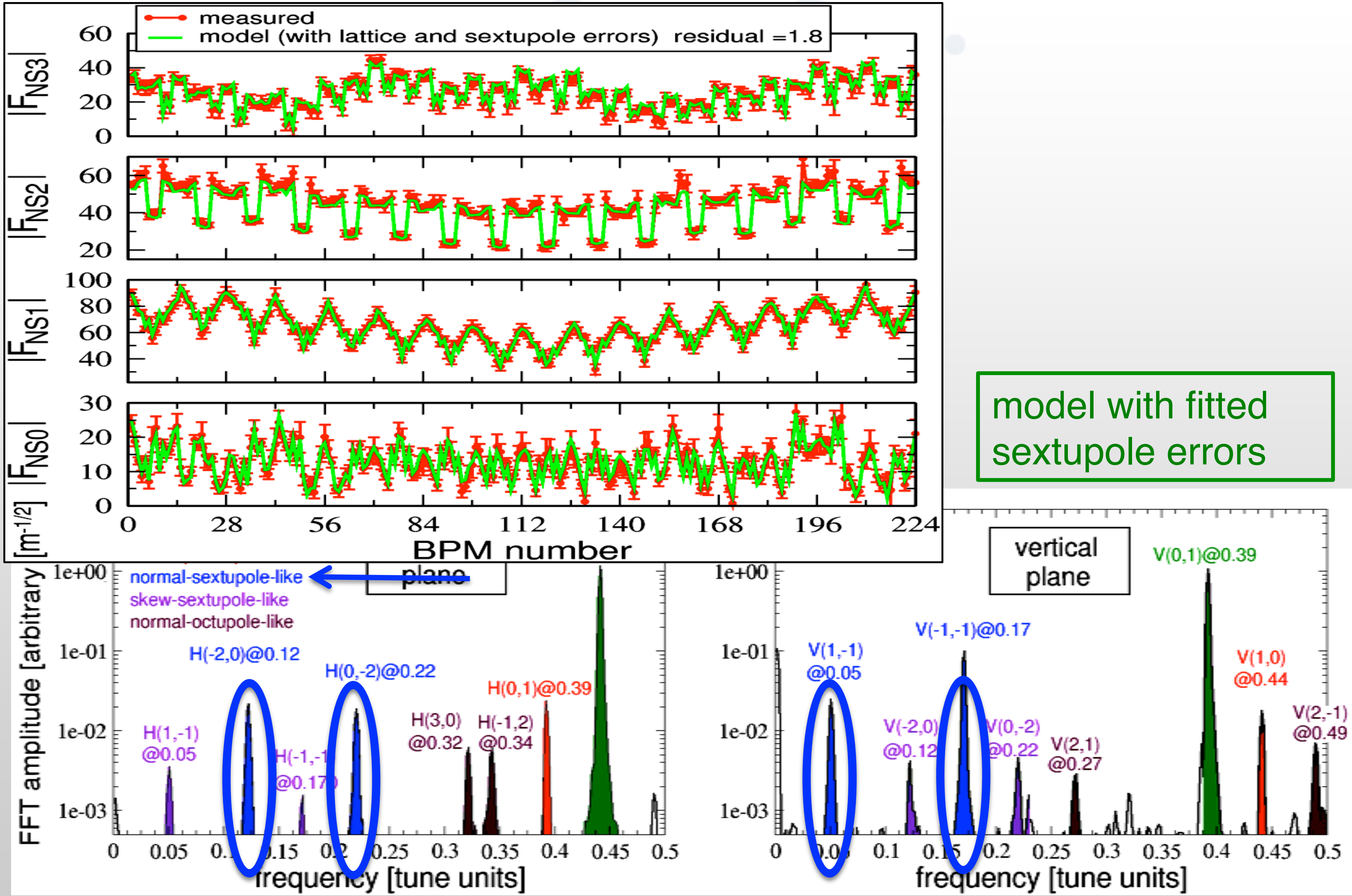
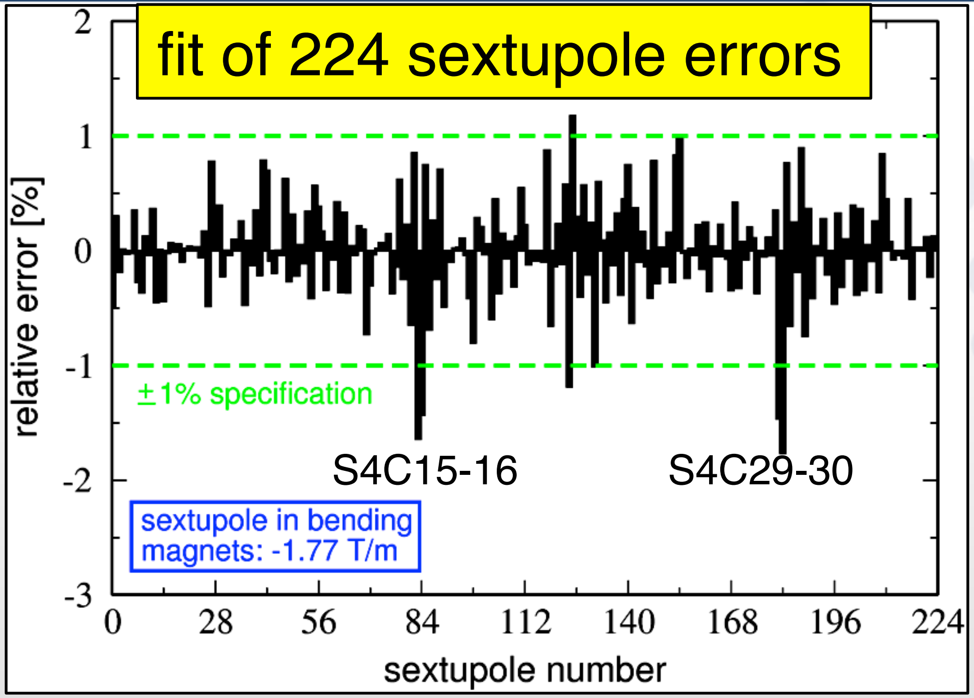
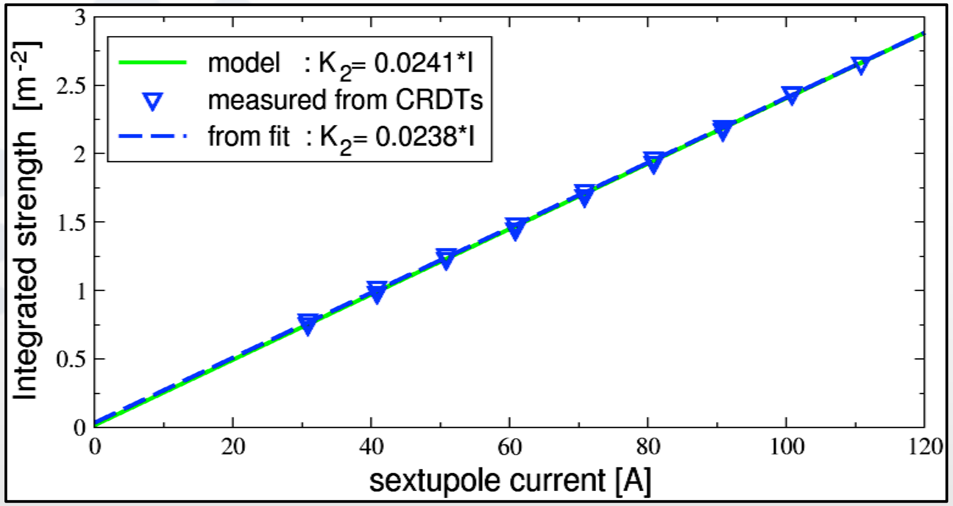


model with fitted sextupole errors

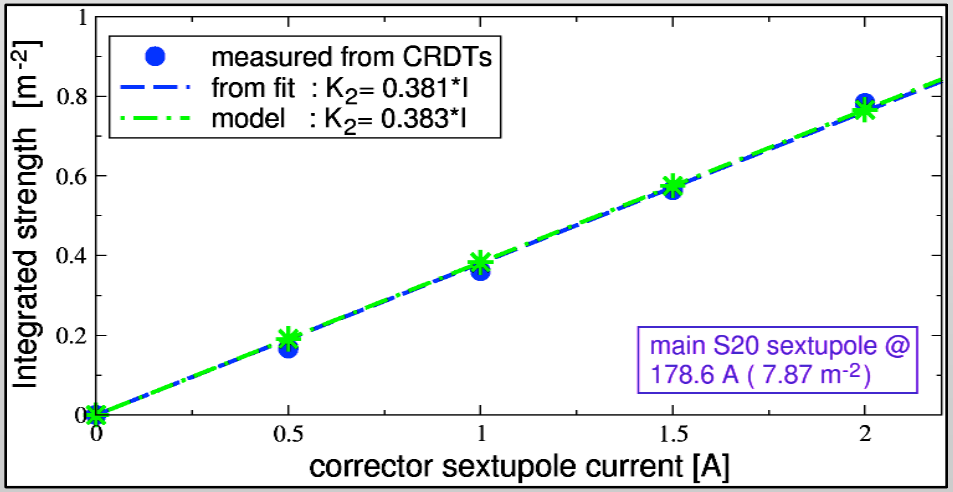
results for sextupole magnets (fields)



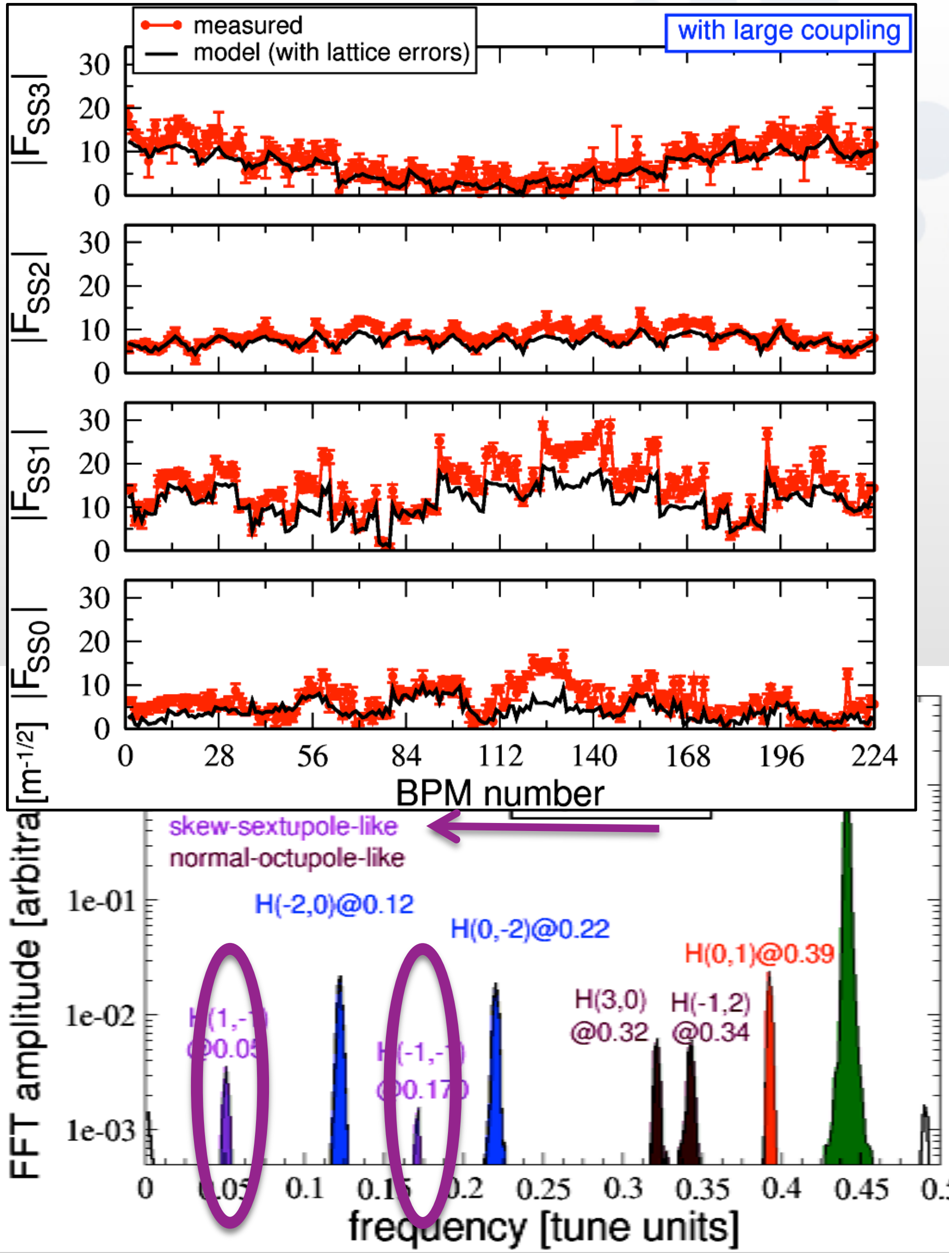
S4C15 calibration

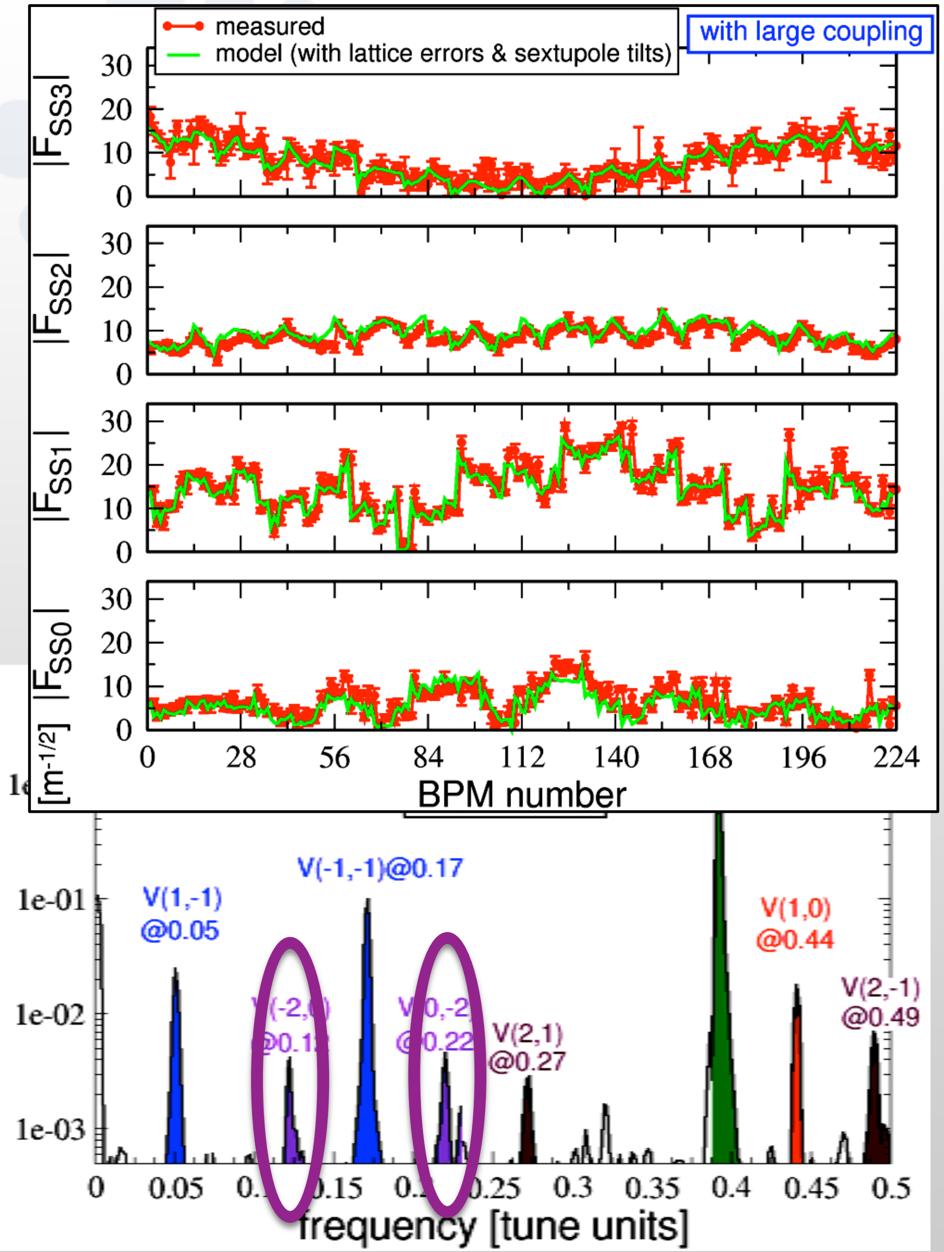


calibration of sextupole correctors



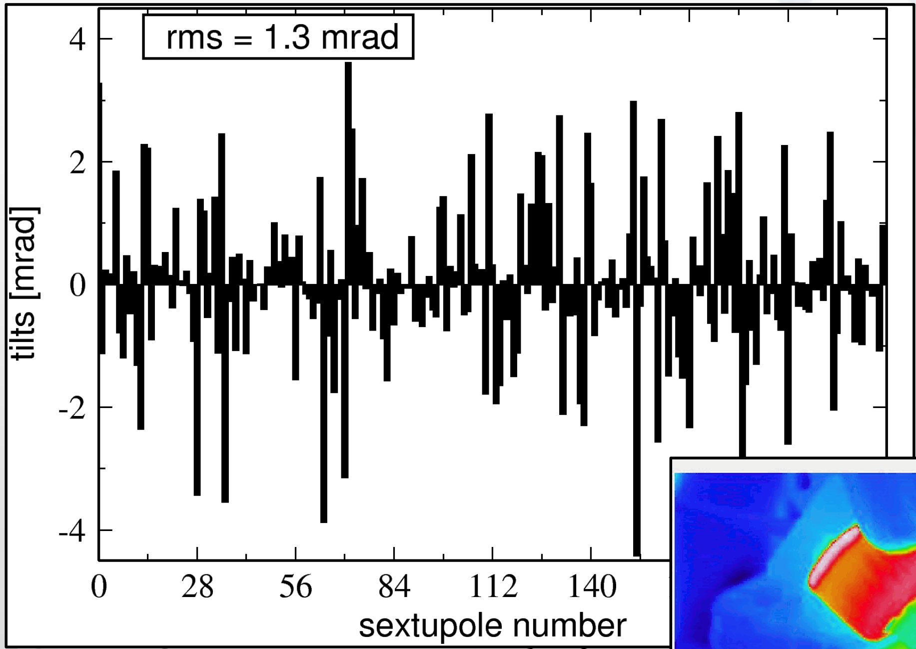
results for sextupole magnets (tilts)

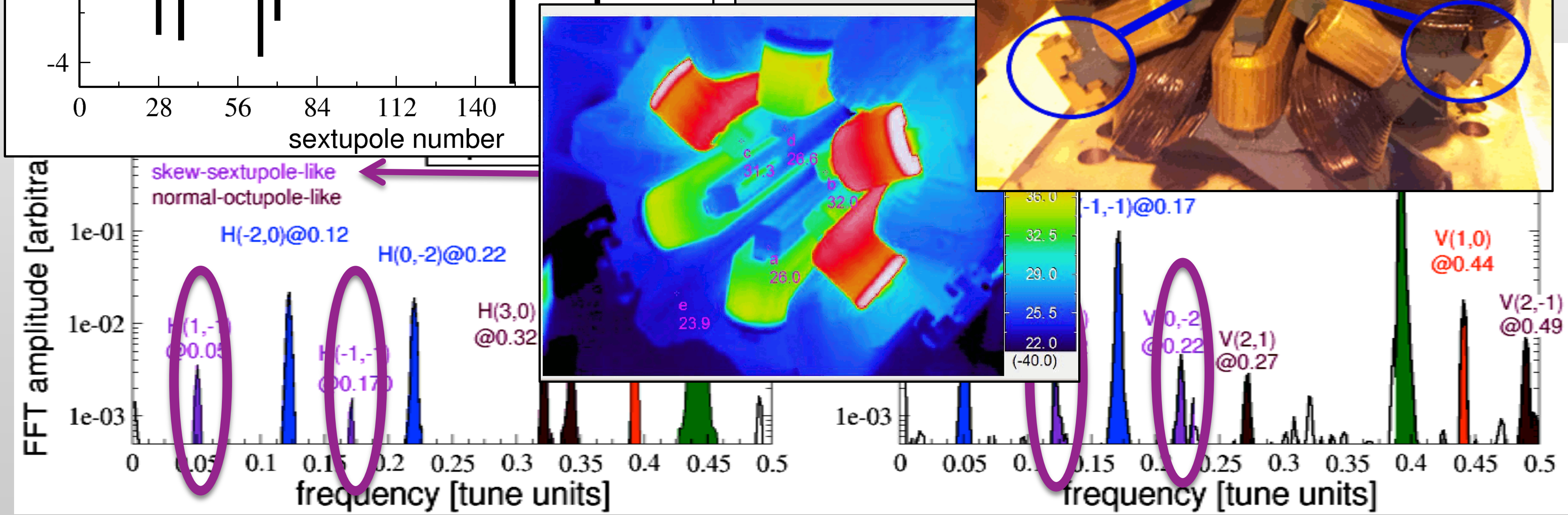


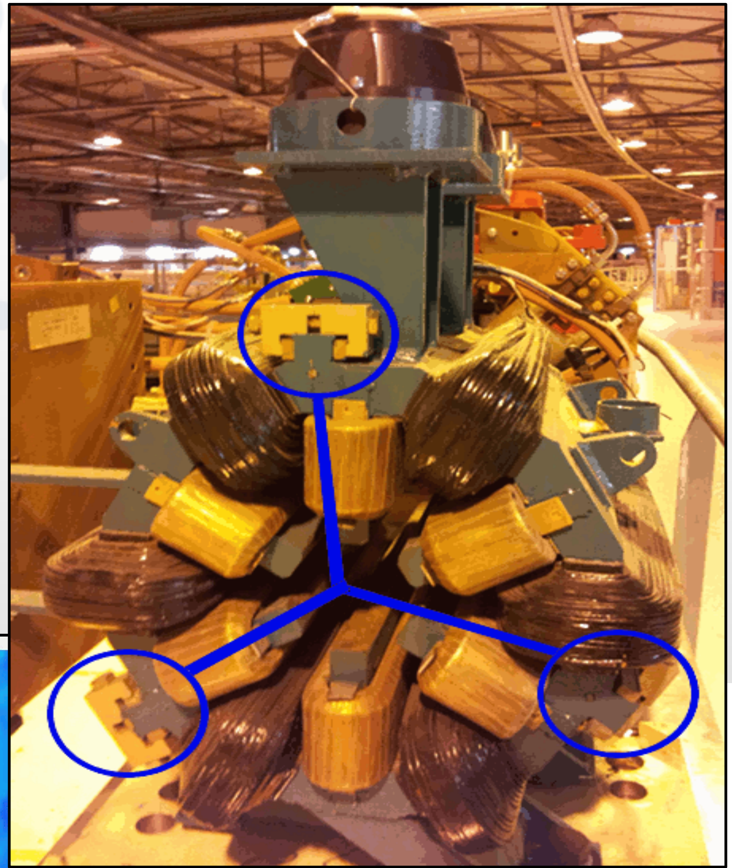


results for sextupole magnets (tilts)

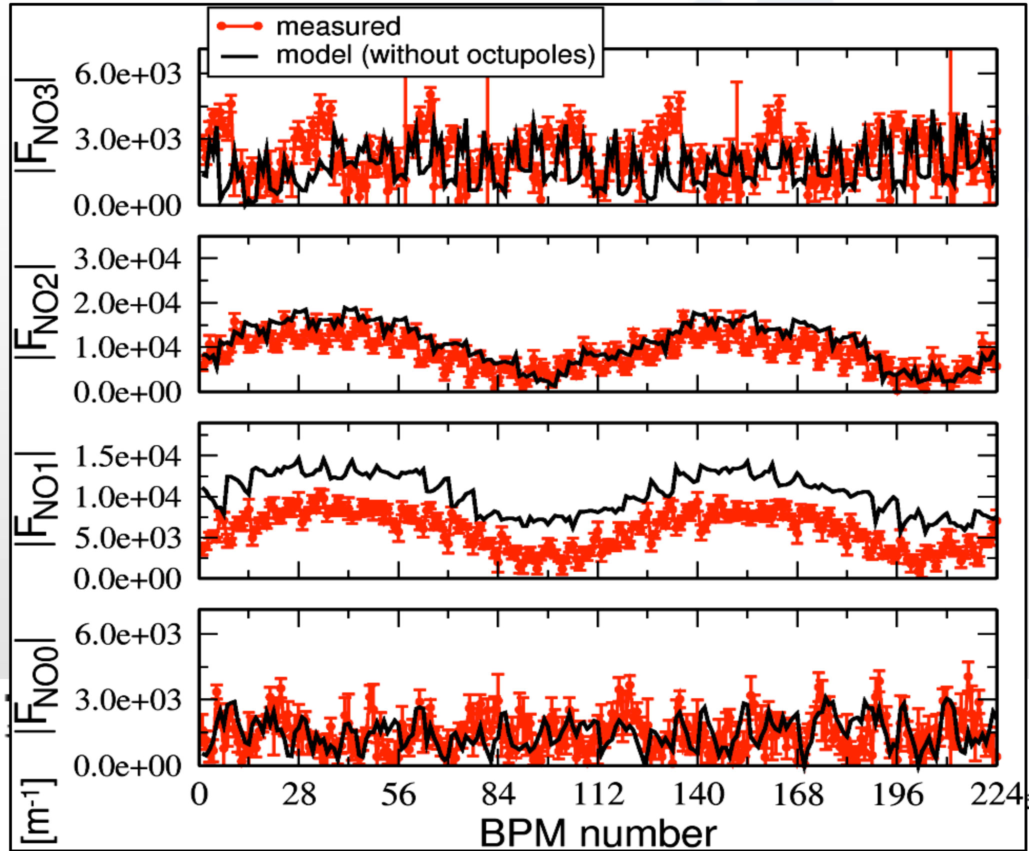
fit of 224 sextupole "effective rotations"
(better call them "skew-sextupole fields")

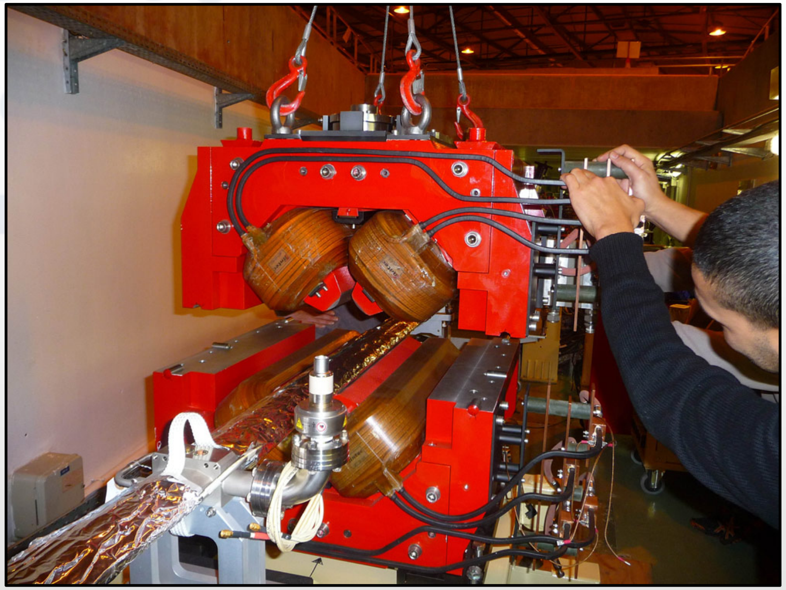


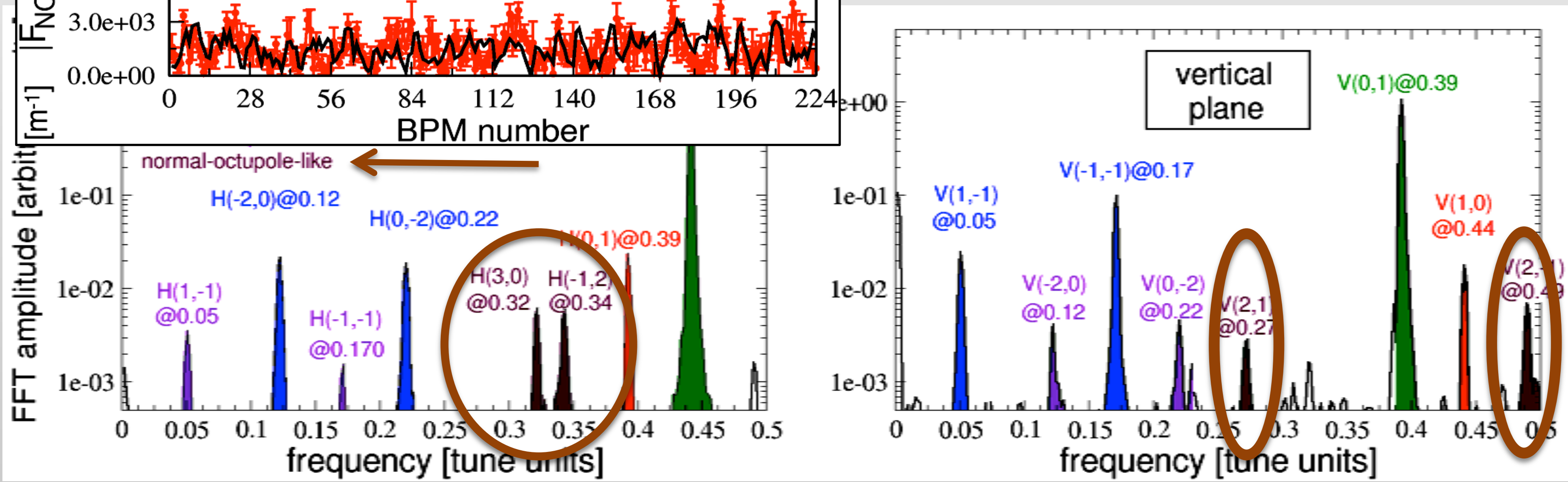


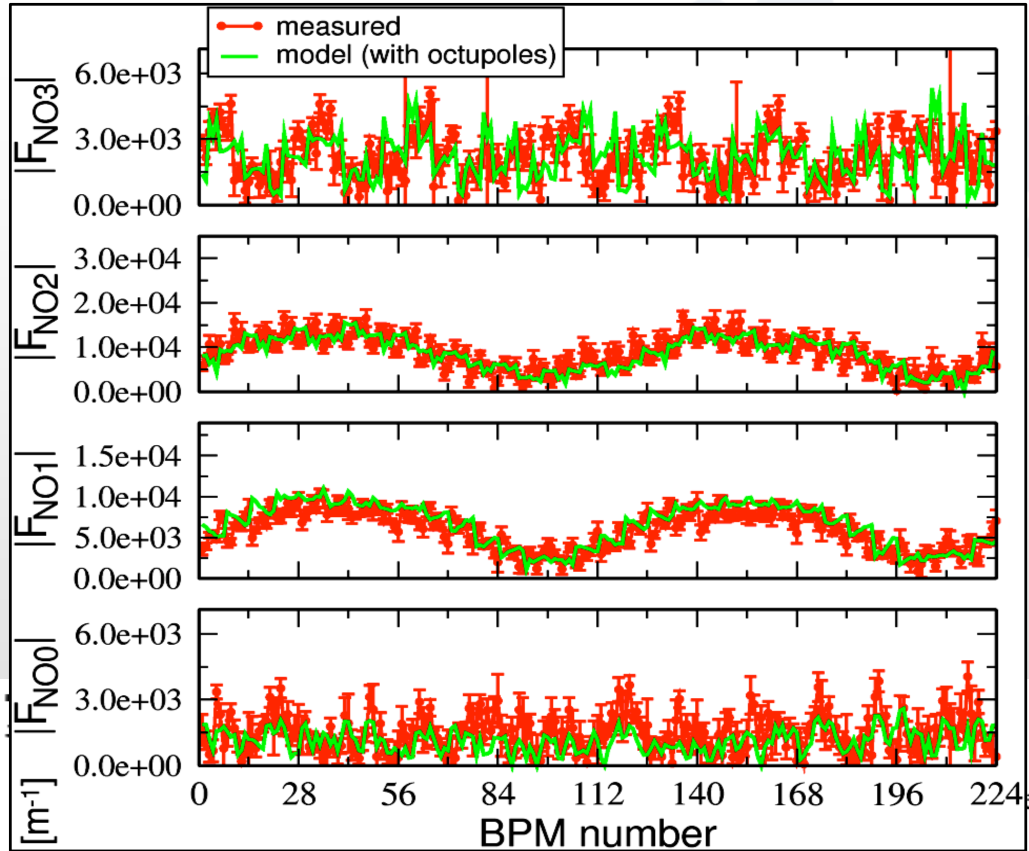


results for octupolar magnetic fields

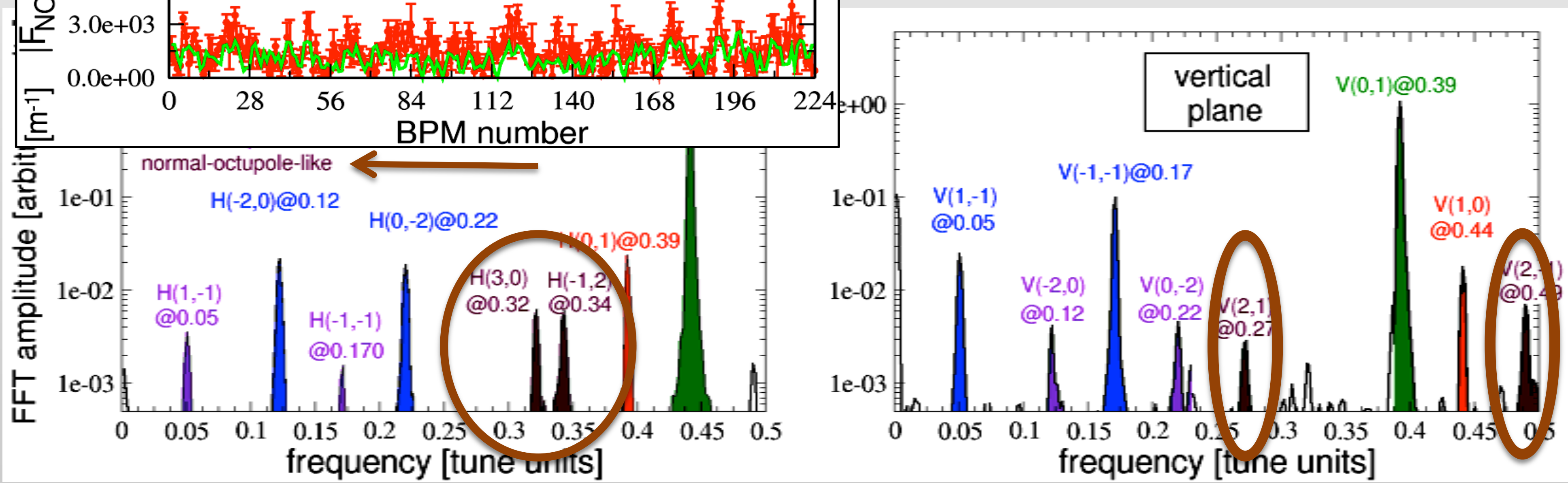








Quadrupole family	K_3 [m^{-3}] from mag. meas.	K_3 [m^{-3}] from TbT analysis (average $\pm$ rms)
QF2	2.1 ± 0.8	4.4 ± 1.6
QD3	-1.8 ± 0.7	-6.9 ± 0.7
QD4	-1.4 ± 0.5	2.5 ± 0.8
QF5	2.2 ± 0.8	-2.2 ± 1.4
QD6	-3.4 ± 1.8	-0.4 ± 2.4
QF7	3.6 ± 1.3	4.0 ± 3.3



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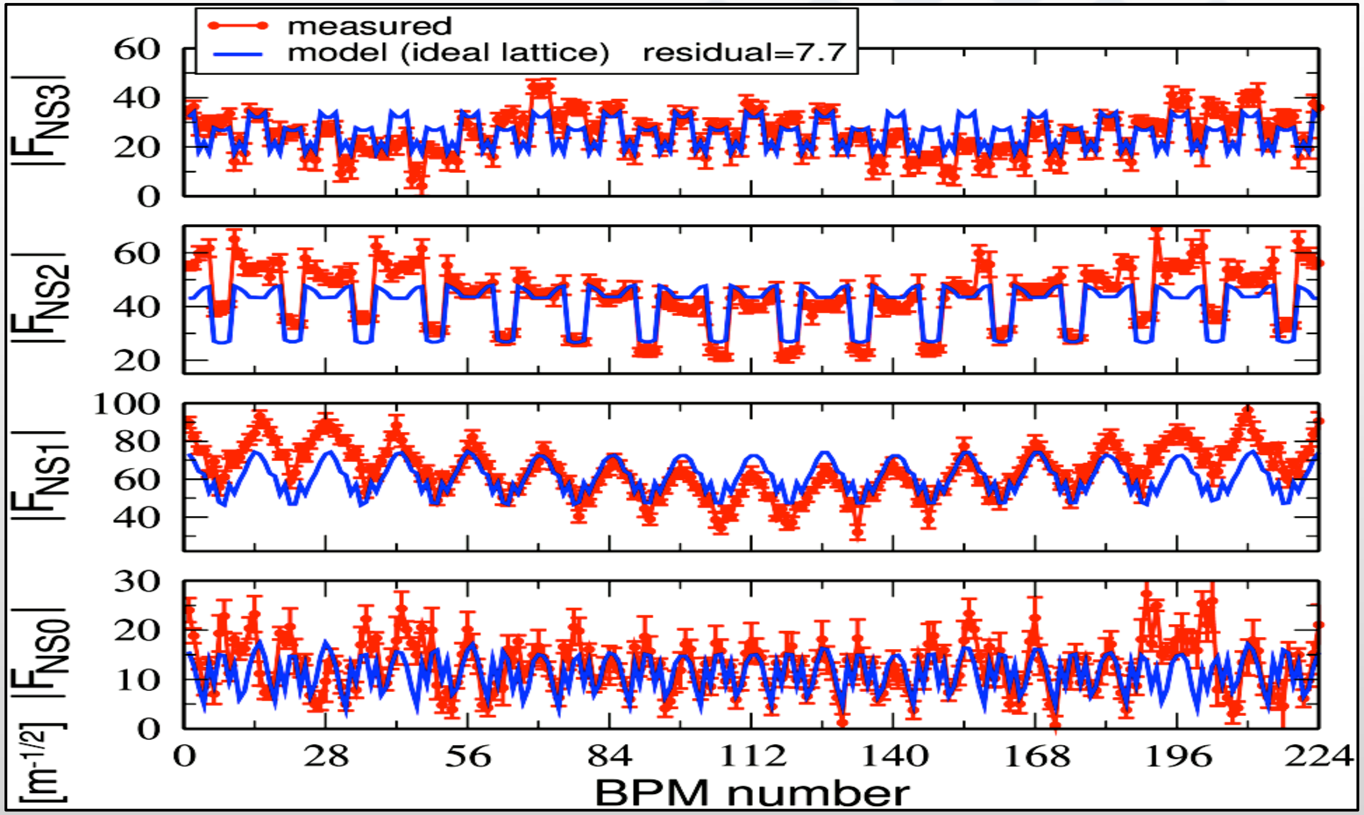

$$\vec{F}_{NS,\mathrm{meas}} - \vec{F}_{NS,\mathrm{ref}} = \mathbf{M}_{\mathbf{NS,cor}}\vec{K}_2^{\mathrm{cor}}$$

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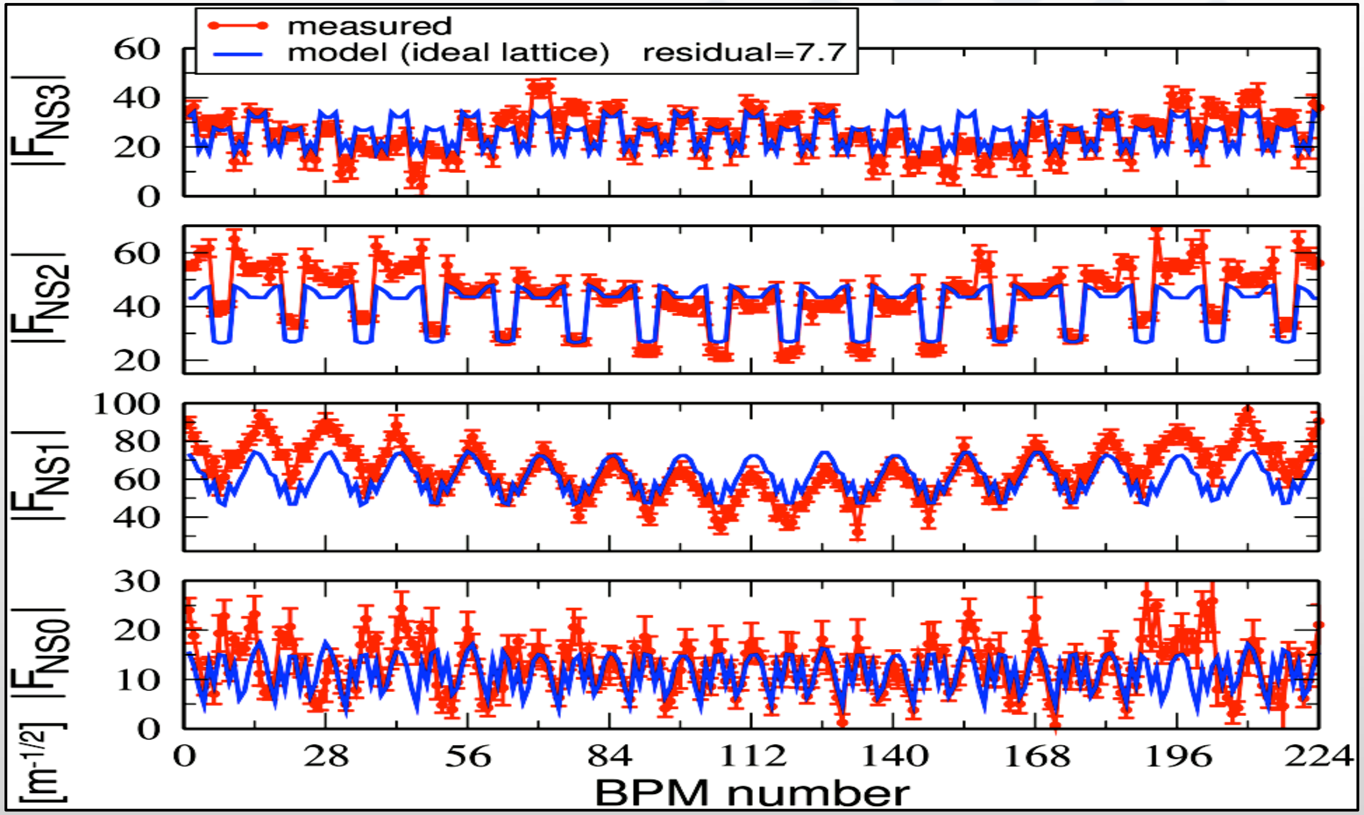
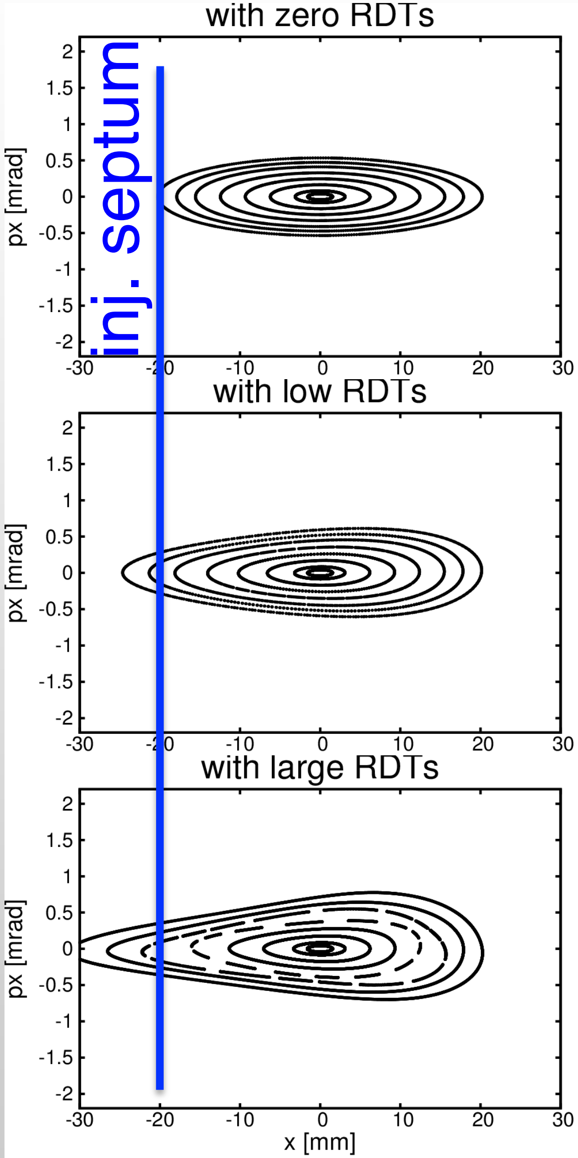
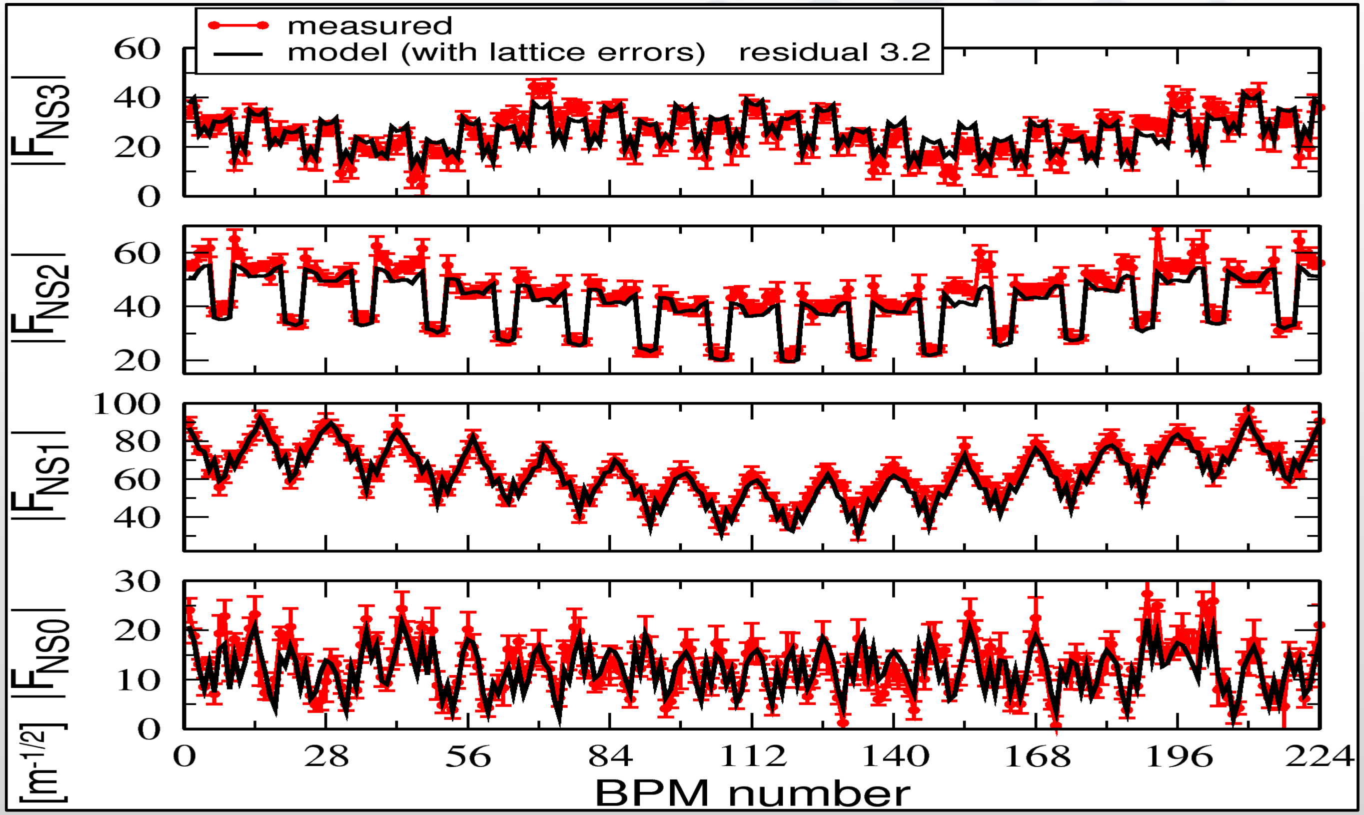




$$\vec{F}_{NS,\text{meas}} - \vec{F}_{NS,\text{ref}} = \mathbf{M}_{\mathbf{NS,cor}} \vec{K}_2^{\text{cor}}$$

sextupole correctors (12 at the ESRF SR) may be used to retrieve the ideal RDTs:



$$\vec{F}_{NS,\mathrm{meas}} - \vec{F}_{NS,\mathrm{ref}} = \mathbf{M}_{\mathbf{NS,cor}} \vec{K}_2^{\mathrm{cor}}$$

WARNING

- most (50%) of the RDT beating is due to focusing (i.e. quad) errors and not to sextupoles
- Correcting these RDTs with sext. correctors will break the sextupole 16-fold periodicity

sextupole correctors (12 at the ESRF SR) may be used to retrieve the ideal RDTs:

hypothesis: the more “matched” the RDTs, the larger the dynamic aperture, and (hopefully) the longer the lifetime

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filling pattern P= 6.03 GeV/c	lifetime correctors OFF	lifetime manual correction	lifetime RDT correction	
1 mA/bunch low chroma	16.2 h	24.2 h	22.4 h	Touschek-limited
6 mA/bunch large chroma	2.5 h	3.2 h	2.0 h	Touschek-dominated

sextupole correctors (12 at the ESRF SR) may be used to retrieve the ideal RDTs:

hypothesis: the more “matched” the RDTs, the larger the dynamic aperture, and (hopefully) the longer the lifetime

Observations:

RDTs <-> on-momentum dynamic aperture

Touschek lifetime <-> off-momentum dynamic aperture & energy acceptance

Sextupoles -> RDTs **and** chromatic terms

Touschek-limited

Touschek-dominated

Sextupoles -> RDTs **and** chromatic terms

Sextupole strengths K_2 drive (linearly): RDTs

	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} =	$M_0(\beta,\varphi)$	×	$K_2(\text{sext})$

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

Sextupoles -> RDTs **and** chromatic terms

Sextupole strengths K_2 drive (linearly): RDTs, lin. chroma

$$
\begin{cases}
Q'_x = -\dfrac{1}{4\pi}\displaystyle\sum_{w=1}^{W}\left(K_{w,1} - K_{w,2}D_{w,x} + J_{w,2}D_{w,y}\right)\beta_{w,x} \\
Q'_y = +\dfrac{1}{4\pi}\displaystyle\sum_{w=1}^{W}\left(K_{w,1} - K_{w,2}D_{w,x} + J_{w,2}D_{w,y}\right)\beta_{w,y}
\end{cases}
$$

Sextupoles -> RDTs **and** chromatic terms

Sextupole strengths K_2 drive (linearly): RDTs, lin. chroma, chromatic beating

$$
\begin{cases}
\left.\dfrac{\partial\beta_x(s)}{\partial\delta}\right|_{\delta=0} \simeq +\dfrac{\beta_x(s)}{2\sin(2\pi Q_x)}\displaystyle\sum_{w=1}^{W}\left(K_{w,1}-K_{w,2}D_{w,x}+J_{w,2}D_{w,y}\right)\beta_{w,x}\cos\left(|2\Delta\phi^{(s)}_{x,w}|-2\pi Q_x\right)\\[2ex]
\left.\dfrac{\partial\beta_y(s)}{\partial\delta}\right|_{\delta=0} \simeq -\dfrac{\beta_y(s)}{2\sin(2\pi Q_y)}\displaystyle\sum_{w=1}^{W}\left(K_{w,1}-K_{w,2}D_{w,x}+J_{w,2}D_{w,y}\right)\beta_{w,y}\cos\left(|2\Delta\phi^{(s)}_{y,w}|-2\pi Q_y\right)
\end{cases}
$$

Sextupoles -> RDTs **and** chromatic terms

Sextupole strengths K_2 drive (linearly): RDTs, lin. chroma, chromatic beating, second-order dispersion

$$
\begin{cases}
h_{w,10002} = \frac{1}{2}\left[-K_{w,0} - J_{w,1}D_{w,y} + K_{w,1}D_{w,x} - \frac{1}{2}K_{w,2}\left(D^2_{w,x} - D^2_{w,y}\right) + J_{w,2}D_{w,x}D_{w,y}\right]\sqrt{\beta_{w,x}} \\
h_{w,00102} = \frac{1}{2}\left[\ J_{w,0} - J_{w,1}D_{w,x} - K_{w,1}D_{w,y} + \frac{1}{2}J_{w,2}\left(D^2_{w,x} - D^2_{w,y}\right) + K_{w,2}D_{w,x}D_{w,y}\right]\sqrt{\beta_{w,y}}
\end{cases}
$$

Sextupoles -> RDTs **and** chromatic terms

Sextupole strengths K_2 drive (linearly): RDTs, lin. chroma, chromatic beating, second-order dispersion & chromatic coupling

$$
\begin{cases}
f_{10011}(s) = \left.\dfrac{d\, f_{1001}(s)}{d\,\delta}\right|_{\delta=0} = -\dfrac{\sum_{w=1}^{W}\left(J_{w,1} - K_{w,2}D_{w,y} - J_{w,2}D_{w,x}\right)\sqrt{\beta_{w,x}\beta_{w,y}}e^{i(\Delta\phi^{(s)}_{w,x}-\Delta\phi^{(s)}_{w,y})}}{4\left(1-e^{2\pi i(Q_x-Q_y)}\right)} + F_{1001}(s,J_1) \\
f_{10101}(s) = \left.\dfrac{d\, f_{1010}(s)}{d\,\delta}\right|_{\delta=0} = -\dfrac{\sum_{w=1}^{W}\left(J_{w,1} - K_{w,2}D_{w,y} - J_{w,2}D_{w,x}\right)\sqrt{\beta_{w,x}\beta_{w,y}}e^{i(\Delta\phi^{(s)}_{w,x}+\Delta\phi^{(s)}_{w,y})}}{4\left(1-e^{2\pi i(Q_x+Q_y)}\right)} + F_{1010}(s,J_1)
\end{cases},
$$

Sextupoles -> RDTs and chromatic terms

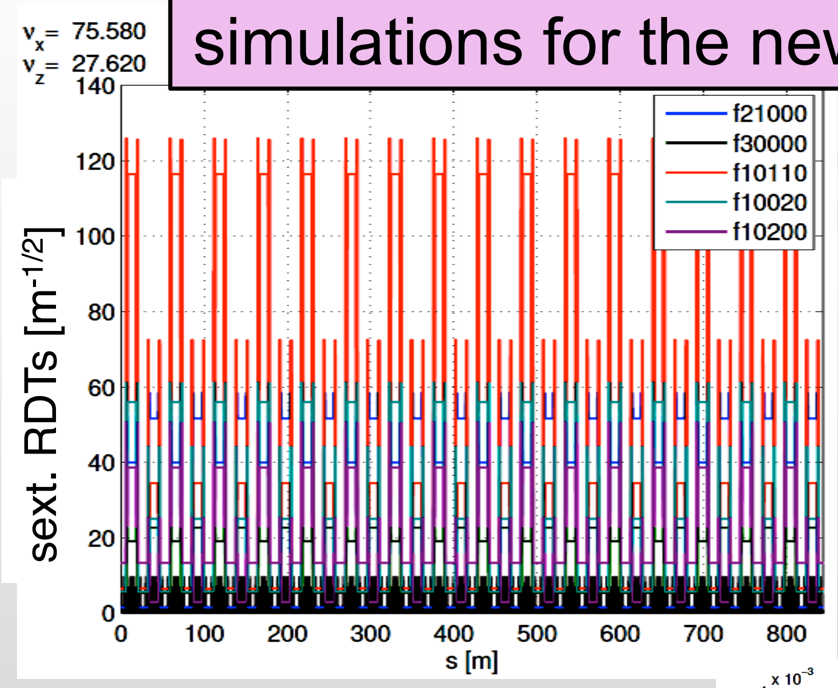
Sextupole strengths K_2 drive (linearly): RDTs, lin. chroma, chromatic beating, second-order dispersion & chromatic coupling

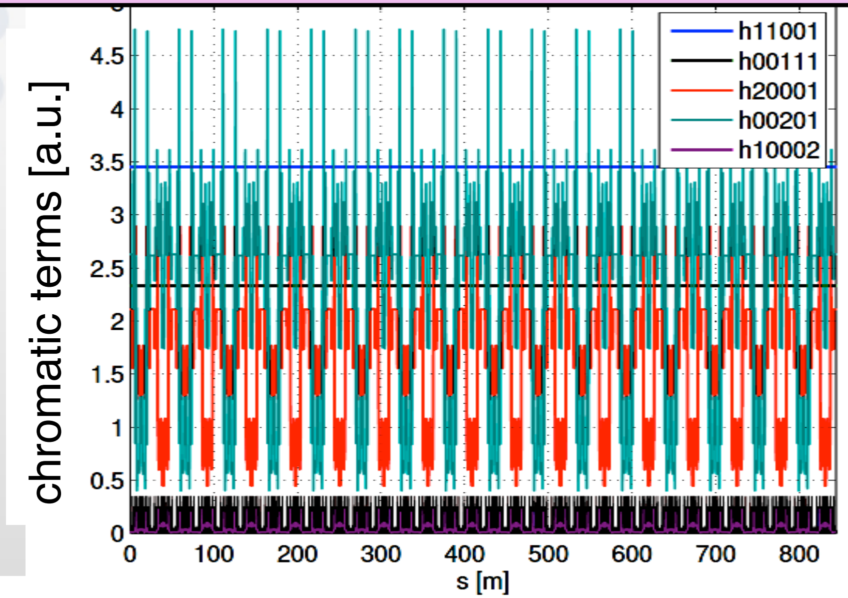
During the RDT correction at the ESRF only lin. chroma was kept constant, while other chromatic terms were left unconstrained (and not measured) : could this explain the loss of lifetime?

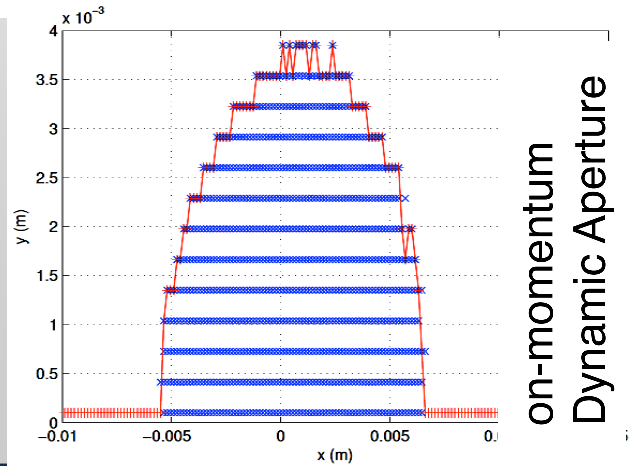
Simulations for the new ESRF storage ring ->

Sextupoles -> RDTs and chromatic terms

simulations for the new ESRF storage ring (N. Carmignani)





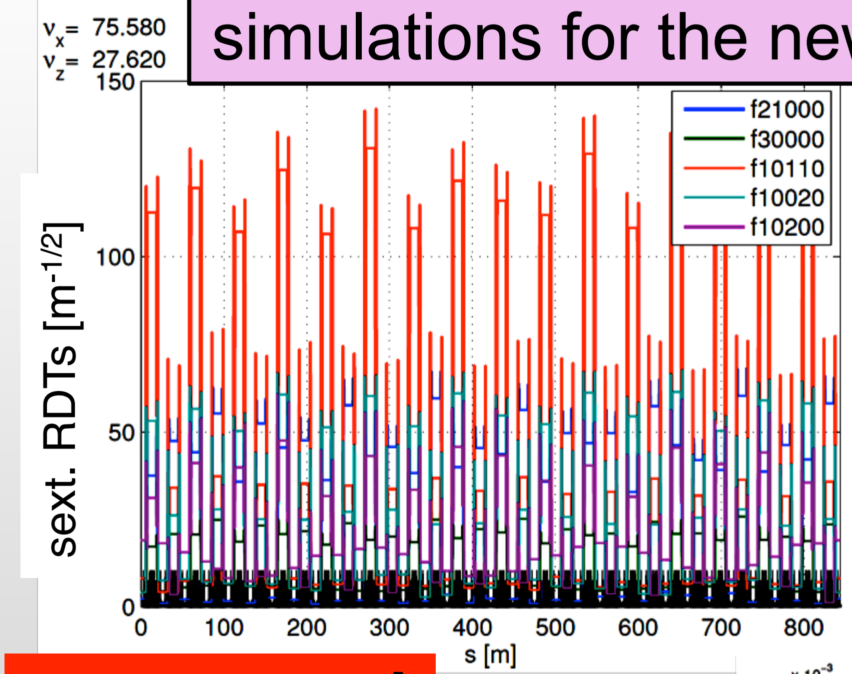


IDEAL CASE:

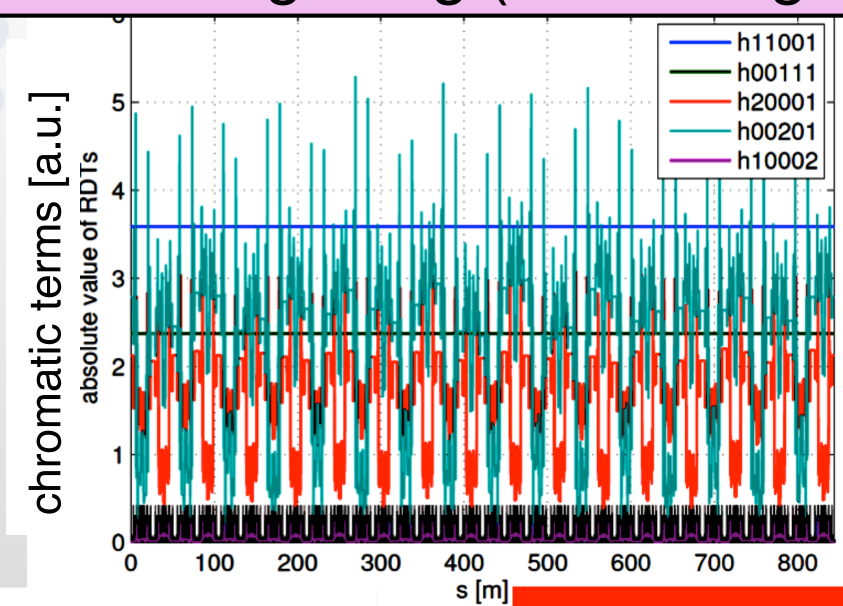
Lifetime = 22.6 h

Sextupoles -> RDTs **and** chromatic terms

simulations for the new ESRF storage ring (N. Carmignani)

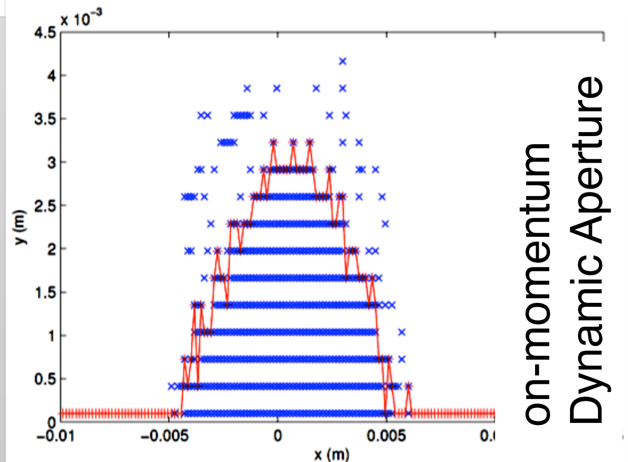


uncorrected



uncorrected

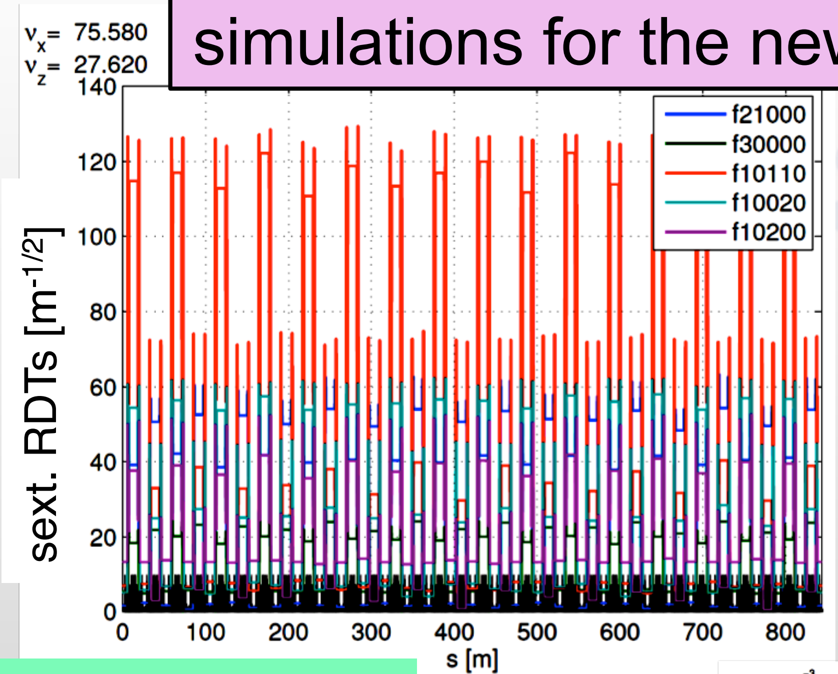
With focusing errors:
RMS β-beating ~5-6%
Lifetime = 8.0 h

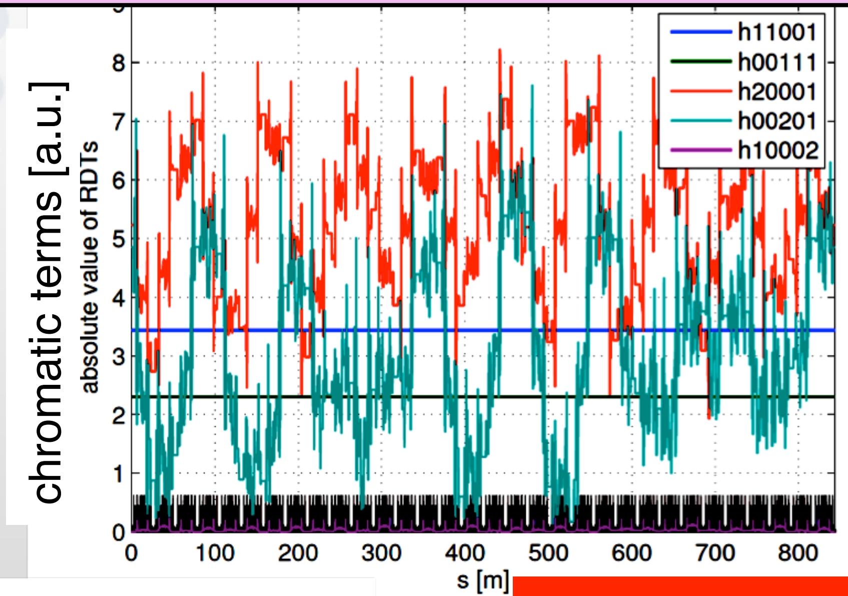


-25% DA
-65% Lifetime

Sextupoles -> RDTs **and** chromatic terms

simulations for the new ESRF storage ring (N. Carmignani)

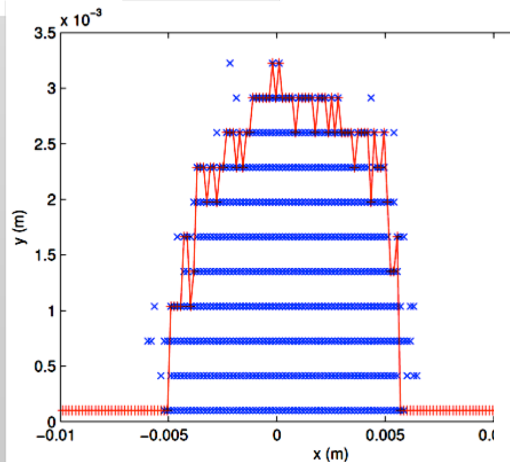




corrected*

*: with all 224 sextupoles

uncorrected



on-momentum Dynamic Aperture

With focusing errors:

RMS β-beating ~5-6%

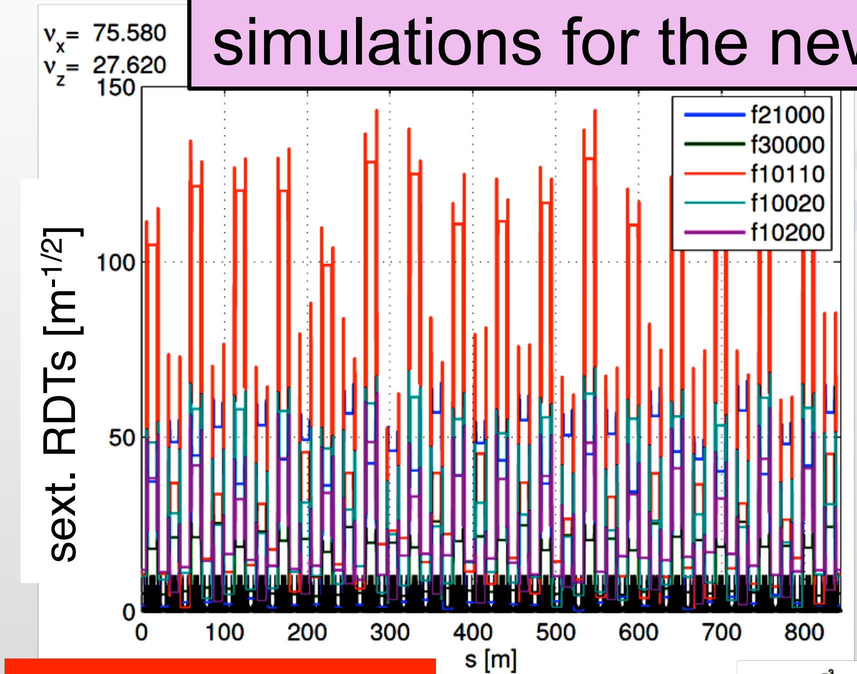
Lifetime = 1.0 h

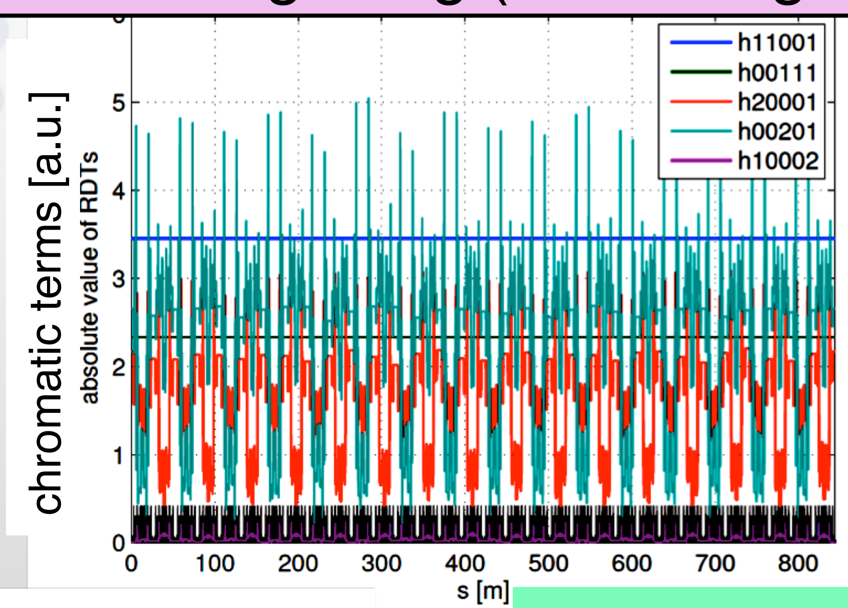
-8% DA

-96% Lifetime

Sextupoles -> RDTs **and** chromatic terms

simulations for the new ESRF storage ring (N. Carmignani)

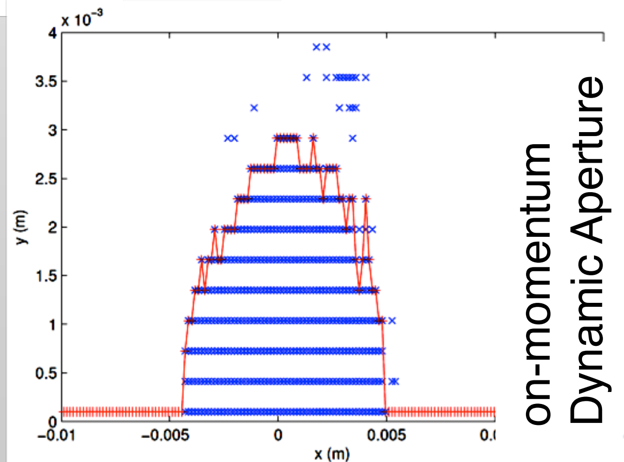




uncorrected

corrected*

*: with all 224 sextupoles



With focusing errors:

RMS β-beating ~5-6%

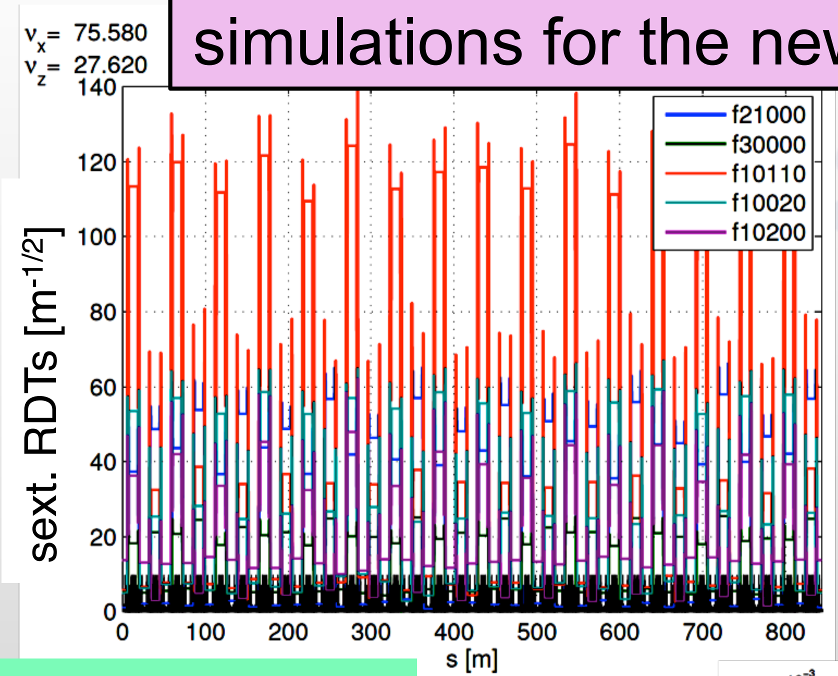
Lifetime = 12.9 h

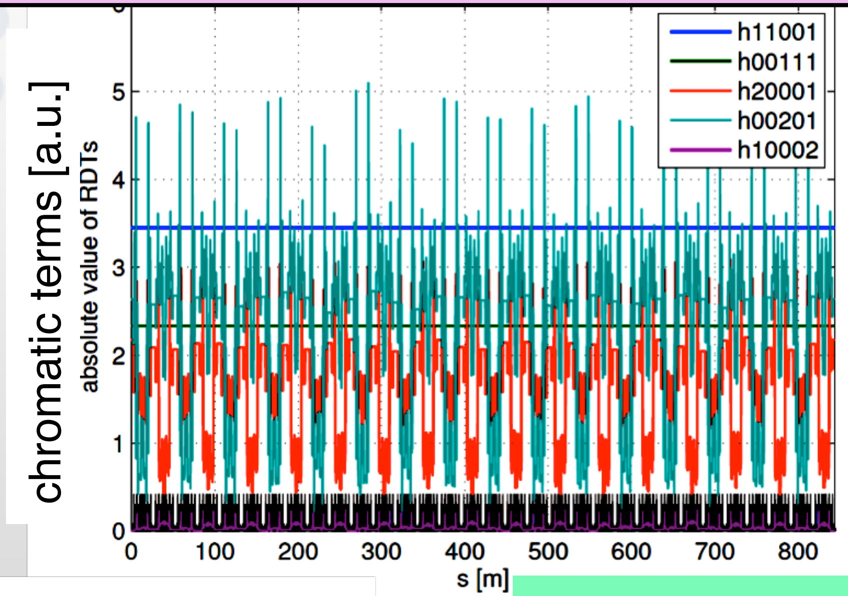
-30% DA

-43% Lifetime

Sextupoles -> RDTs and chromatic terms

simulations for the new ESRF storage ring (N. Carmignani)

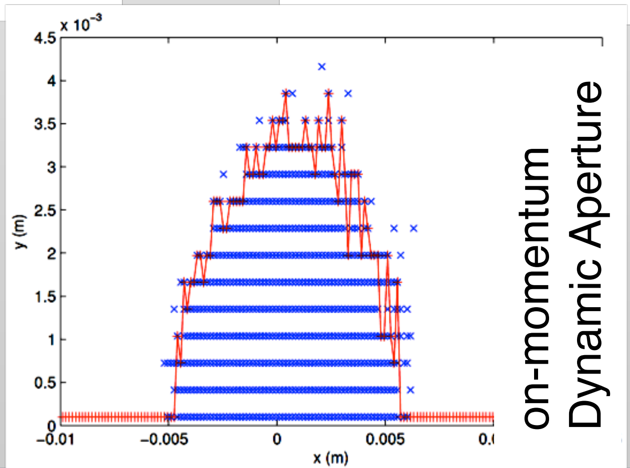




corrected*

corrected*

*: with all 224 sextupoles



<u>With focusing errors:</u>

RMS β-beating ~5-6%

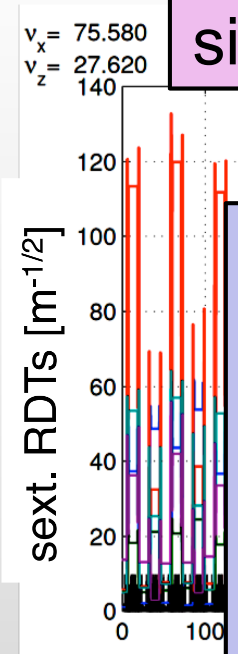
Lifetime = 13.6 h

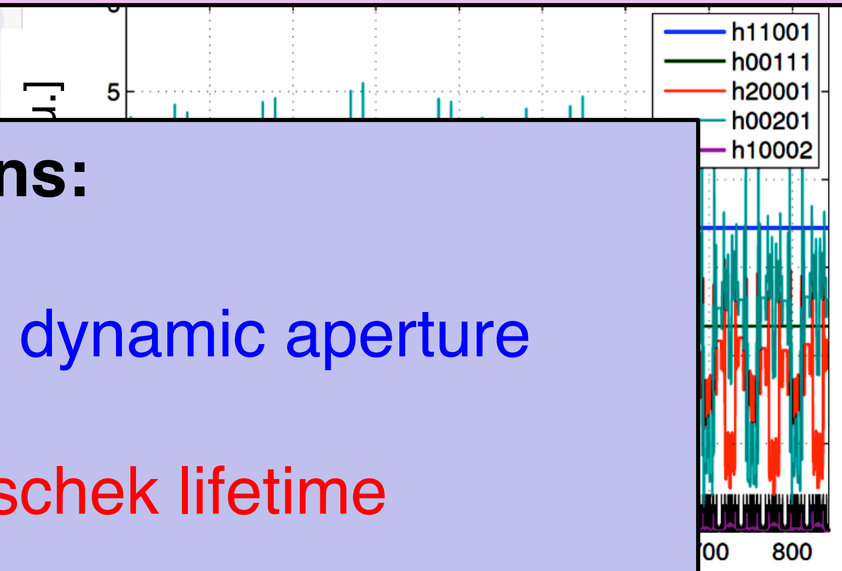
-7% DA

-40% Lifetime

Sextupoles -> RDTs **and** chromatic terms

simulations for the new ESRF storage ring (N. Carmignani)





Results from simulations:

RDTs <-> on-momentum dynamic aperture

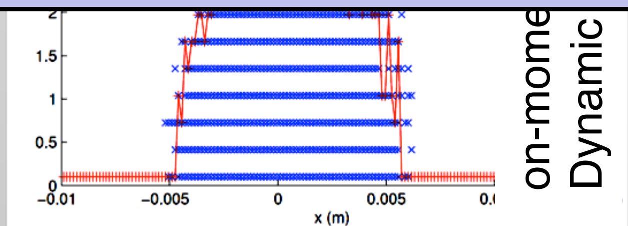
Chromatic terms <->Touschek lifetime

Sextupoles act on RDTs **and** chromatic terms
(best relative weights to be yet found)

corre ... **rected***

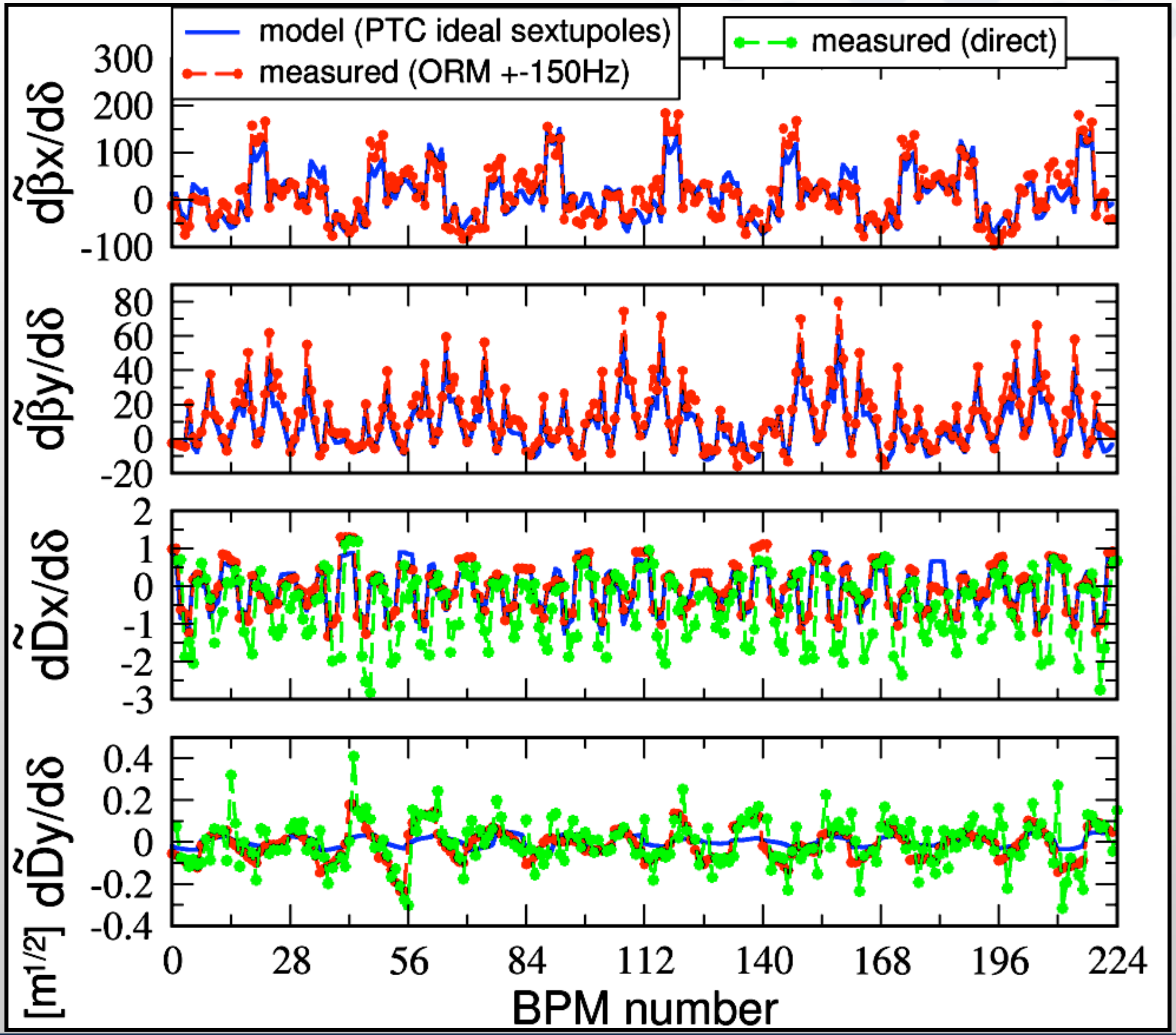
*: with all

With focusing errors:
RMS β-beating ~5-6%
Lifetime = 13.6 h



-7% DA
-40% Lifetime

First (preliminary) measurement of chromatic terms @ ESRF storage ring



- chromatic beating from two off-momentum orbit response matrices (sextupole errors to be yet included)
- Same measurement from TbT BPM data ongoing
- 2^{nd}-order dispersion directly measured but poor fit without sextupole errors

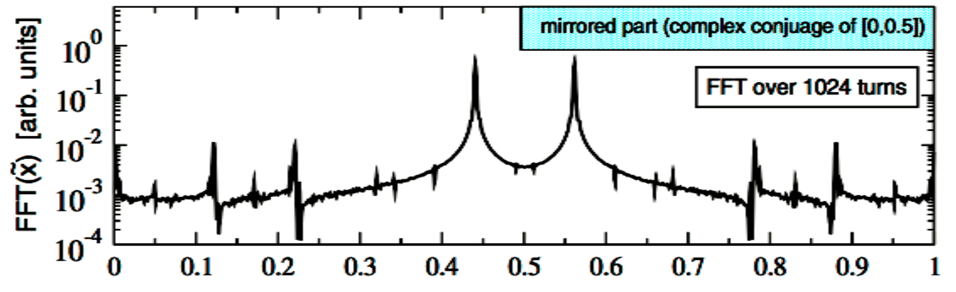
Conclusion

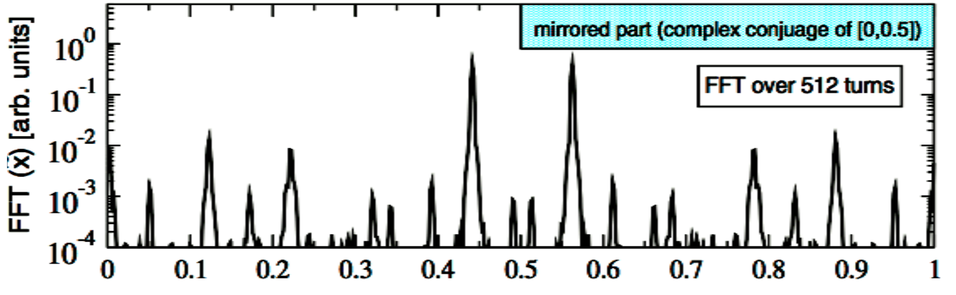
- The harmonic analysis of turn-by-turn BPM data provides a direct measurement of the resonant driving terms (RDTs, i.e. the β-functions of the nonlinear lattice)
- RDTs are a powerful tool to check linear and nonlinear lattice models, and for beam-based calibration of nonlinear magnets
- Correcting RDTs (alone) seems not effective in improving beam lifetime, specially for Touschek-dominated beams: simultaneous correction of RDTs and chromatic terms looks promising
- Anybody got a ring with large number of sextupole correctors to perform tests?

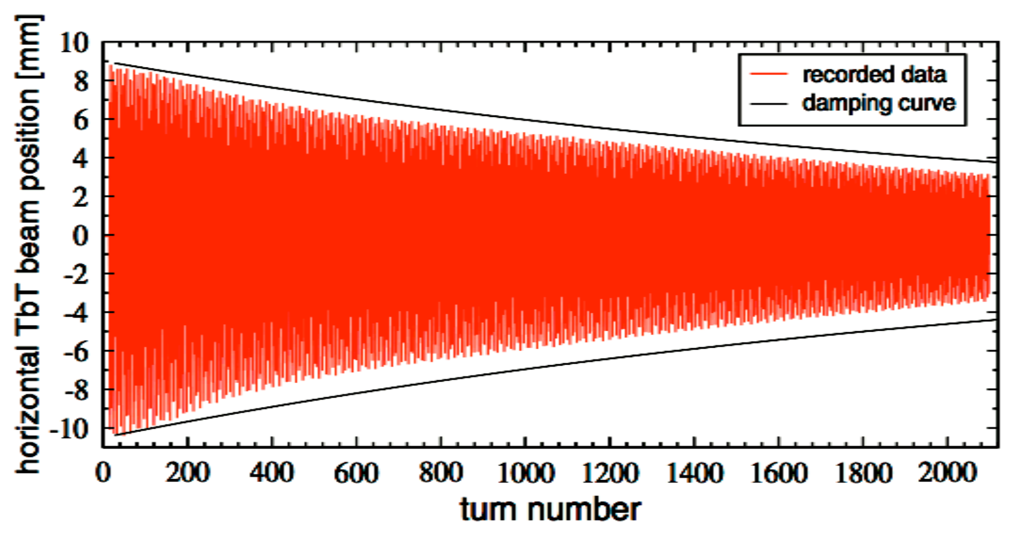
EXTRA SLIDES

Extra slides: some precautions

- Enough turns with suitable BPM data are needed to increase FFT resolution Vs. radiation damping (check FFT background noise)

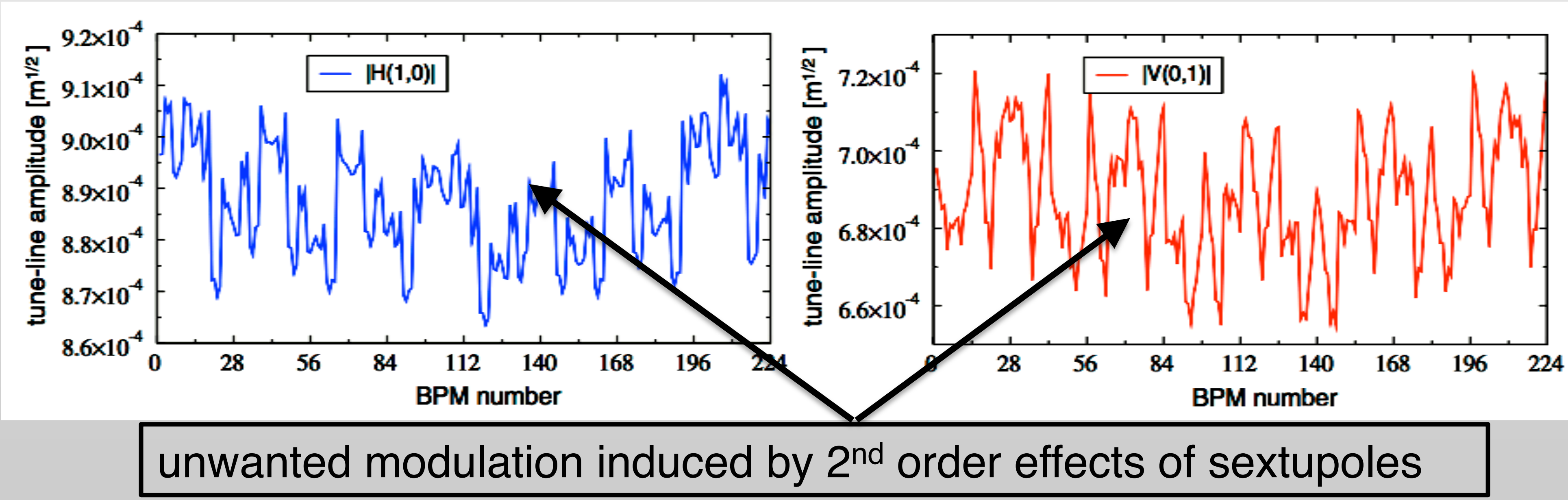


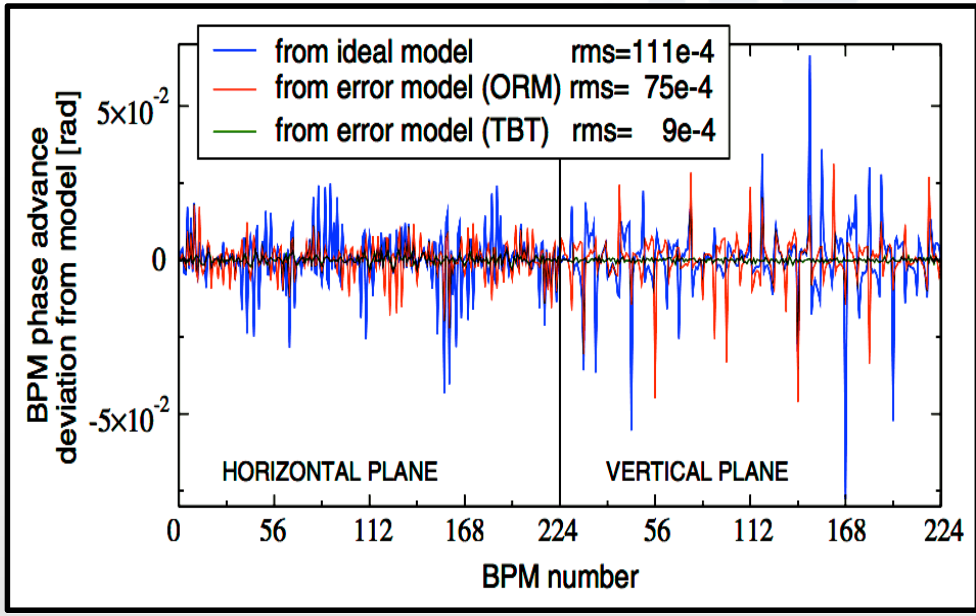


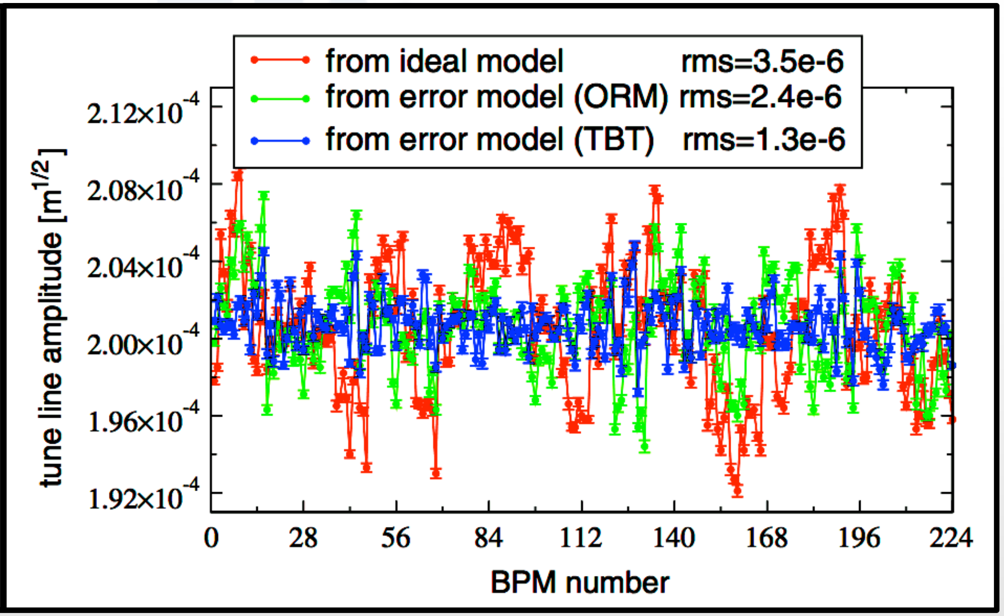


- Enough turns with suitable BPM data are needed to increase FFT resolution Vs. radiation damping (check FFT background noise)

- Large kicker strength to increase FFT resolution Vs. second & higher-order contribution to RDTs (checks are possible, simulations and data analysis)







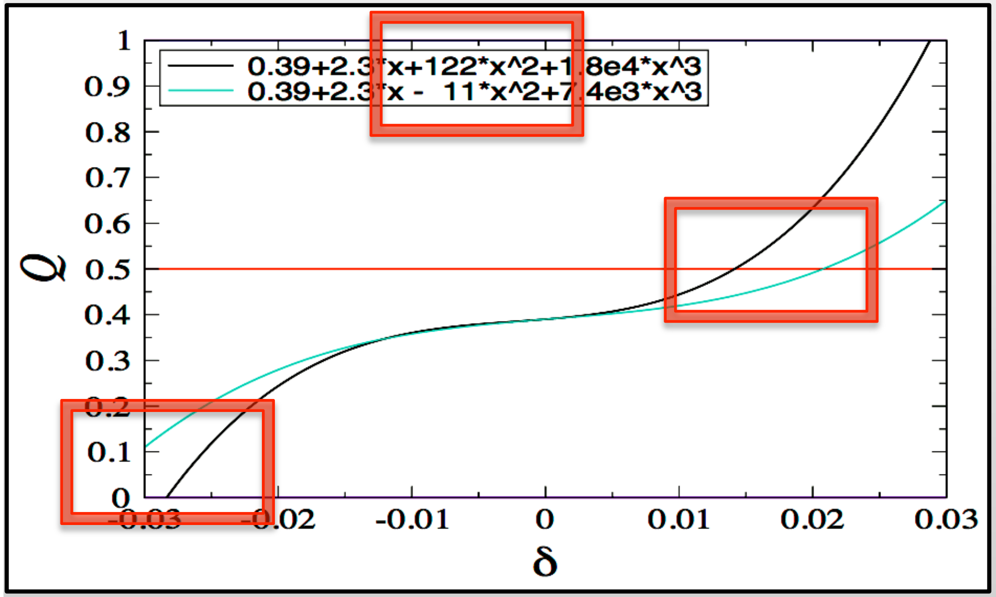
- linear model (β,φ) needs to be robust otherwise model & measured RDTs get corrupted (check BPM phase advance and invariance of tune line amplitude)

Extra slides: some precautions

- Enough turns with suitable BPM data are needed to increase FFT resolution Vs. radiation damping (check FFT background noise)
- Large kicker strength to increase FFT resolution Vs. second & higher-order contribution to RDTs (checks are possible, simulations and data analysis)
- linear model (β,φ) needs to be robust otherwise model & measured RDTs get corrupted (check BPM phase advance and invariance of tune line amplitude)
- Magnet calibration Vs cycling at different currents

"optimizing" global parameters without looking at the chromatic terms may result in poorer lifetime

second setting better than first one?



“optimizing” global parameters without looking at the chromatic terms may result in poorer lifetime

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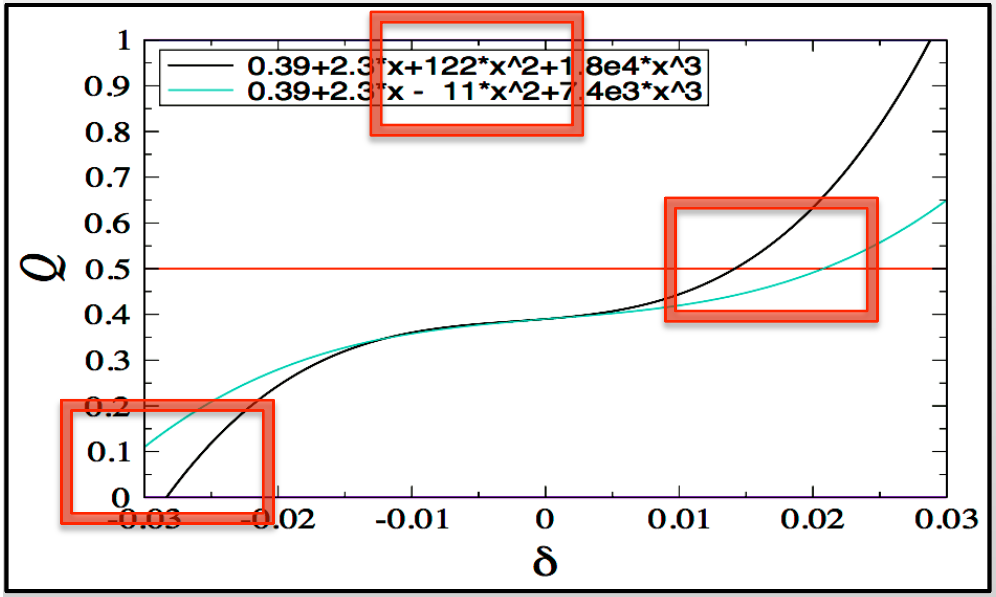
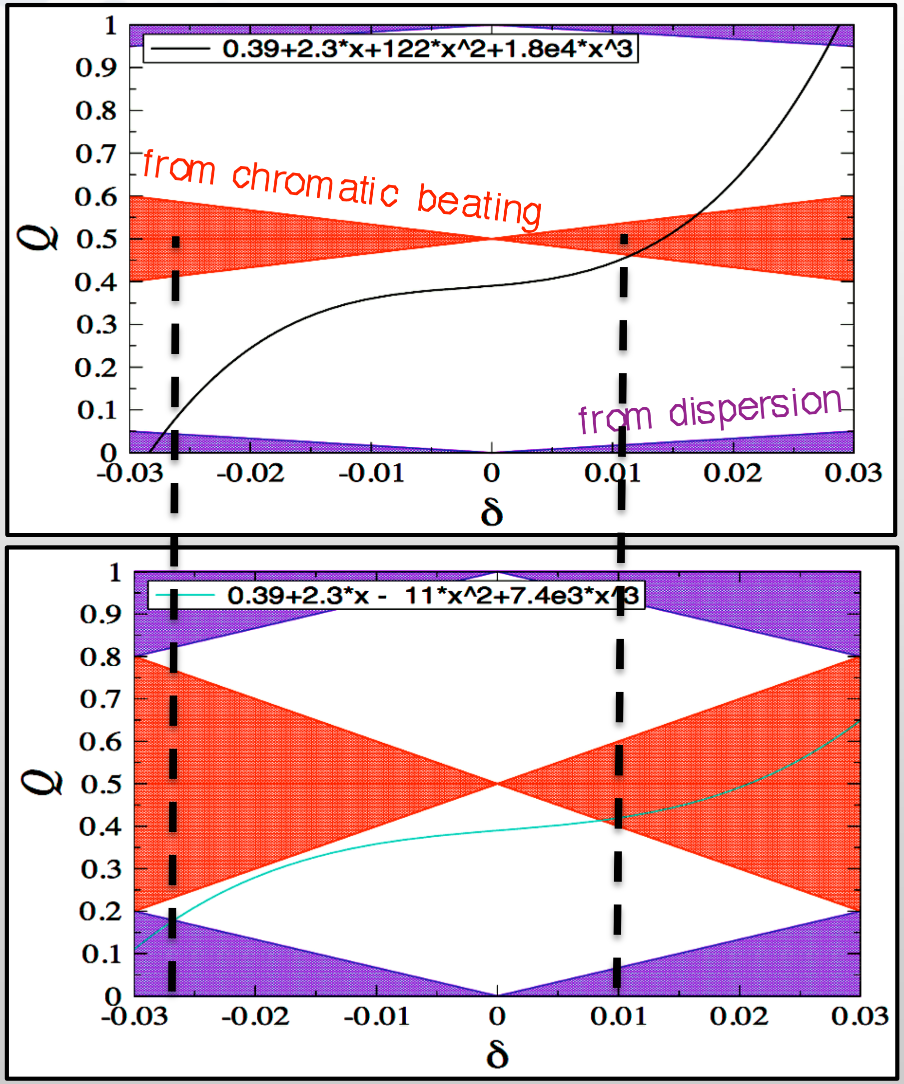


not necessarily



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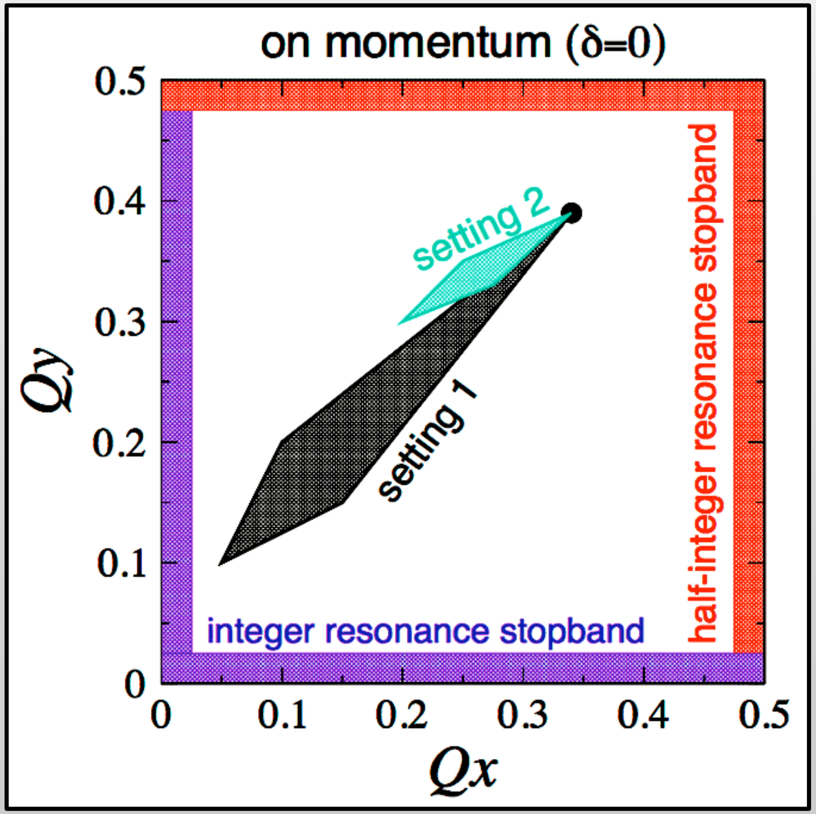

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