Turn-by-turn measurements at the SLS

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CLIC WORKSHOP

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Outline

1. Fourier Analysis and NAFF Algorithm
2. Application on TBT data from the SLS storage ring
3. Betatron Tunes Measurements
4. A Different Approach to Tune Estimation
5. Two Methods for Betatron Function Estimation
6. Frequency Maps Analysis
7. Conclusions
8. Prospects

- Fourier analysis of turn by turn transverse position data measurements can determine several beam properties.e.g. transverse tunes, optics functions, phases, chromatic properties, coupling
- Most common used Fast Fourier Transform (FFT) $\Longrightarrow$ very long integration, many data or turns are needed

- And here comes the Numerical Analysis of the Fundamental Frequency (NAFF)

- Advantage of this method$\Longrightarrow$If $f(t)$ is a signal given numerically, it is possible to recover an approximation of $f(t)$ over a time span [-T T] with a precision of $\frac{1}{T^4}$
- In the case of a storage ring like SLS, f(t) can be a measured signal representing beam position data
- Expanding in Fourier series:

$$f(t) = \sum_{k=1}^{\infty} a_k e^{i\omega_k t} \tag{1}$$

  where ω_k are the unknown frequencies of the system and a_k the amplitudes, which NAFF's work is to find
- Its convergence is as fast as $\frac{1}{T^4}$ in comparison with standard FFT $\frac{1}{T}$

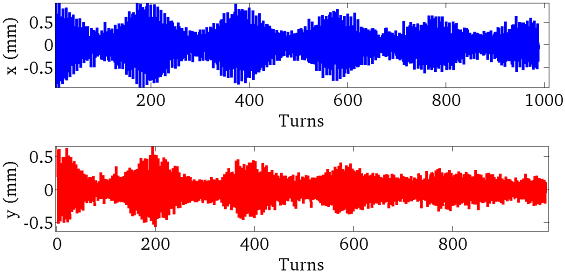
The SLS is a third generation light source which provides photon beams of high brilliance to 20 beam lines.

Table: Main Parameter of the SLS storage ring.

Parameter	Value
Circuference	288 m
Beam energy	2.4 GeV
Lattice	12 TBA
No. of BPMs	73
Betatron tunes (H/V)	20.44 / 8.74

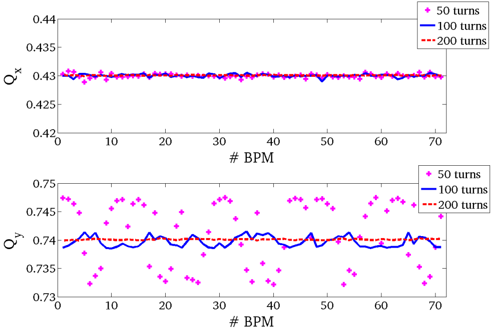
- In order to estimate the transverse tunes and other ring parameters, the bunches are kicked transversally by a kicker magnet to induce coherent betatron oscillations
- The resulting transverse position data are analysed with the NAFF method

- Some sample TBT data:



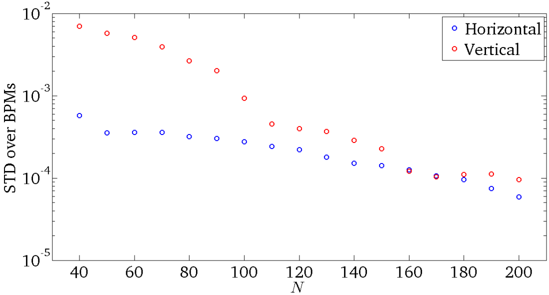
- BPMs 16 and 43 were noisy and they had to be ignored leaving a total of 71 BPMs for the analysis
- In the presence of chromaticity and amplitude dependent tune-shift, the BPM signal decoheres leaving a limited number of turns to be analysed

- Measurement of the fractional part of the tune⟹frequency analysis of the signal of each BPM indepedently



- The precision of the tune evaluation grows with the number of available turns
- 50 Turns⟹Large tune estimation fluctuation over the BPMs
- 200 Turns⟹Minimum tune estimation fluctuation especially in the vertical plane

Information about the accuracy of the tune estimation can be extracted from the standard deviation of the measured tune over all the BPMs

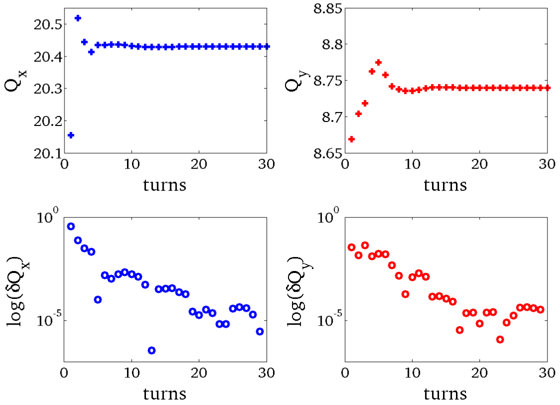


- Horizontal plane⟹less than 10^{-3} from only 40 turns and gets even less towards 200 turns
- Vertical plane⟹less than 10^{-3} from 100 turns.

- Consider N BPMs that are symmetric to the ring optics (azimuthal position)
- Mixing the BPM data simultaneously for every turn$\Longrightarrow$Fast and accurate evaluation of the tune including its integer part provided that there are more BPMs than the tune integer units to prevent aliasing

- Lack of BPMs' azimuthal symmetry$\Longrightarrow$ Induces a periodic Error in every turn

- Reminder$\Longrightarrow$SLS ring tune values: Q_x=20.44, Q_y=8.74



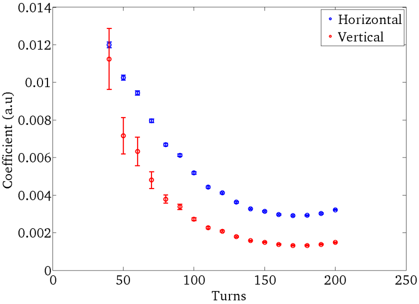
- Tune calculation almost from 10 turns for the horizontal plane. For the vertical 20 turns are needed $\Longrightarrow$Speed
- Difference of 10^{-5} and less between consecutive tune values from 20 turns$\Longrightarrow$Accuracy

- Fourier component amplitude associated to the main tunes is:

$$A_z^i = c_z \cdot S_i \sqrt{\beta_z^i} \tag{2}$$

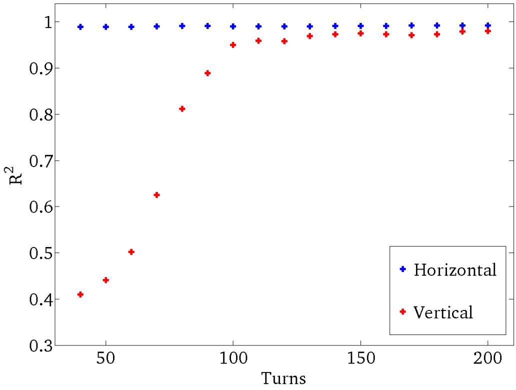
- Assuming well calibrated BPMs ($S_i = 1$), the beta function can be estimated by a linear fit of $(A_z^i)^2$ to the linear machine model

Representing the coefficient as a function of the time window used:



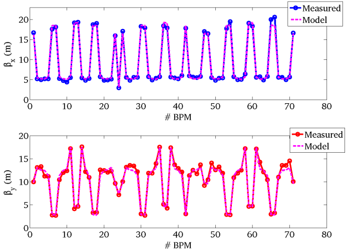
- Errorbars$\Longrightarrow$standard deviation of the least square fit$\Longrightarrow$Fit works even with 40 turns for Horizontal plane but for the Vertical plane at least 100 turns are needed to be less than 10^{-4}
- Increase of the step of turns converges to a single value of c_z with the least offset

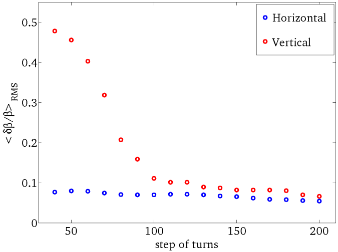
The precision of the linear fit can be evaluated from the correlation coefficient R^2



- Horizontal plane:R^2 is very close to 1 already for 40 turns
- Vertical Plane: At least 100 turns are needed

- The agreement between the measured beta functions and the ideal model values is excellent



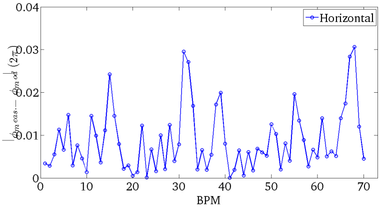


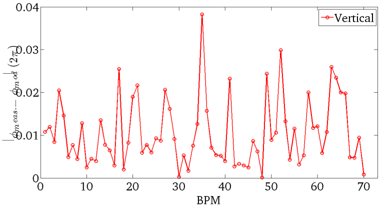
- From the plot of $< \frac{\delta\beta}{\beta} >_{RMS}$ $(Turns)$ $\Longrightarrow$Very good accuracy from less than 50 turns for the Horizontal plane, 150 turns are needed for the vertical plane$\Longrightarrow$ SLS operation is close to the ideal one

The phases of the main spectral lines for each BPM can also be used for evaluating the beta function difference between the machine and the model, using the measured phase advances between 3 concecutive BPMs(see P.Castro-Garcia Doctoral Thesis)

$$\tilde{\beta}_1 = \beta_1 \frac{\cot\tilde{\phi}_{12} - \cot\tilde{\phi}_{13}}{\cot\phi_{12} - \cot\phi_{13}}$$
$$\tilde{\beta}_2 = \beta_2 \frac{\cot\tilde{\phi}_{12} - \cot\tilde{\phi}_{23}}{\cot\phi_{12} - \cot\phi_{23}} \quad (3)$$
$$\tilde{\beta}_3 = \beta_3 \frac{\cot\tilde{\phi}_{23} - \cot\tilde{\phi}_{13}}{\cot\phi_{23} - \cot\phi_{13}}$$

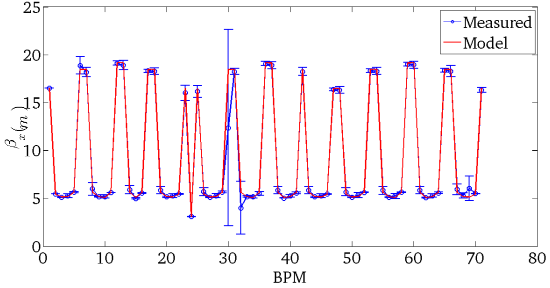
Plotting $|\phi - \phi_{model}|$ would visualize that





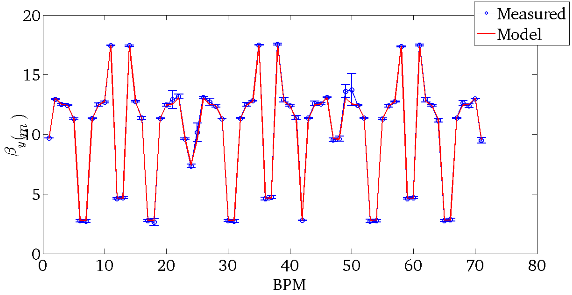
- The differences are below $4 \cdot 10^{-2}$ for most of BPMs in both planes
- At first glance the method can be applied for the SLS case since the measured phase advances are relatively close to the model ones

For this method three beta function estimates per location can be obtained allowing for some statistics



- The beta value differences between machine and model are for most BPMS very small$\Longrightarrow$Some discrepancies do exist

The same for the vertical plane:

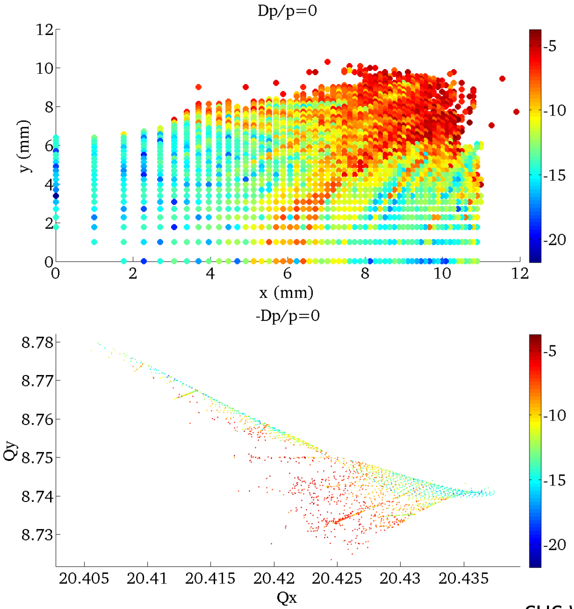


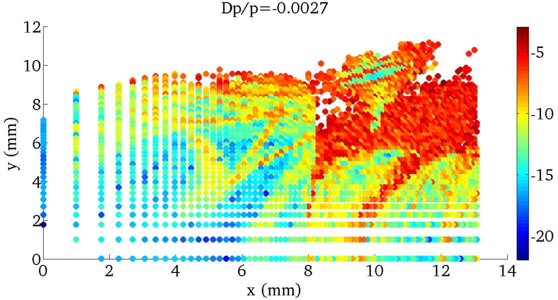
- High order perturbation theory has been used to enlight the nonlinear aspects of the particles' motion
- Instabilities such as resonances do not permit the contruction of variables for observation of the distorted phase space ⟶ We cannot see trajectories that are situated in the vicinity of resonances or chaotic regions
- NAFF algorithm can give frequencies of tranjectories that "insist on existing" on the perturbed phase space
- These frequencies can be used to build the Frequency Map of the system and explore the dynamics of the system

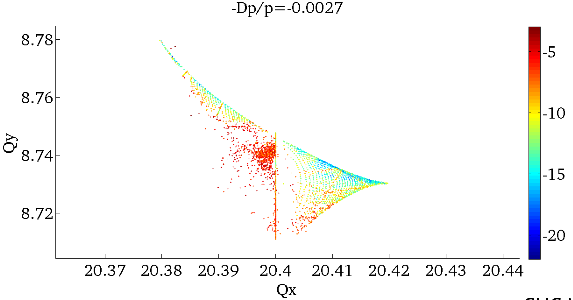
- Tracking data for a large number of initial conditions($\approx 10^3$) and for $\approx$ 1000 turns can be used to build the FM for the SLS
- A diffusion indicator can be introduced to distinguish between stable and chaotic trajectories:

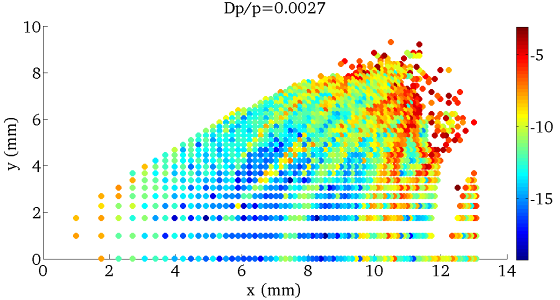
$$\mathbf{D}|_{t=\tau} = \mathbf{v}|_{(0,\tau/2)} - \mathbf{v}|_{(\tau/2,\tau)} \tag{4}$$

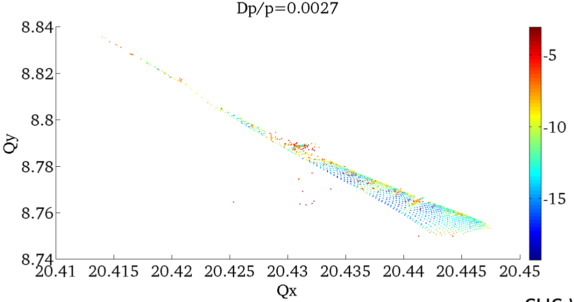
- An amplitude diffusion map can be constructed also
- For this SLS optics case, the Partile Tracking Code (PTC) of MADX was used for the tracking
- Selecting an arbitrary section of the phase space and holding $p_x, p_y = 0$ for all orbits, a $\sqrt{x}, \sqrt{y}$ mesh was used $\longrightarrow$Total of 9700 (x,y) initial conditions
- For the case under study, Dp/p= 0.0009. The maps were produced for cases of (-3*Dp/p, 0 ,3*Dp/p)


Dp/p=0
y (mm)
x (mm)
-Dp/p=0
Qy
Qx
12
10
8
6
4
2
0
-5
-10
-15
-20
8.78
8.77
8.76
8.75
8.74
8.73
20.405
20.41
20.415
20.42
20.425
20.43
20.435


Dp/p=-0.0027
y (mm)
x (mm)
0
2
4
6
8
10
12
14
-5
-10
-15
-20


-Dp/p=-0.0027
Qy
Qx
8.78
8.76
8.74
8.72
20.37
20.38
20.39
20.4
20.41
20.42
20.43
20.44
-5
-10
-15
-20


Dp/p=0.0027
y (mm)
x (mm)
10
8
6
4
2
0
0
2
4
6
8
10
12
14
-5
-10
-15


Dp/p=0.0027
Qy
Qx
8.84
8.82
8.8
8.78
8.76
8.74
20.41
20.415
20.42
20.425
20.43
20.435
20.44
20.445
20.45
-5
-10
-15

- NAFF algorithm is a powerful refined Fourier analysis tool which reduces the computation time and reveals many details of the beam dynamics
- The measured fractional tune was measured quite accurately in around 200 turns using the traditional method
- Another method which uses combined BPM data in every turn was demonstrated. The measurement of the tune was possible in around 10 turns
- The amplitude and phase of the fundamental spectral line for each BPM were used to estimate beta functions revealing the accuracy of NAFF once again. The first method showed excellent accuracy but the second one did not and it must be further investigated for the SLS case
- The Frequency Maps showed the dynamic behavior (for some cases) of the SLS ring and revealed resonances and chaotic regions of the phase space

There are many open subjects under investigation using the capabilities of the NAFF algorithm:

- Chromaticity and energy deviation measurement from the Fourier spectrum, dispersion relation to the amplitude of the main spectral lines
- Signs of synchrobetatron coupling due to the presence of tune shift modulation as it was shown
- Possibility of estimating the beta functions by only using the measured phase advances
- Insertion of magnet alignment errors in the lattice and observation of the spectrum-closed orbit distortion, betatron coupling ,vertical dispersion and vertical equilibrium emittance measurement
- Possibility of data acquirement with transverse and longitudinal kicks and use Fourier spectrum for dispersion high order represantation

Thank You!