Experimental frequency maps for the ESRF storage ring

Yannis Papaphilippou

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Acknowledgments

Main Contributors:

- Laurent Farvacque, Eric Plouviez, Jean-Luc Revol (ESRF)
- Jacques Laskar (IMCEE-ASD), Charis Skokos (Ac.Athens)

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- Jean-Pierre Koutchouk, Frank Zimmermann (CERN)
- David Robin (ALS)
- Giovanni Rumolo (GSI)

Outline

- A brief introduction to frequency map analysis
- First experimental frequency maps for the ESRF storage ring through the MTOUR system
  - Identification of resonance and correction
  - Phase advance measurements
- Limitations of the system and improvements
  - Tune-determination using multiple BPM
  - Frequency maps with a dedicated turn-by-turn BPM
  - Off-momentum frequency maps
- Frequency analysis of data with longitudinal excitation
  - Synchrotron tune and RF voltage calibration
  - Off-momentum optics functions' beating and chromaticity

Frequency Map Analysis

Laskar A&A1988, Icarus1990

Quasi-periodic approximation through **NAFF** algorithm $f'_j(t) = \sum_{k=1}^{N} a_{j,k} e^{i\omega_{j,k} t}$

of a complex phase space function $f_j(t) = q_j(t) + i p_j(t)$ defined over $t = \tau,$

for each degree of freedom $j = 1, \ldots, n$ with $\omega_{j,k} = \boldsymbol{k}_j \cdot \boldsymbol{\omega}$

and $a_{j,k} = A_{j,k} e^{i\phi_{j,k}}$

<u>Advantages of NAFF</u>:

a) Very accurate representation of the "signal" $f_j(t)$ (if quasi-periodic) and thus of the amplitudes $a_{j,k}$

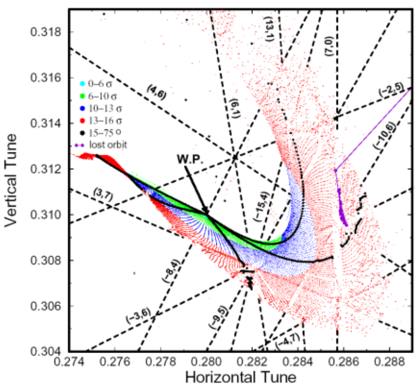
b) Determination of frequency vector $\boldsymbol{\omega} = 2\pi\boldsymbol{\nu} = 2\pi(\nu_1, \nu_2, \ldots, \nu_n)$

with high precision ⟶ $\frac{1}{\tau^4}$ for Hanning Filter Laskar NATO-ASI 1996

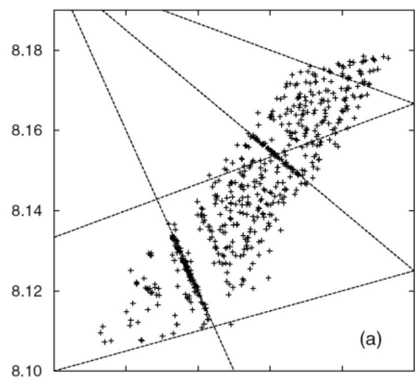
Aspects of frequency map analysis

- Construction of frequency map

$$\mathcal{F}_\tau \; : \; \begin{array}{ccc} \mathbb{R}^n & \longrightarrow & \mathbb{R}^n \\ q|_{p=p_0} & \longrightarrow & \boldsymbol{\nu} \end{array}$$



LHC Simulations
Papaphilippou PAC99



ALS Measurements
Robin et al. PRL2000

- Determination of resonance driving terms associated with amplitudes $a_{j,k}$

Bengtsson PhD thesis CERN88-05

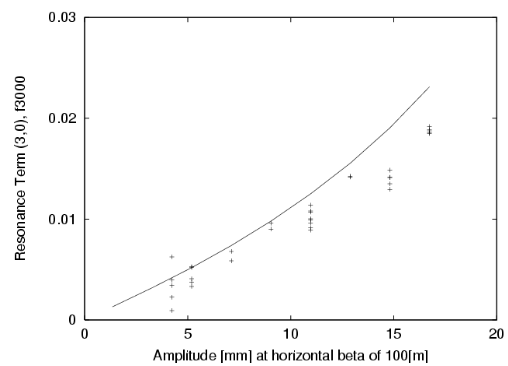
- Determination of tune diffusion vector

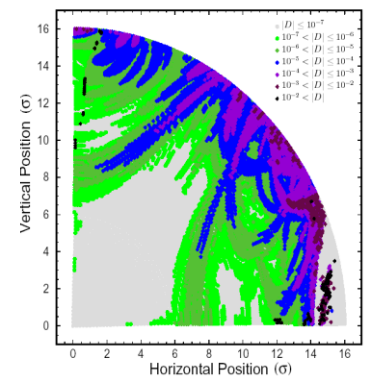
$$\boldsymbol{D}|_{t=\tau} = \boldsymbol{\nu}|_{t\in(0,\tau/2]} - \boldsymbol{\nu}|_{t\in(\tau/2,\tau]}$$

and construction of diffusion map

$$\mathcal{D}_\tau \; : \; \begin{array}{ccc} \mathbb{R}^n & \longrightarrow & \mathbb{R}^n \\ q|_{p=p_0} & \longrightarrow & \boldsymbol{D} \end{array}$$

SPS Measurements
Bartolini et al. PAC99





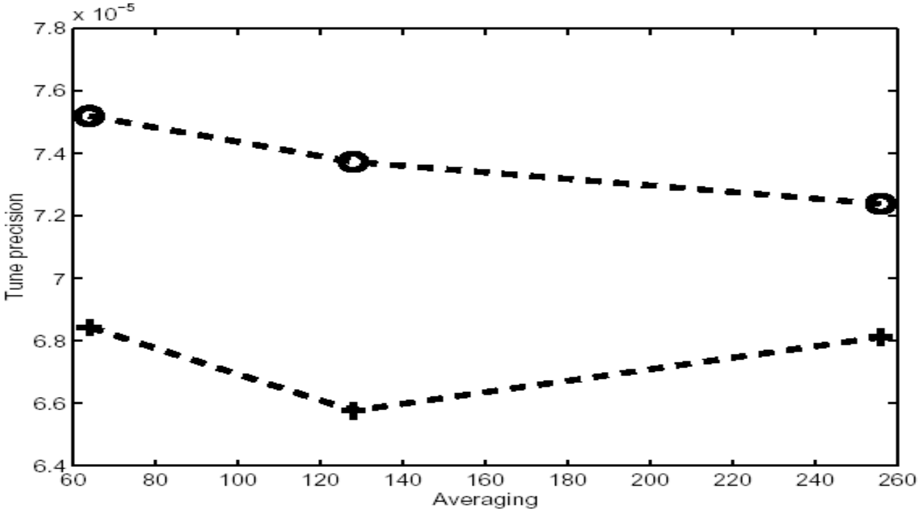
LHC Simulations
Papaphilippou PAC99

First Experimental Frequency Maps @ ESRF

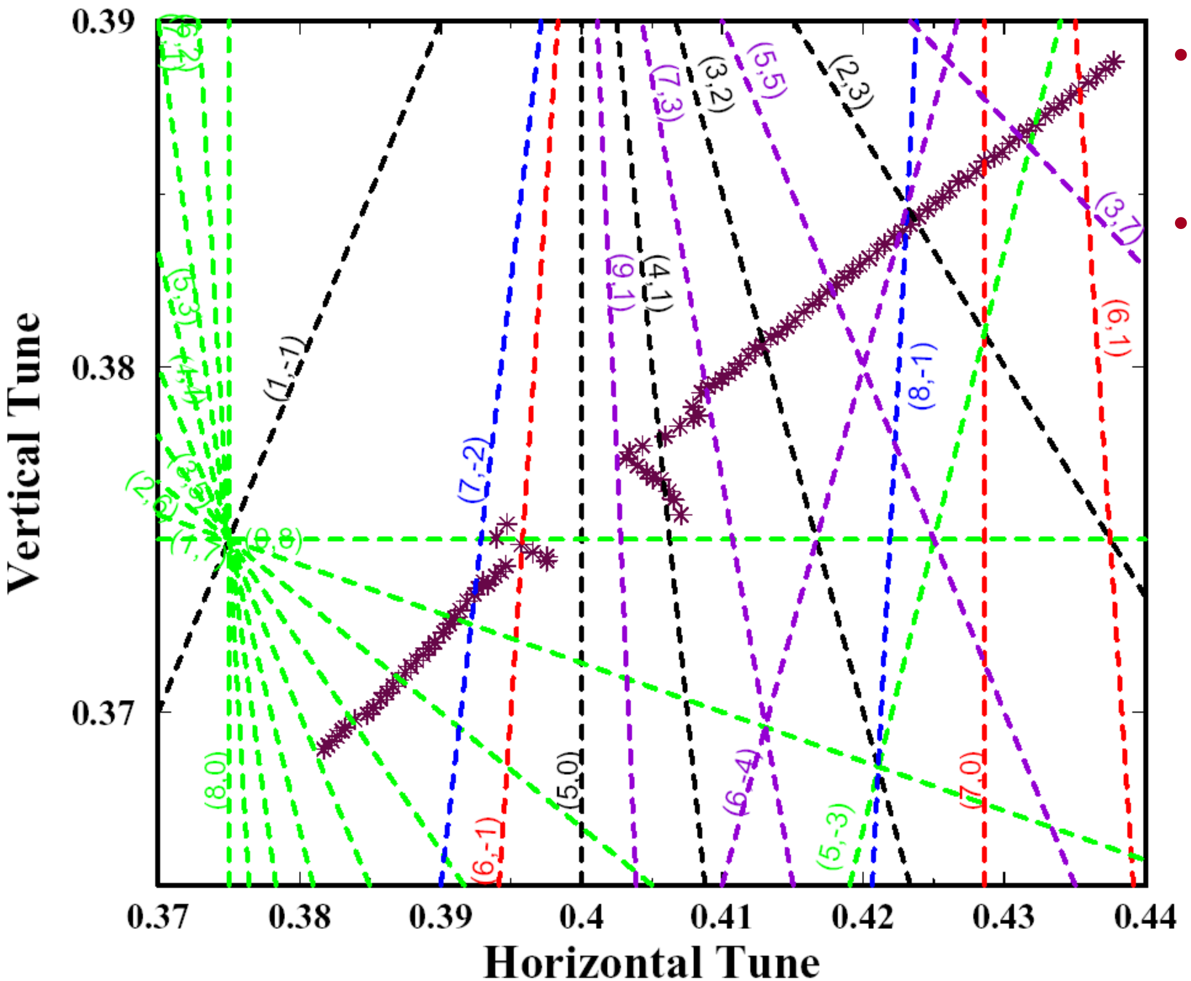
- Machine setup:
  - Injection of 10mA in 1/3 filling
  - Nominal tunes (36.44,14.39)
  - Chromaticity $\xi_{x,y} = 0$ to limit decoherence
  - Corrections optimized @ 10 mA and nominal chromaticity
  - Timing at 10Hz

- Experimental procedure:
  - Apply synchronous transverse kicks with fast injection kicker and tune monitor shaker (automatic control)
  - Record turn-by-turn data for 252 turns from all the 214 BPMs with the MTOUR system (K.Scheidt)
  - Analyze the results off-line with MATLAB version of NAFF algorithm

- Remarks:
  - Maximum horizontal kick (where first losses occur) gives amplitude of 12mm (middle of the straight section)
  - The vertical shaker was limited to an amplitude of 1mm (50% of aperture)
  - MTOUR system is not a "turn-by-turn" acquisition (averaging is set to 32)
  - Whole experiment was taking **4 hours!!!**

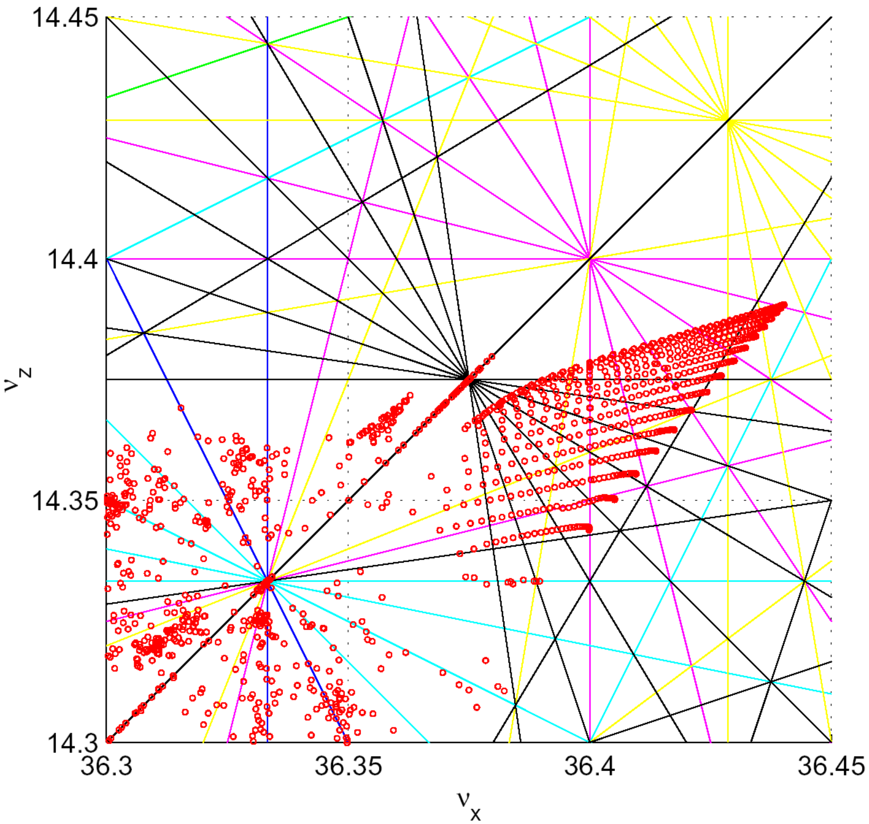


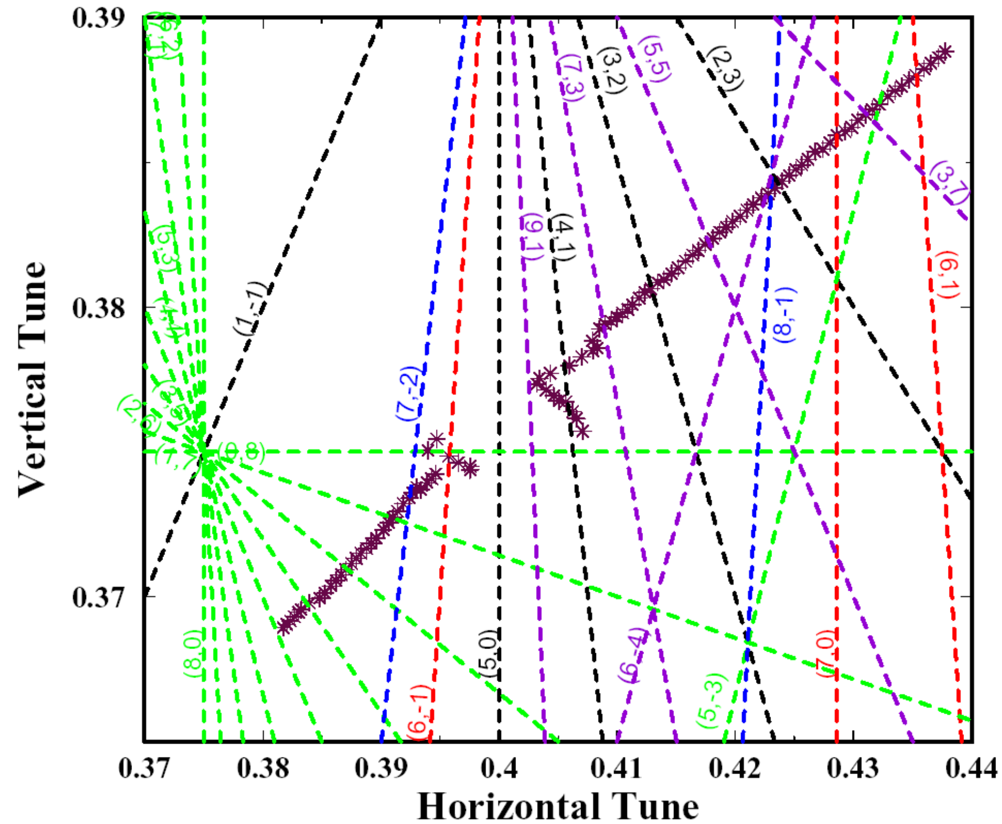
First experimental frequency map



- Tune-shift essentially coming from horizontal excursion of the beam
- 3 regions:
  - Small amplitudes (up to 8mm hor.amp.): regular motion
  - Medium amplitudes (between 8 and 10mm) : multiple high-order resonance crossing (especially fifth)
  - Large amplitudes (>10mm): regular motion up to the point where losses occur.

Comparison with tracking data

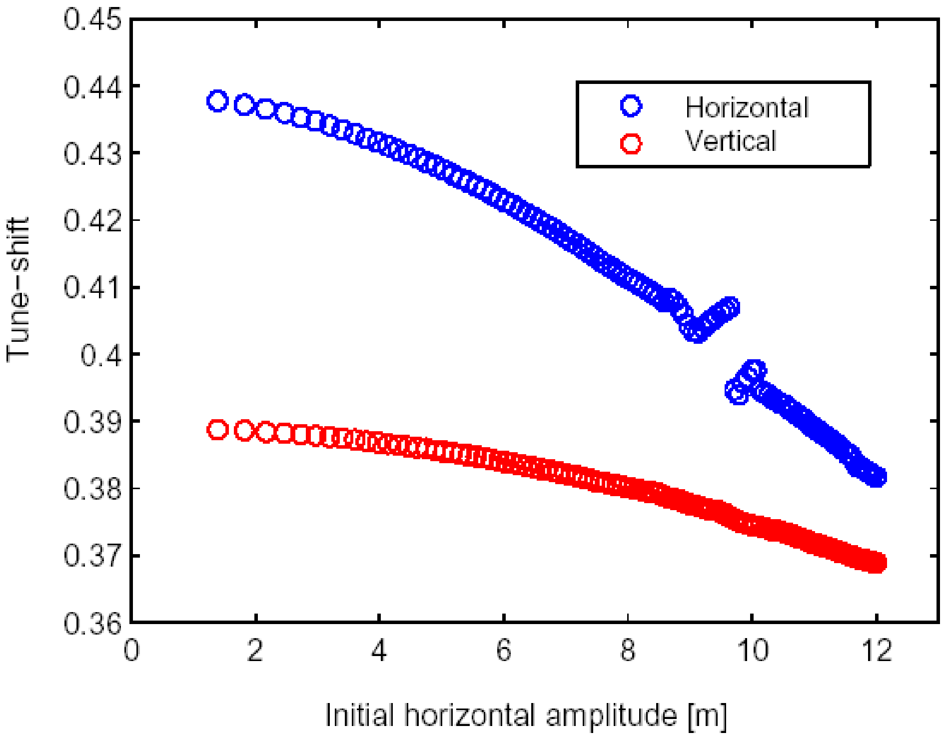


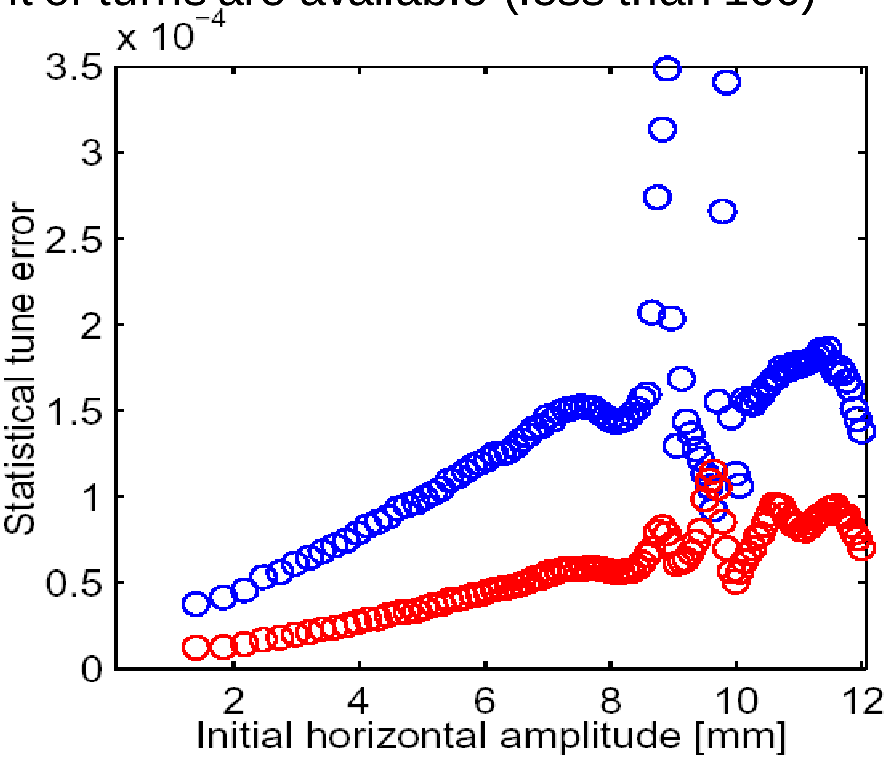


- Losses are attributed to third order resonance crossing point
  (simulations by M.Belgroune. L.Nadolski and A.Ropert)

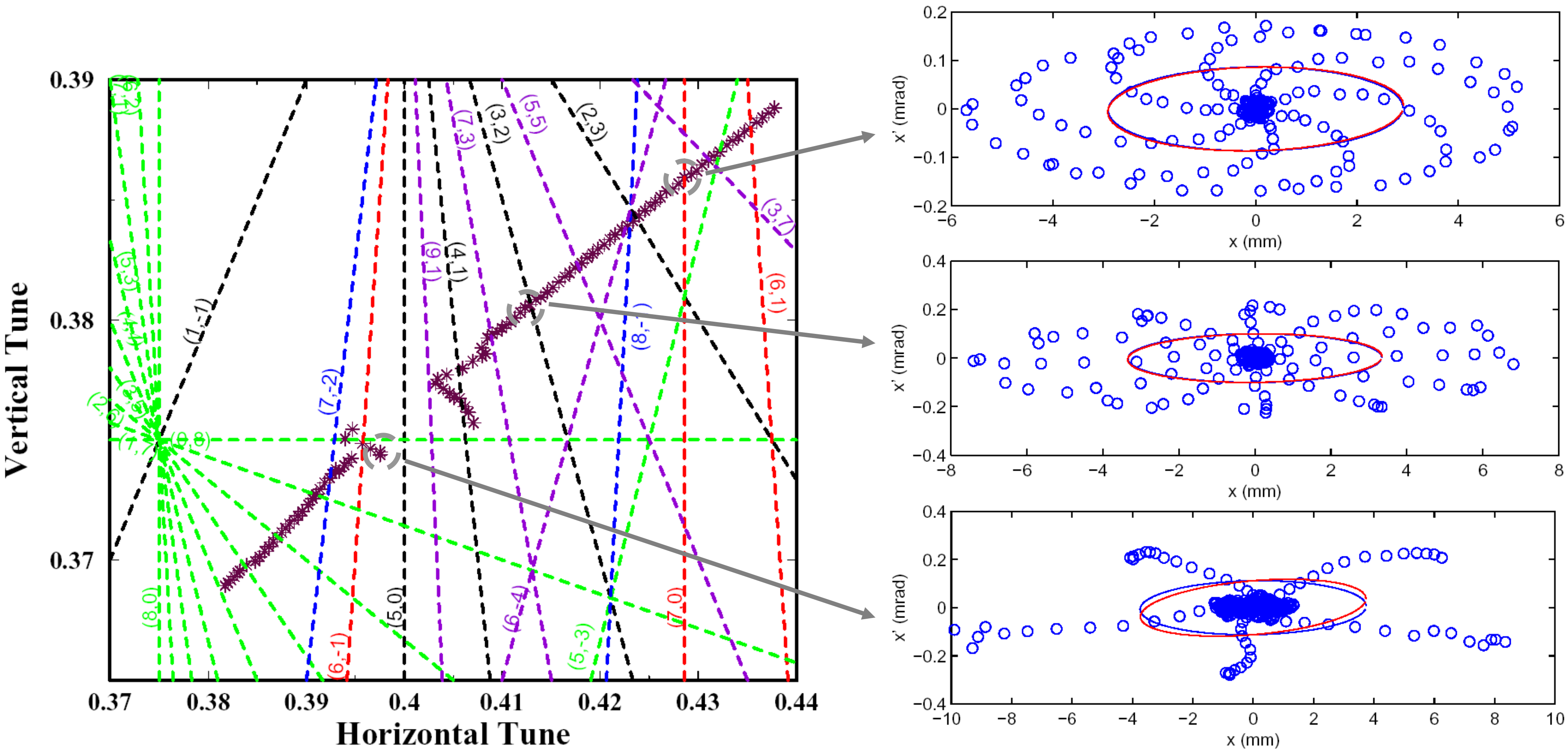
Tune-shift with horizontal amplitude and tune precision

- Tune error depends on number of analyzed turns and regularity of phase space
- For lowest amplitudes, error of the order of 10^{-5}
- In most cases less than 10^{-4} apart from area of instability
- For large amplitudes, very small amount of turns are available (less than 100)



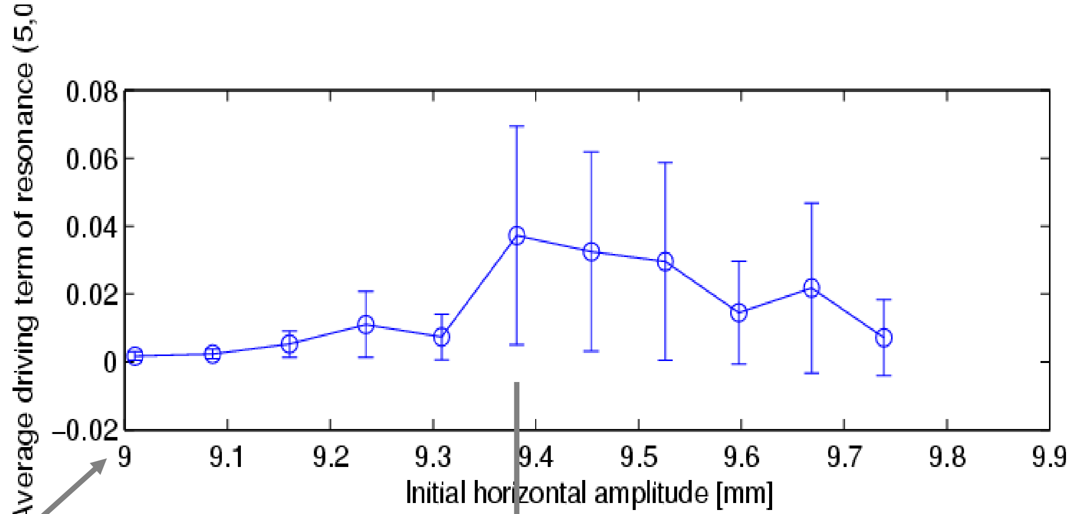


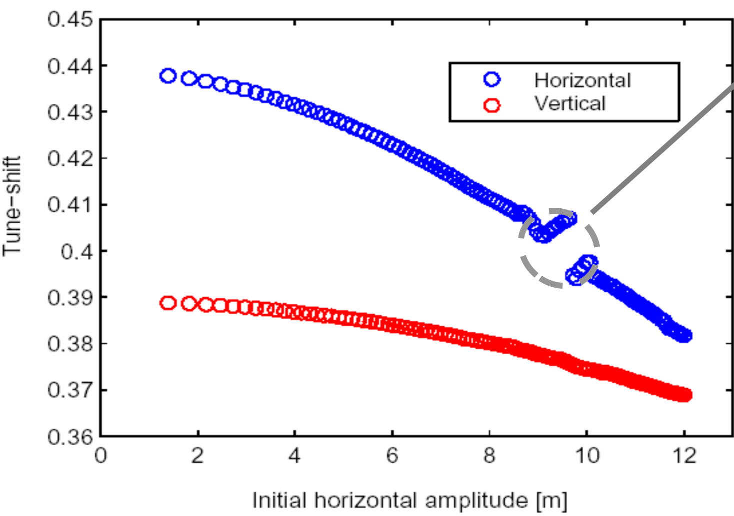
Phase-space plots

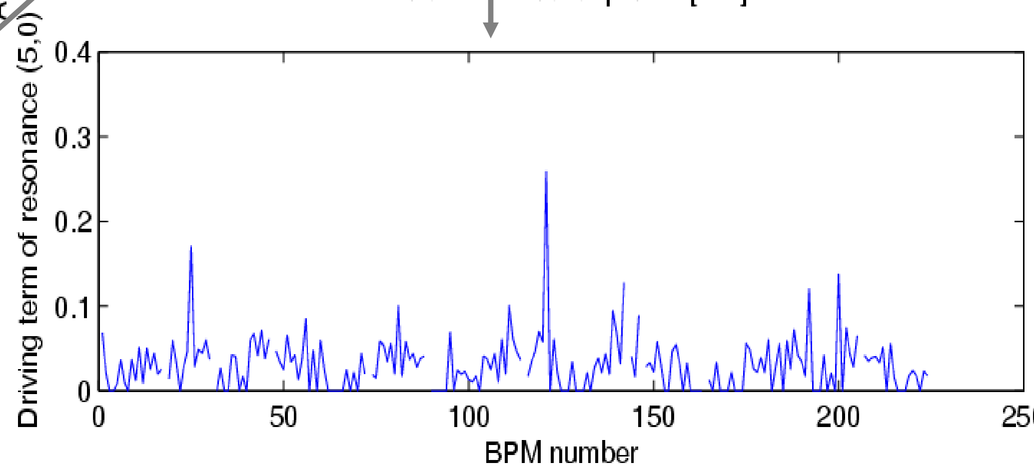


5th order resonance driving term

- $a_{(-4,0)}$ spectral amplitude associated with resonance (5,0)
- Increases when particles enter into resonance and then gradually decreases
- Maximum in areas of big beta functions

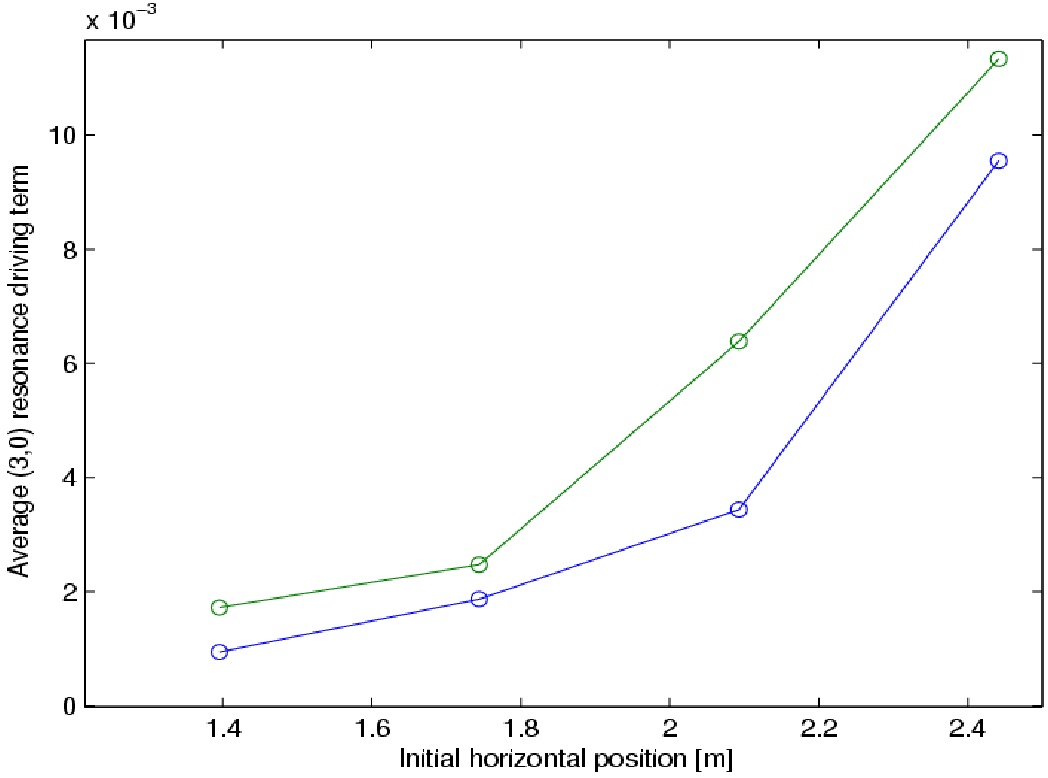






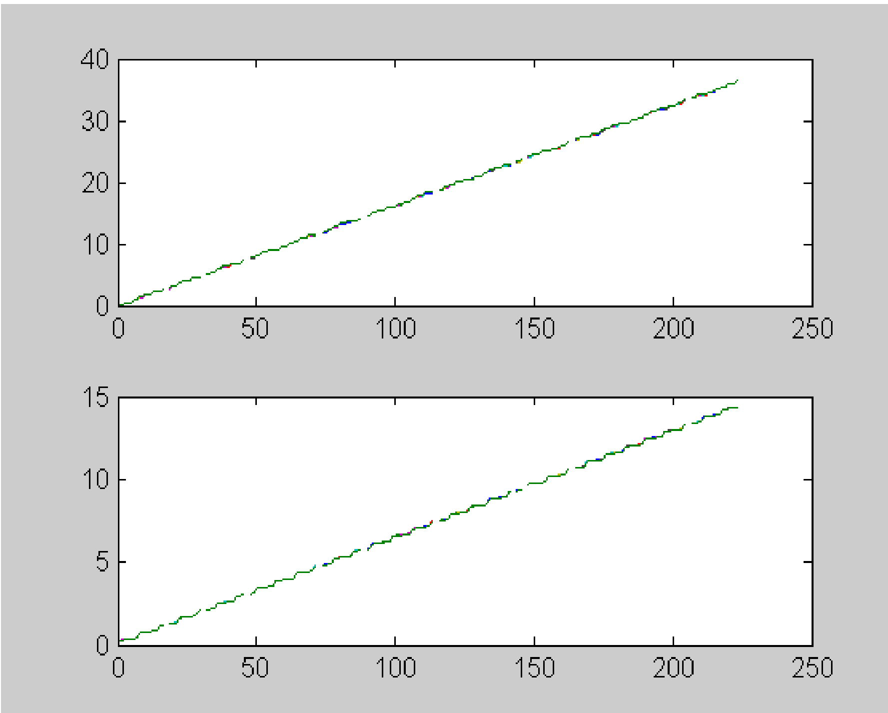
3rd order resonance driving terms and correction

- $a_{(-2,0)}$ spectral amplitude associated with (3,0) resonance
- Lattice tuned in the vicinity of this resonance
- Amplitude reduced when correction with sextupole correctors is applied

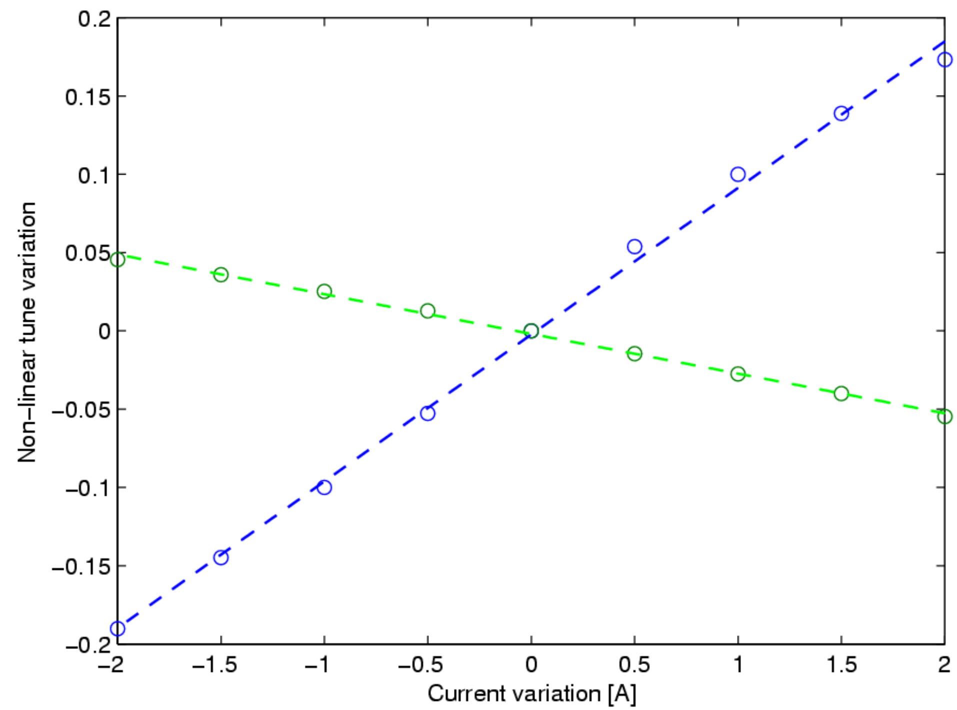


Phase advance measurements

Phase Advance around the machine



Tune variation with quadrupole currents



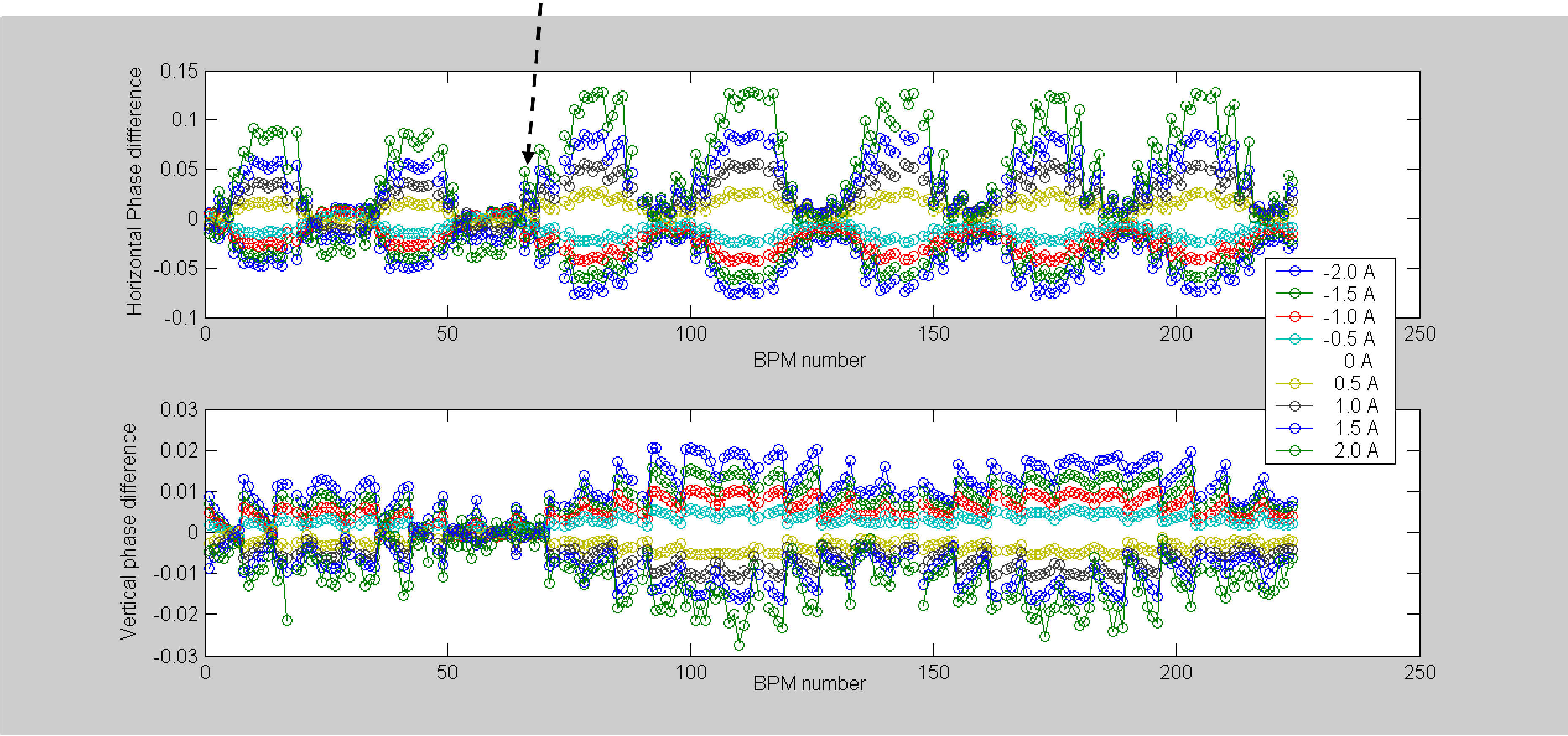
$$\beta_{x,y} = \pm\frac{2}{\Delta K}\left(\cot(2\pi Q_{x,y})\left(1-\cos(2\pi\Delta Q_{x,y})\right)+\sin(2\pi\Delta Q_{x,y})\right)$$

or $\beta_{x,y} \approx \pm 4\pi\frac{\Delta Q_{x,y}}{\Delta K}$

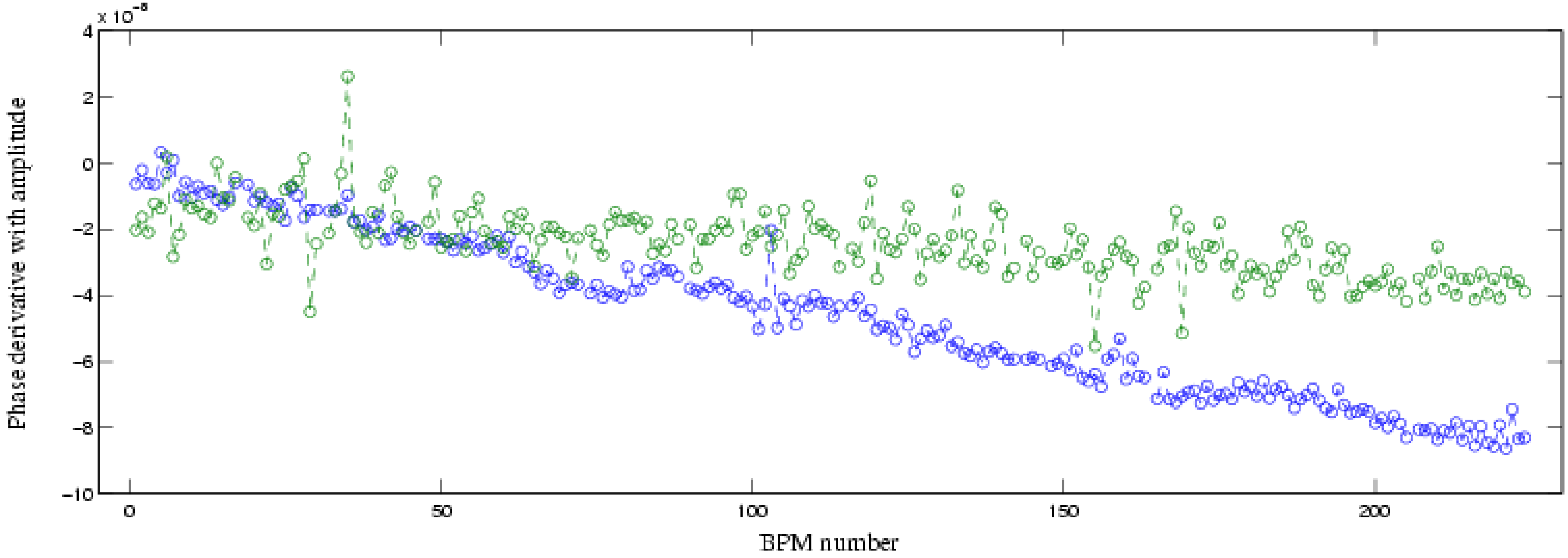
Localization of quadrupole errors with phase advance modulation

Quadrupole corrector

See also work by R.Nagaoka

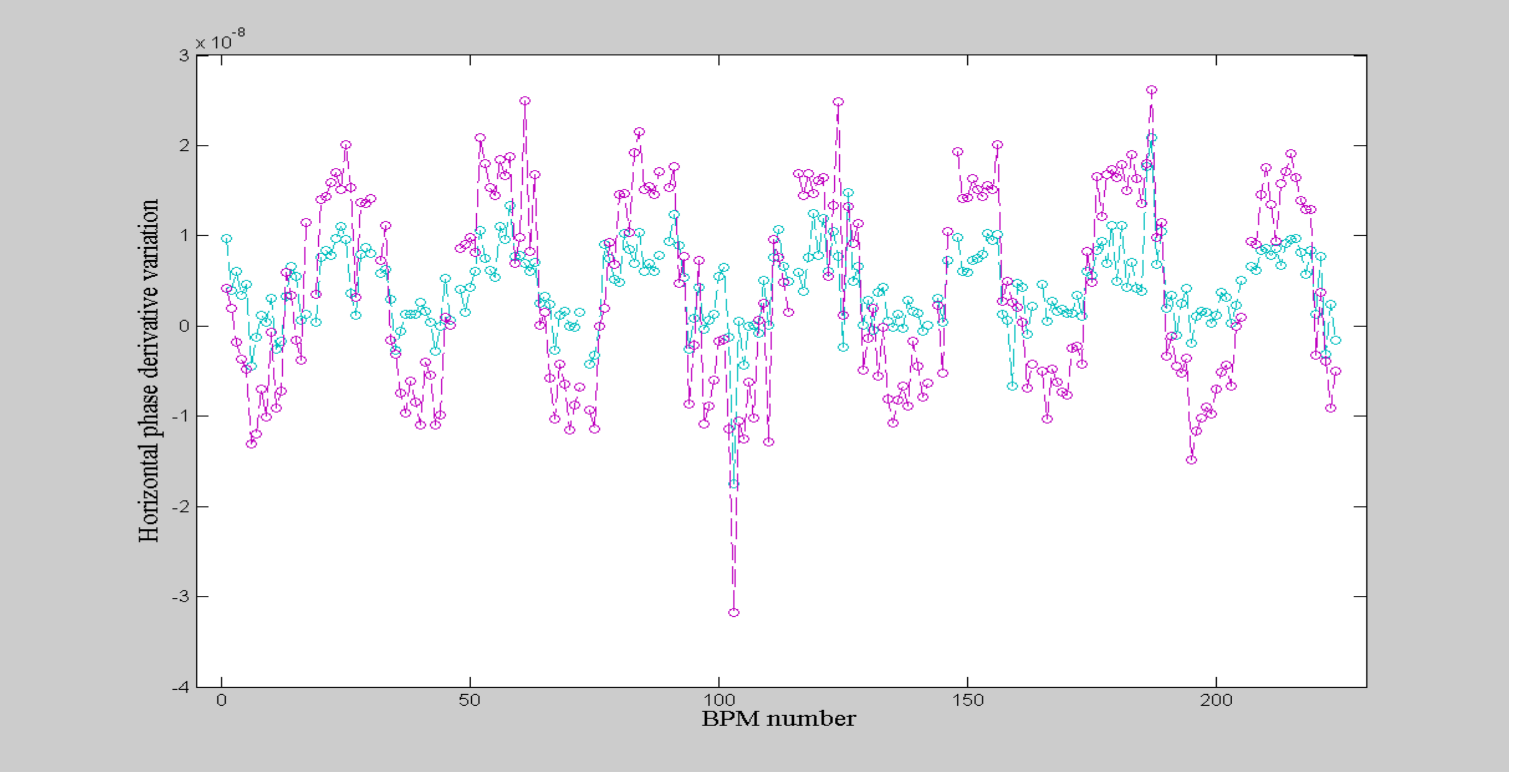


Phase advance derivative with amplitude



- Kick the beam in several horizontal amplitudes and record MTOUR measurements
- Determine the derivative of the phase advance with the kick amplitude with a linear fit
- Repeat the same measurement for different sextupole corrector currents
- Compute the difference of the phase advance derivative with and without sextupole excitation

Horizontal phase advance derivative modulation



Improving the experimental set-up and analysis

ESRF

Limitations

- MTOUR is not a real turn-by-turn system
- Acquisition time too long (4 hours for 200 points)

- Vertical shaker with limited strength (half of the full vertical aperture)

- Decoherence limits the number of available turns

Improvements

Present

- Dedicated frequency mapping BPM (ADAS system)

- Vertical shaker switch repaired giving kicks to almost the full vertical aperture

- Analysis of limited number of turns using information from all the BPM around the ring

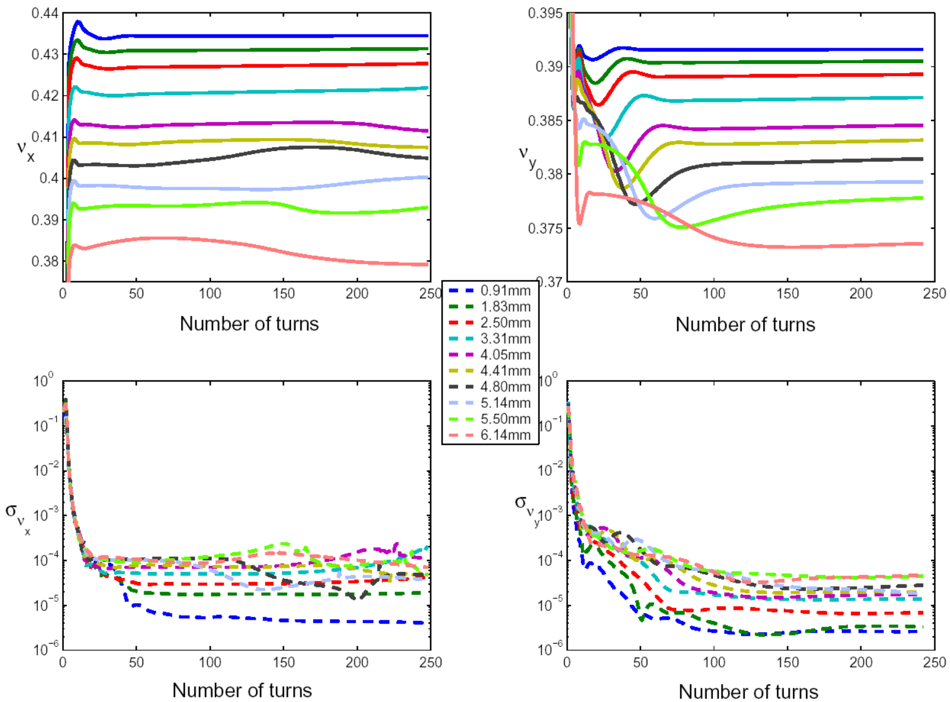
Future

- High-precision turn-by-turn BPM

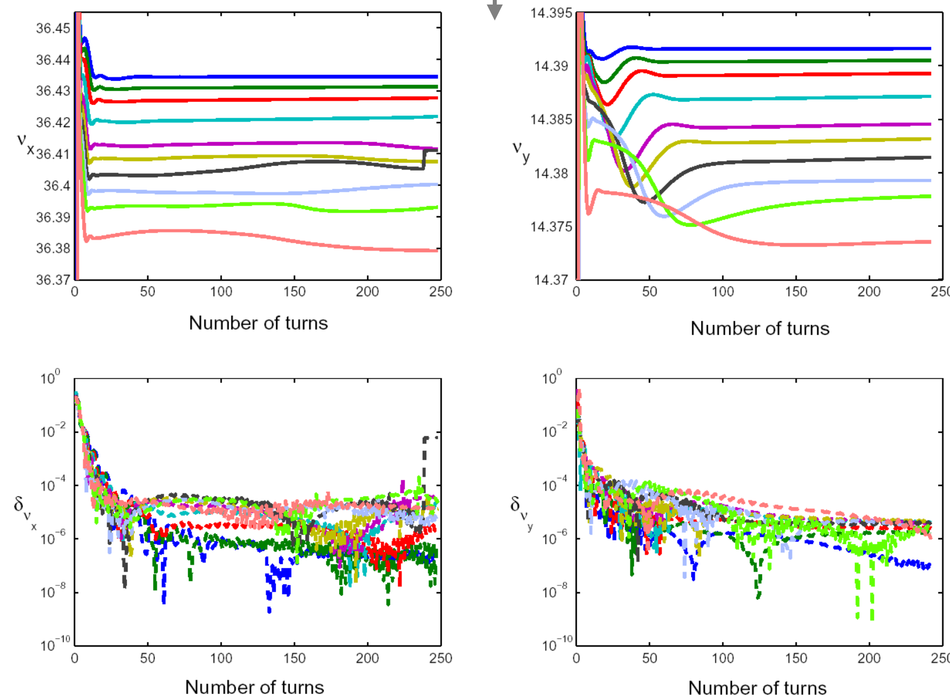
- New vertical kicker already installed and tested

Tune determination using multiple BPM

with J.Laskar and Ch.Skokos



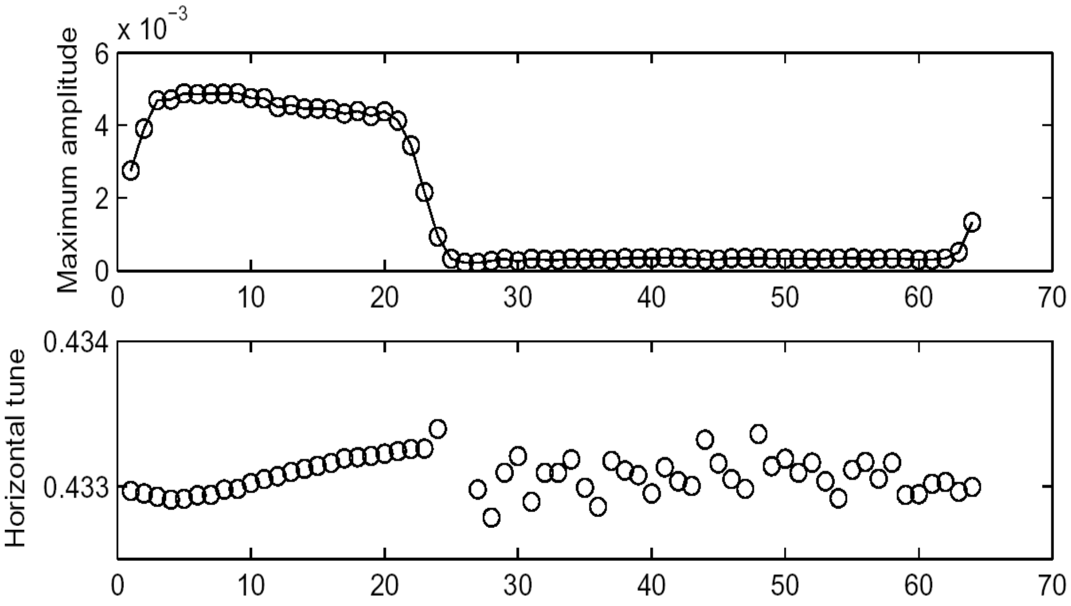
- Tune determination using data from all symmetric BPM (9 families out of 14)
- Tune determination using all 214 BPM



- Tune precision below 10^{-4} at 20-30 turns
- Interpolation between BPM (“virtual BPM”) can slightly increase precision
- Similar results in simulations
- Significant gain in time (at least a factor of 5)

Experimental Frequency Maps with dedicated BPM

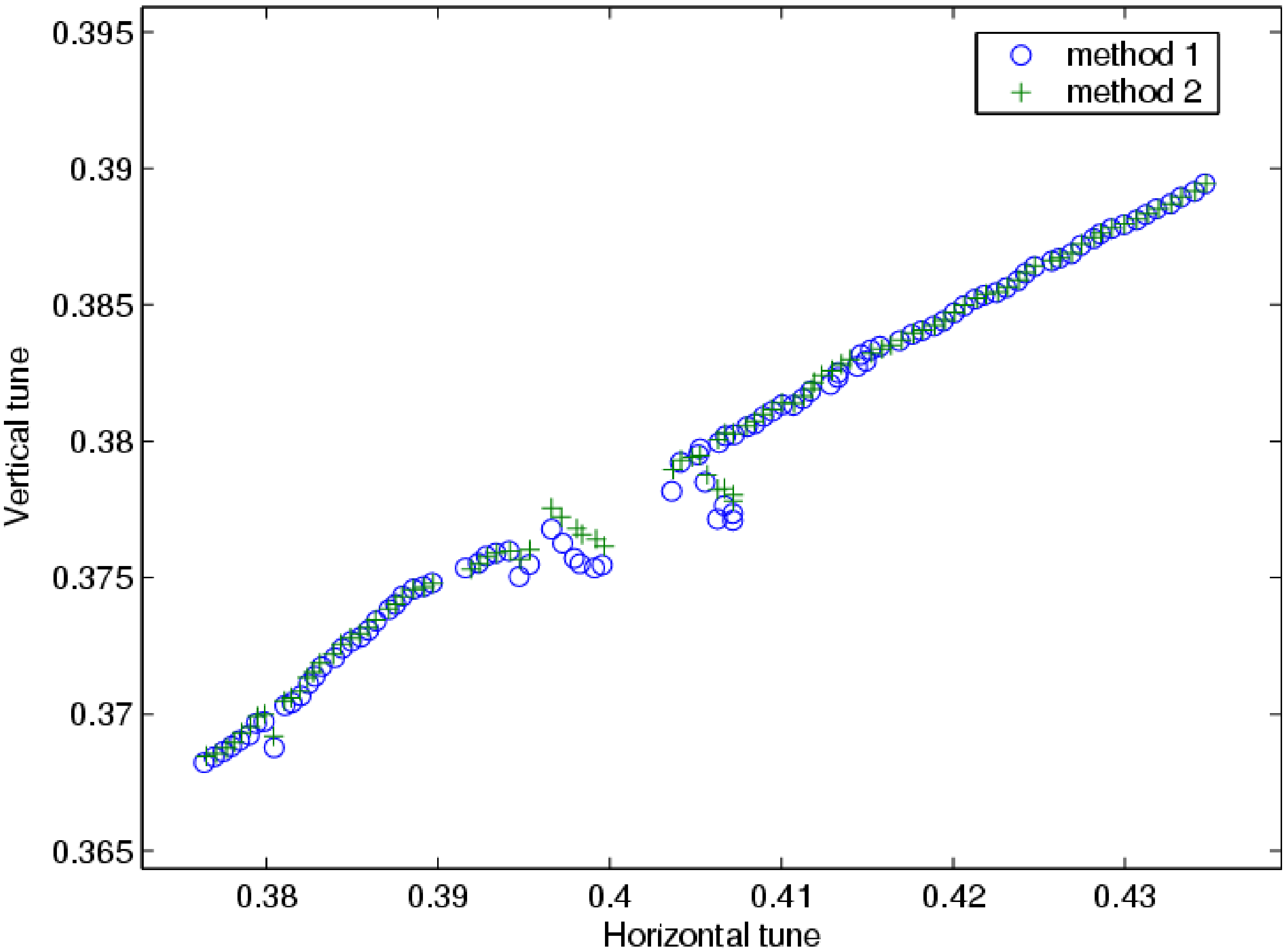
- Machine setup:
  - Injection of 10mA in 1/3 filling
  - Nominal tunes (36.44,14.39)
  - Chromaticity $\xi_{x,y} = 0$ to limit decoherence
  - Corrections optimized @ 10 mA and nominal chromaticity
  - Timing at 10Hz



- Experimental procedure:
  - Apply synchronous transverse kicks with fast injection kicker and tune monitor shaker (automatic control)
  - Record 64 samples of turn-by-turn data in the dedicated ADAS BPM (E.Plouviez)
  - Analyze the results with MATLAB version of frequency analysis algorithm
  - Frequency map in a few minutes (less then 5 seconds per acquisition)

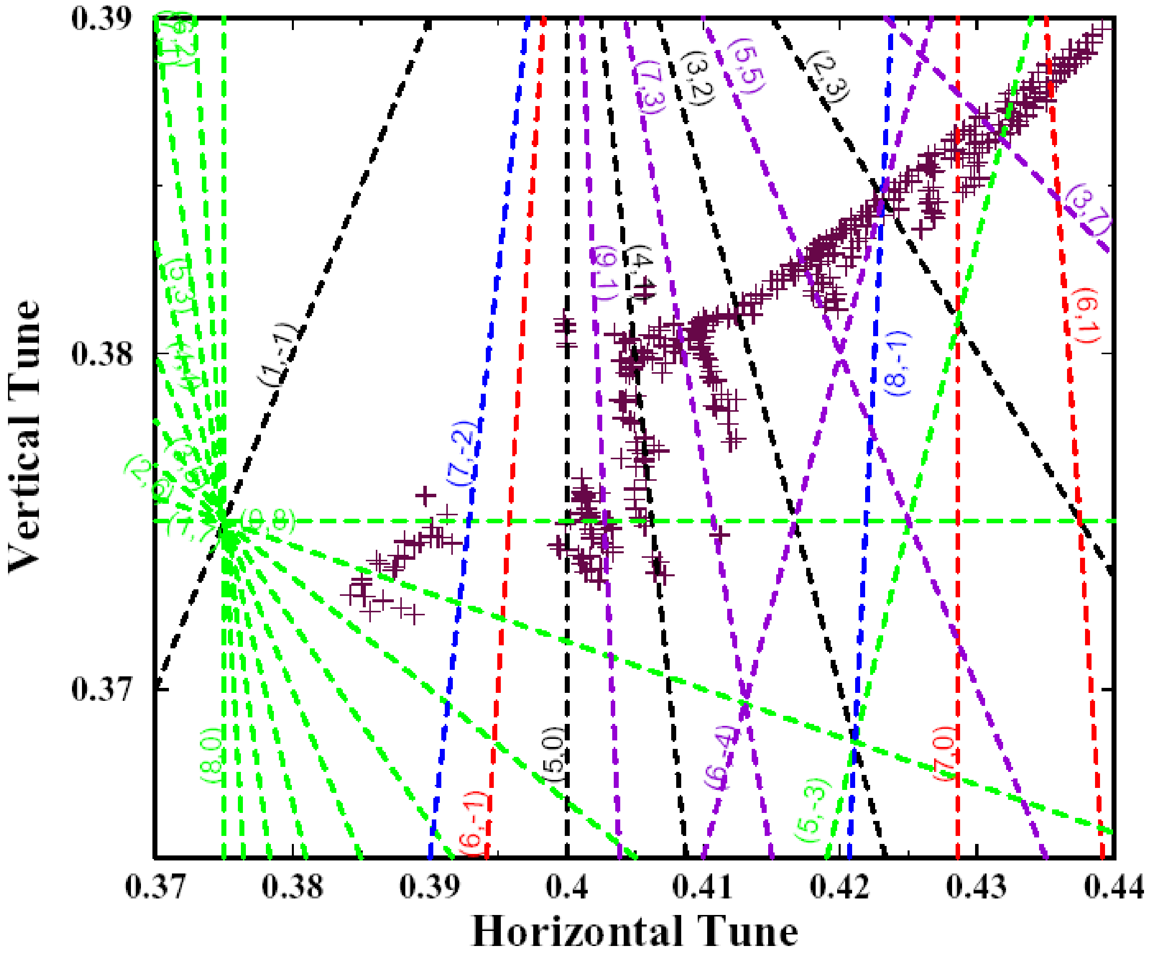
- Tests:
  - Find the samples with useful data
  - Slight dependence of tune with signal current

Frequency Maps with dedicated BPM-precision tests

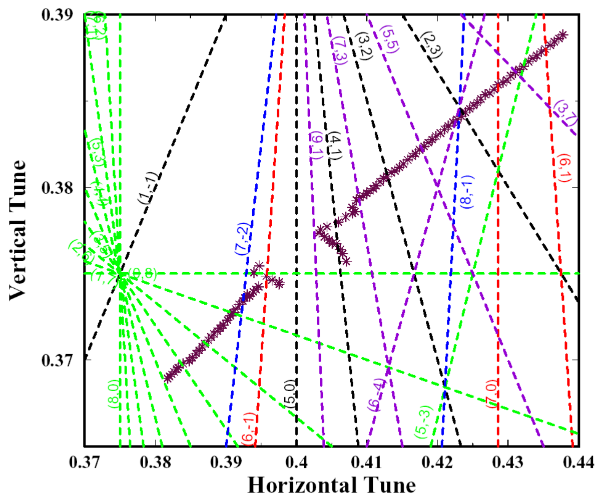


Method 1: Extract tunes for each position sample and average
Method 2: Average each position sample and extract tunes

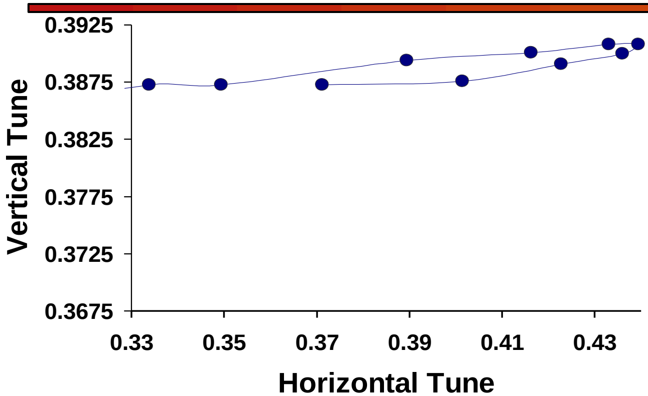
Experimental frequency map for different sextupole settings

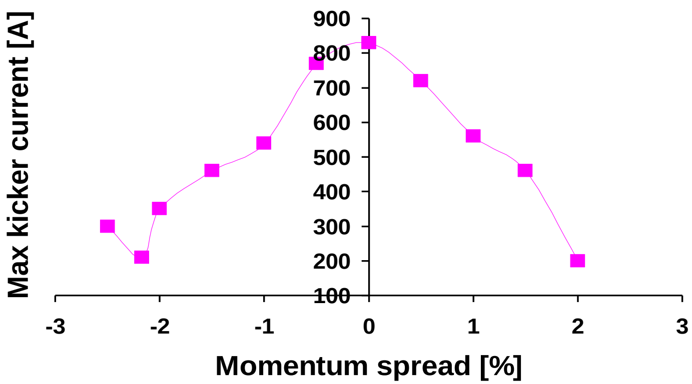


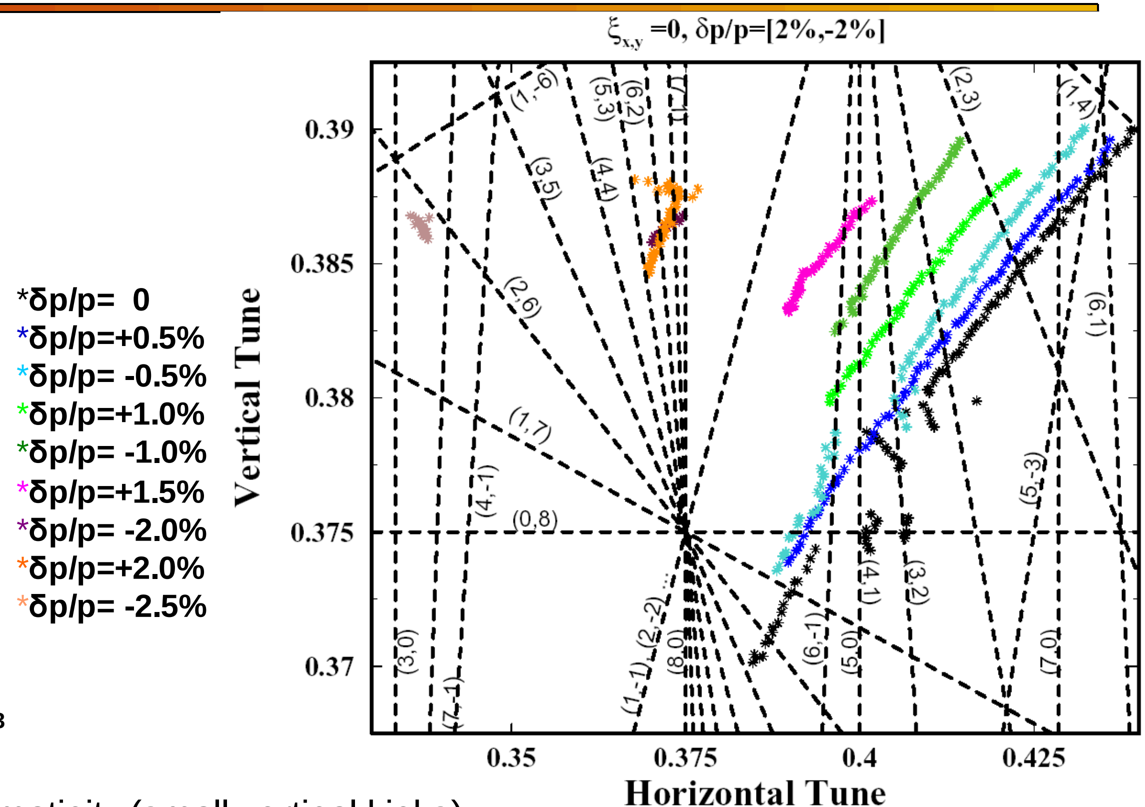
- Able to kick the beam vertically up to 2mm, producing a real two dimensional frequency map
- Appearance of two dimensional resonances, even of very high order
- Frequency space very distorted, and dynamic aperture limited.
- Frequency map can be used as a guide to understand the impact of different machine settings



Off-momentum frequency maps



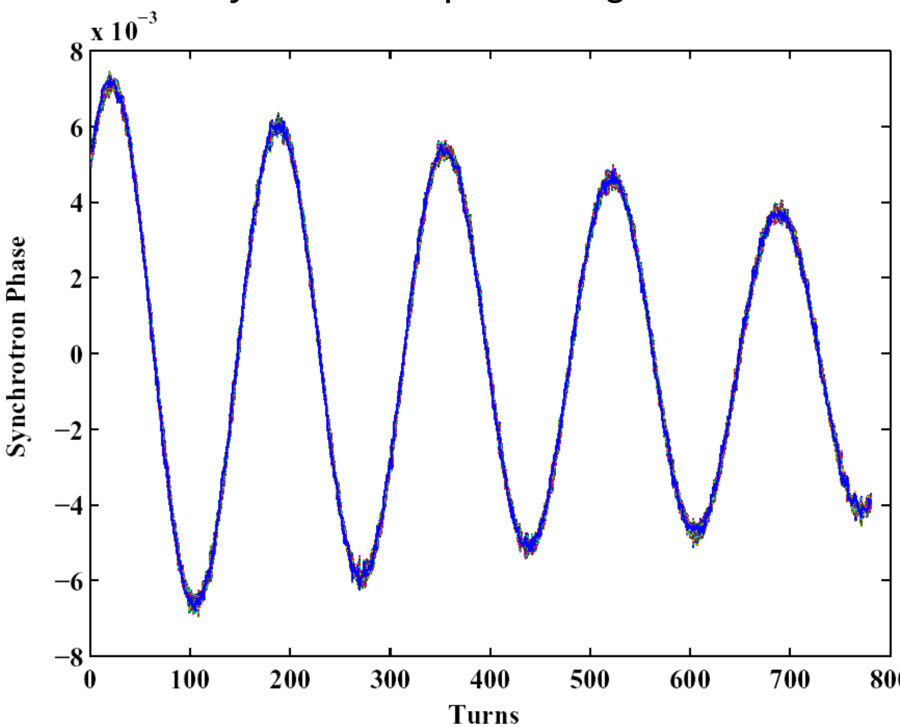


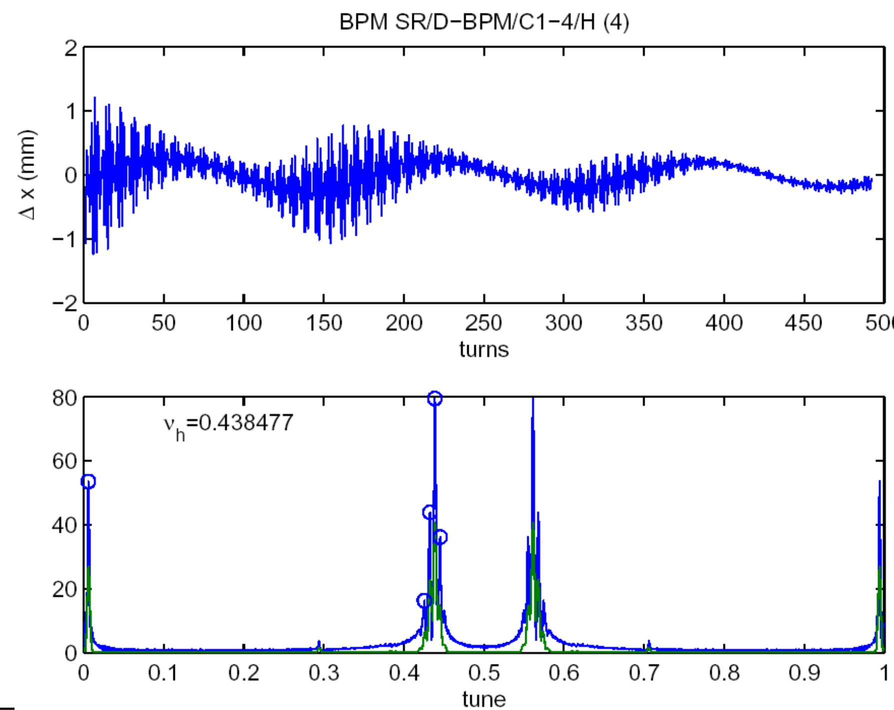


- Off-momentum frequency maps for 0 chromaticity (small vertical kicks)
- For positive momentum spread, distortion due to 5th order resonance seem to be weaker
- For momentum spreads +/- 1.5, appears the distortion due to coupling (or 4th order) resonance
- The dip of the dynamic aperture appears when crossing 8th order resonances
- The normal sextupole resonance limits the off-momentum dynamics aperture at –2.5%

Frequency analysis of data with longitudinal excitation

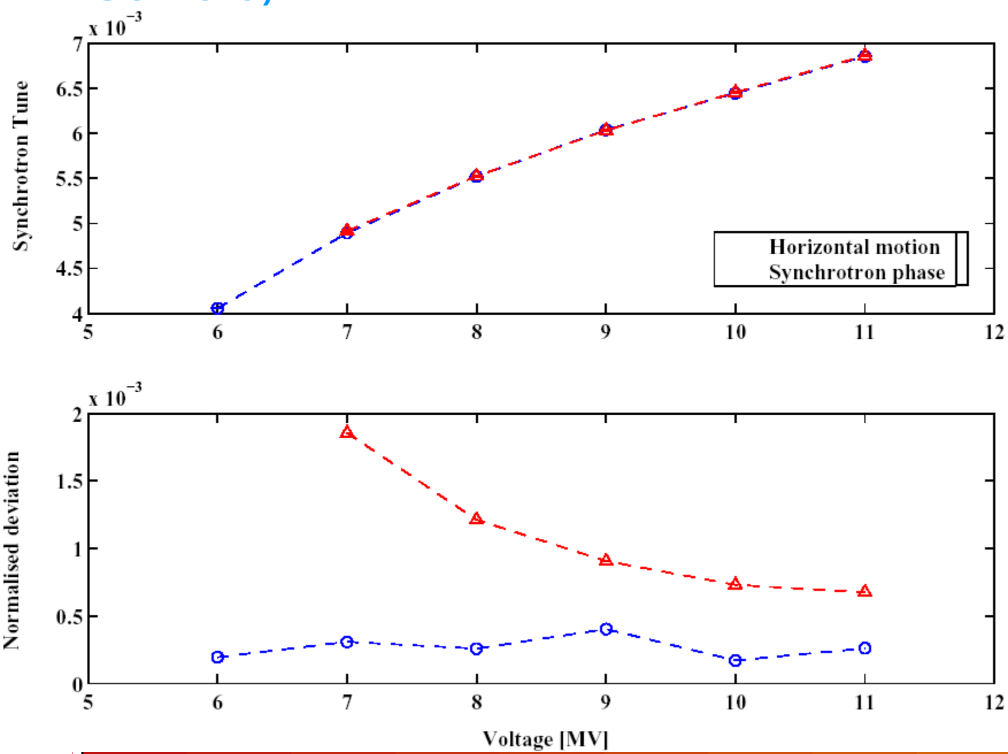
- Apply a longitudinal kick with an RF phase shifter, synchronised with a transverse kick (J.L.Revol)
- Record turn-by-turn transverse data in all BPM with MTOUR system and in the dedicated ADAS BPM
- Possibility to record phase signal in the ADAS BPM



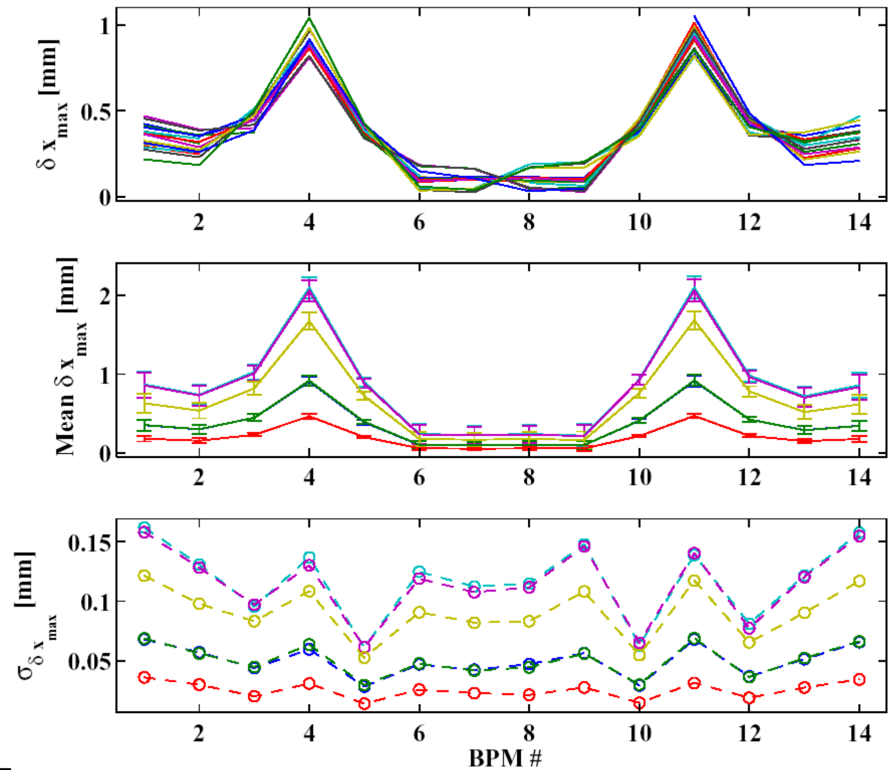


Synchrotron tune and dispersion

- Normalised precision in synchrotron tune determination better than 10^{-3}
- Possibility to calibrate the RF Voltage (V. Serrière)

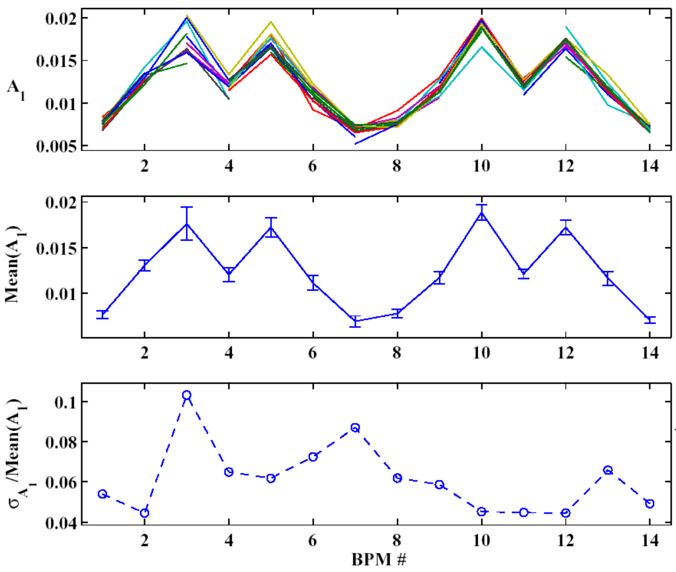


- Measuring dispersion in one kick.
- Use the measurements to calibrate the phase kick



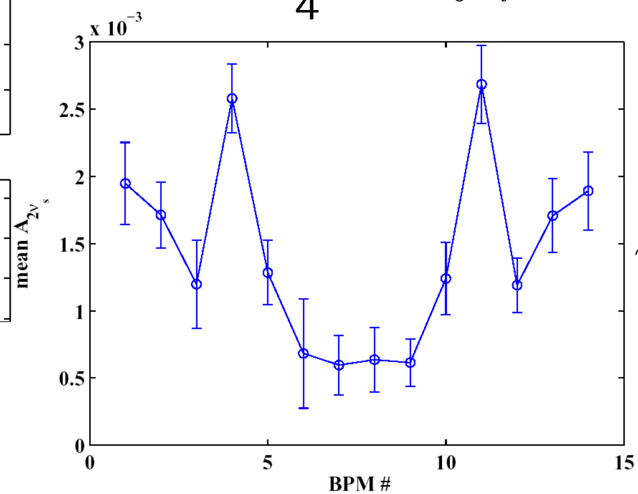
Off-momentum optics beating and chromaticity

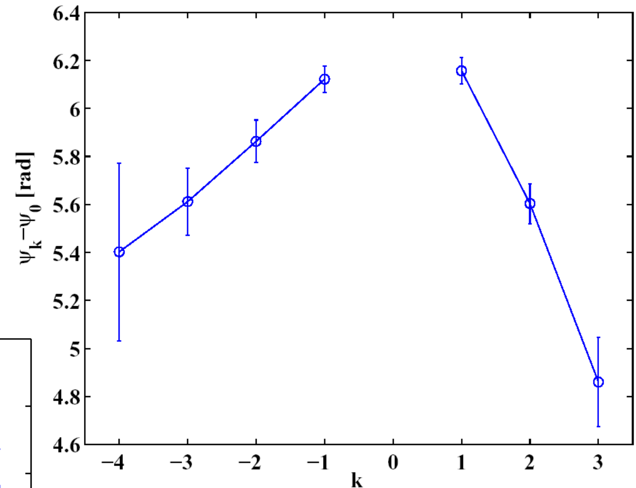
- The Fourier amplitude of the main peak can be used to measure the beta beating around the ring



- Possibility to measure chromaticity by the phase of synchrotron side-bands
- Measure 2nd order dispersion by amplitude of $2Q_s$ (G.Rumolo and R.Tomàs)

$$A_{2s} = \frac{1}{4}\eta_1(s)\sigma_\delta^2 k_l^2$$





$$\psi_q - \psi_0 = -|k| \arctan\left(\frac{k_l Q_s}{Q'_x \sigma_\delta}\right)$$

Conclusions - Perspectives

- Frequency analysis reveals unknown feature of the ESRF storage ring non-linear dynamics, for the nominal working point
- Numerical simulations to compare and adjust the non-linear model of the machine with the observed behavior
  - Why skew sextupole and high order resonances are excited?
  - How can we correct?
- Repeat the whole procedure for all interesting working points
  - Now capable with fast frequency map measurement dedicated BPM
- Understand off-momentum dynamics (lifetime limitations)
  - Use longitudinal excitation to measure chromaticity and off-momentum optics beating
- Limitation of the frequency analysis: few number of turns (beam decoherence)
  - Method of computing the tune in a few turns by using all BPM
- Establish new correction procedure by using driving term minimisation
- All necessary ingredients are present in order to establish experimental frequency map analysis as a routine operation on-line tool