Optics characterisation at KARA including the high wiggler field

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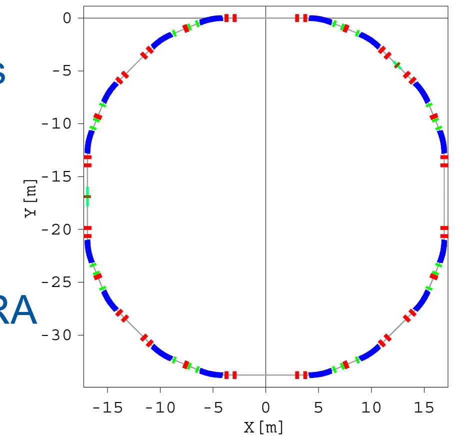
Outline

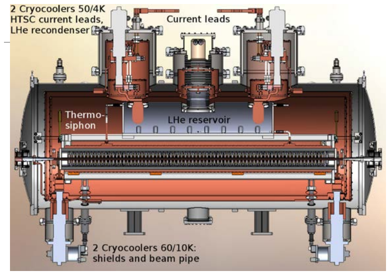
- **The CLIC DR SC Wiggler prototype at KARA**
- **Theoretical impact on beam dynamics**
- Experimental procedure
- Tune measurements
- Chromaticity measurements
- Conclusions

The CLIC SC Wiggler prototype at KARA

Parameter	ANKA
Energy / Magnetic rigidity	2.5 GeV (8.339T·m)
Circumference, m	110.4
Beam current, mA	150–170
Long/short straight sections, m	5.604 / 2.236
Natural ε_x (nm·rad) TME/DBA	56 / 90
Natural Chromaticity ξ_X/ξ_Y	–12/–13
High (low) chromaticity ξ_X/ξ_Y	+2/+6 (+1/+1)
Int.Sxt strength,m^{-2} (high) (low)	(+4.9/–4) (+4/–3)
Hor/vertical tunes Q_X/Q_Y	6.779 / 2.691
High tune operation Q_X/Q_Y	6.761 / 2.802
RF frequency (MHz)/ h_{RF}	500 / 184
CATACT field, T	2.5
CATACT length / period	0.96 m / 48 mm
Octupole CATACT, $g_3(k_3 \cdot L_W)$	≤120 T/m^3 (≤20m^{-3})
CLIC field, T	2.9
CLIC length / period	1.84 m / 51 mm

- KARA (previously named ANKA) is a 4-fold DBA ring with very flexible optics, able to serve 19 beamlines
- The CLIC SC Nb-Ti Wiggler prototype was installed at KIT-KARA in 2016.
- This project is the result of a fruitful collaboration between KIT, BINP and CERN
- Several ongoing studies to characterize the impact of the wiggler on beam dynamics





Cross-section of the assembled wiggler cryostat. Mezentsev N.A., 2012

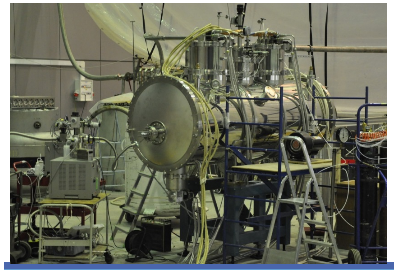


Photo taken during FAT at BINP

J. Gethmann et al, IPAC 2017, WEPIK068, p.3087-3089

A. Bernhard et al, IPAC 2016, WEPMW002, p.2412-2415

A. Papash et al, IPAC 2017, WEPAB011, p.2586-2589

The impact of the CLIC SC Wiggler on beam dynamics

- The KARA beam dynamics are not dominated by the CLIC wiggler.
- A slight emittance reduction of 6% is expected for Dispersion Achromat optics (D,D'=0 at LSS)
- A slight emittance blowup is expected in the Distributed Dispersion mode (D,D' $\neq$ 0 at LSS)

Parameter	Value (0 T / 2.9 T)
I_1 [m]	1.058 / 1.058
I_2 [m^{-1}]	1.140 / 1.258
I_3 [10^{-1} m^{-2}]	2.069 / 2.427
I_4 [10^{-2} m^{-1}]	-1.488 /-1.488
I_5 [10^{-3} m^{-1}]	6.830 / 7.125

**J. Gethmann, simulations with ELEGANT*

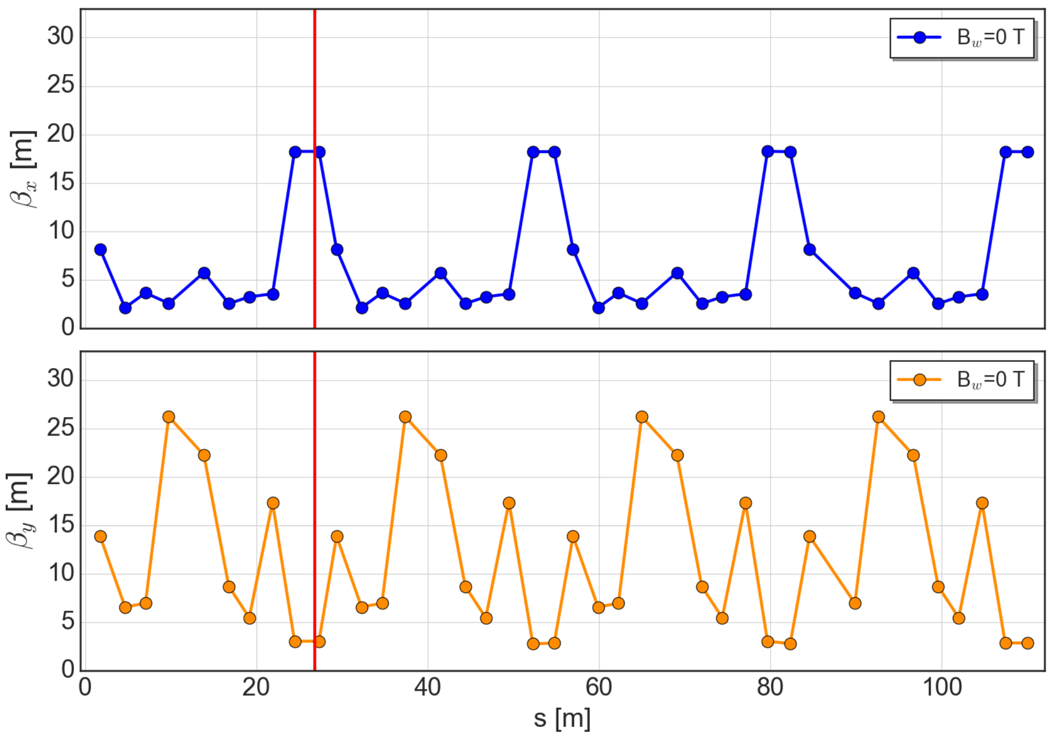
Scaling laws for the radiation integrals

- $I1_w = -\frac{\mathrm{L_w}}{2kw^2}\ \frac{1}{{\rho_w}^2} \approx -5.0\ \cdot 10^{-4}$
- $I2_w = \frac{\mathrm{L_w}}{2}\ \frac{1}{{\rho_w}^2} \approx 1.2 \cdot 10^{-1}$
- $I3_w = \frac{4\mathrm{L_w}}{3\pi}\frac{1}{{\rho_w}^3} \approx 3.7\ \cdot 10^{-2}$
- $I5_w = \frac{8\mathrm{Nw}}{15{\rho_w}^3 k_w}\ (\frac{\beta_x}{{\rho_w}^2{k_w}^2} + \frac{5\ \eta^2}{\beta_x}) \approx 2.4\ \cdot 10^{-4}$

Period length λ_w	mm	51.4
Total length L_w	m	1.8504
On-axis field amplitude B	T	2.9
β_x at the position of the wiggler	m	18.96
β_y at the position of the wiggler	m	2.17

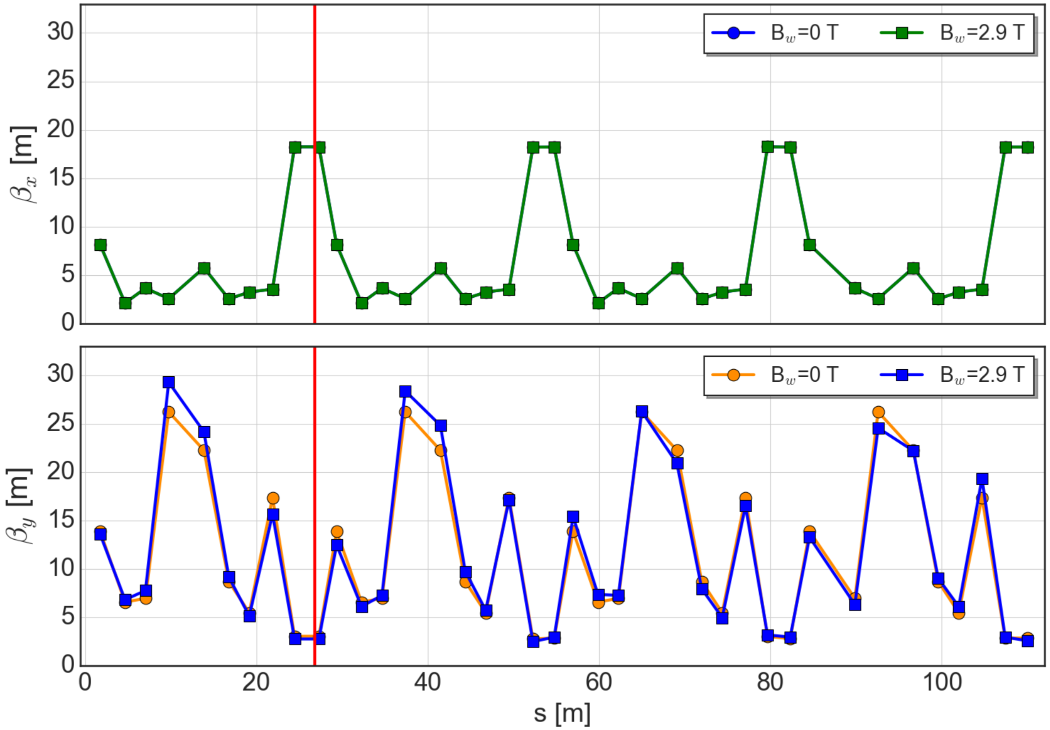
with ρw=B_W/Bρ, L_W the length of the wiggler, N_W the number of periods, η and β_X the dispersion and beta functions at the wiggler

Beta-beating in simulations



- The CLIC wiggler is situated at a position where βy is minimum, to minimize optics beating, tune-shift etc.

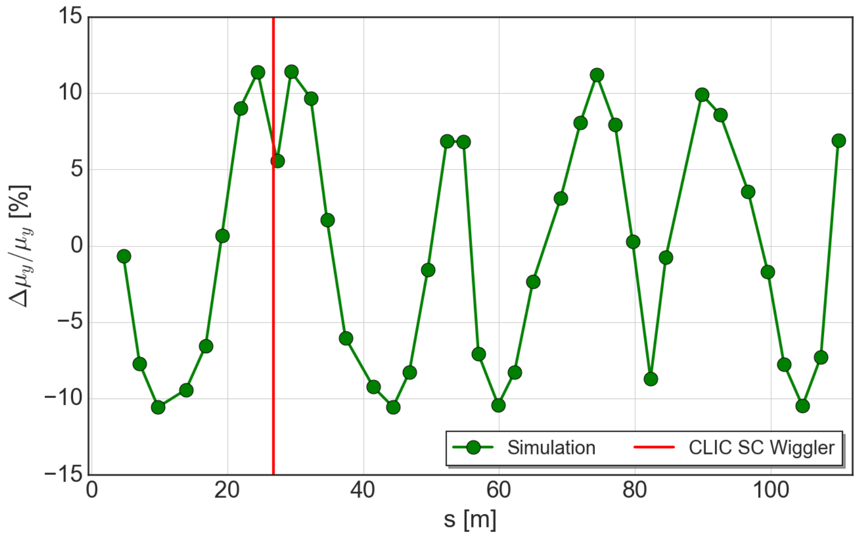
Beta-beating in simulations

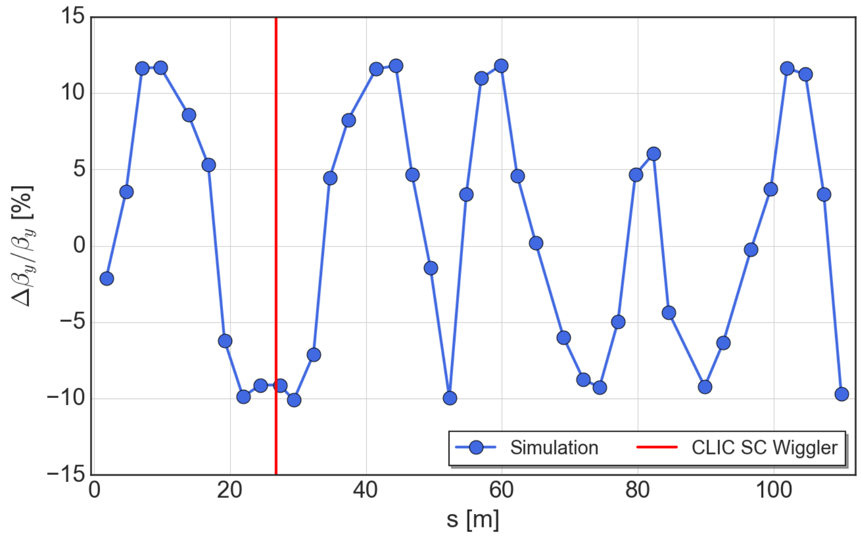


- The CLIC wiggler is situated at a position where βy is minimum, to minimize optics beating, tune-shift etc.

- The Wiggler at maximum field generates vertical beta-beating as expected.

Beta-beating in simulations





- Vertical Phase beating at the order of 5 % at the CLIC Wiggler location

- The wiggler induced beta-beating is at the order of **10 %**
- Tune-shift from simulations: **ΔQ=+0.018**

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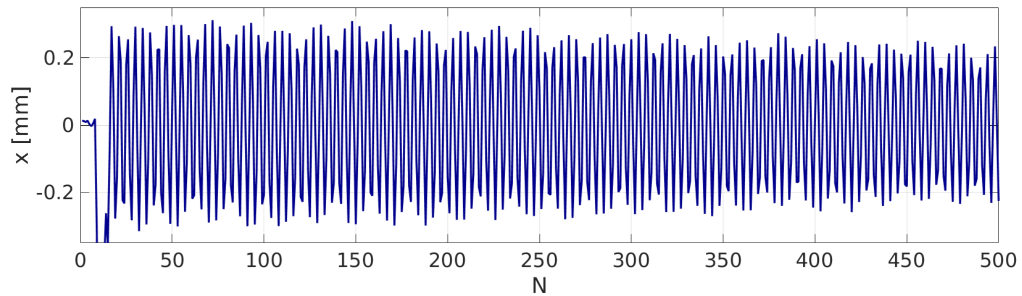
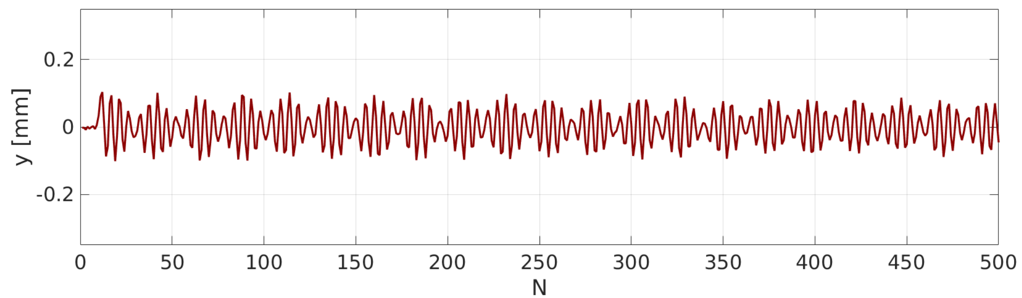
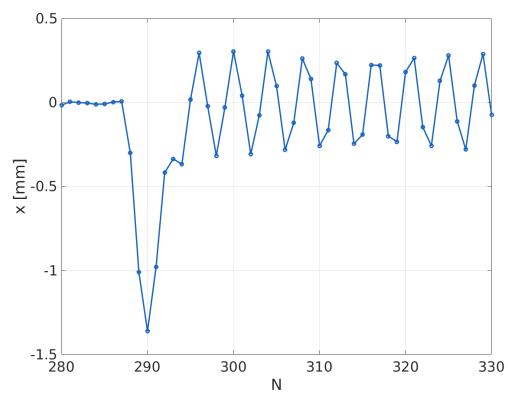
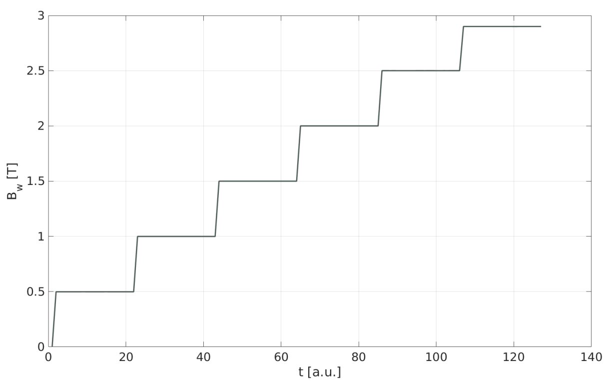
The outline of the experiment at KARA

- Turn by turn data were recorded from the 39 BPMs at KARA for about 1700 turns (~760 μs)
- The CLIC Wiggler was ramped up in 0.5 T steps from 0 T to 3 T
- During each ramp, the RF frequency was modulated to induce radial steering for chromaticity measurements
- The injection kicker was used to excite the beam horizontally and vertical oscillations were possible through betatron coupling.



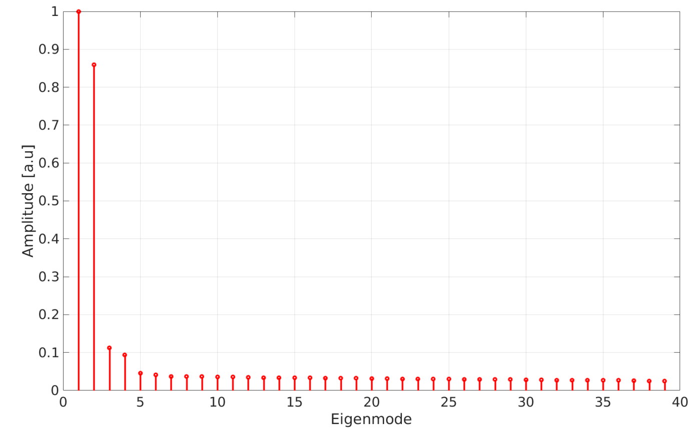


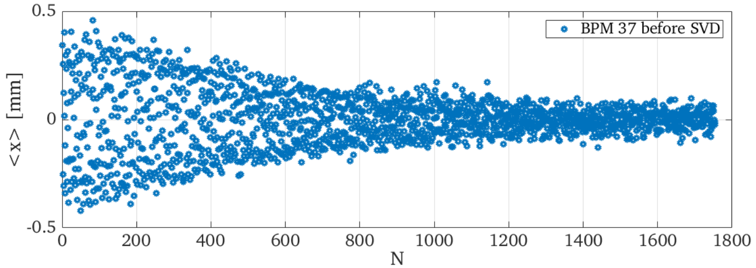


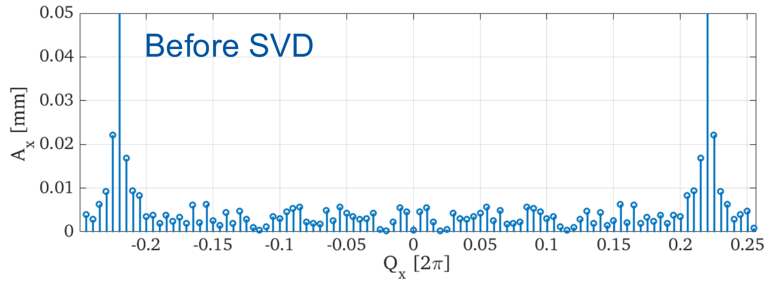


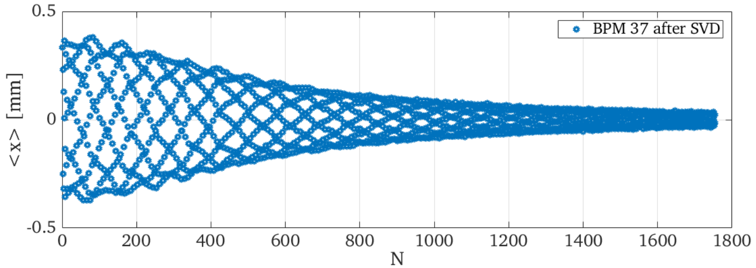
Preparation of the TbT data

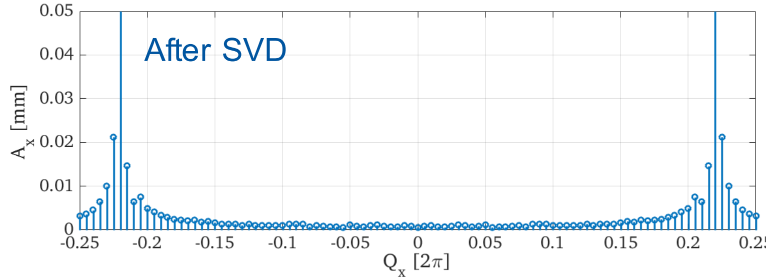
- Filtering of noise is always a good practice as long as it is justified.
- A powerful method exists by using Singular Value Decomposition analysis.











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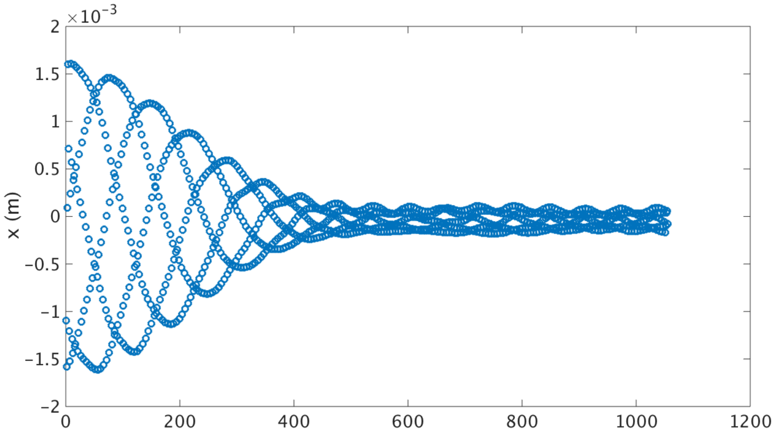
Methodology I: Tune measurements



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PHYSICA D

Frequency analysis for multi-dimensional systems.
Global dynamics and diffusion

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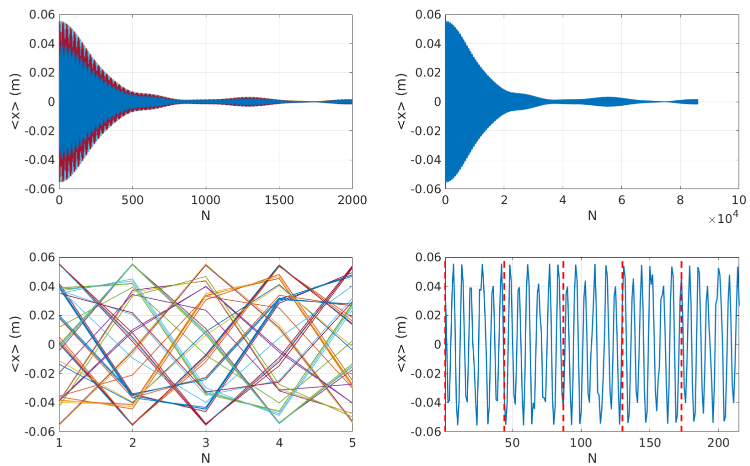
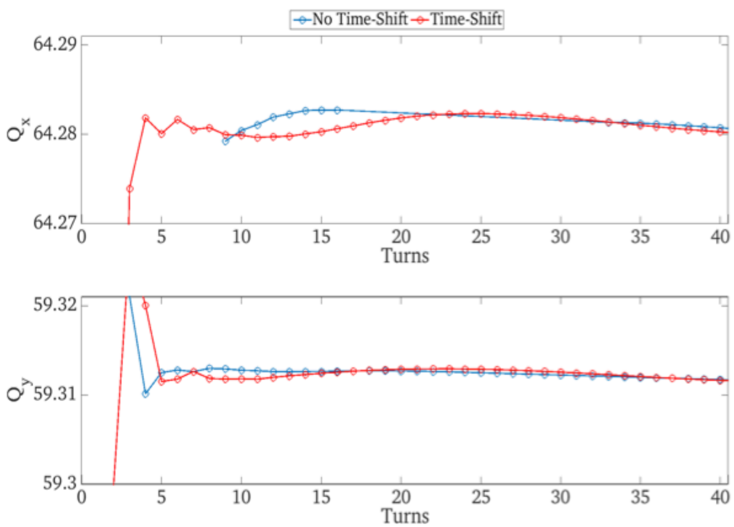
Frequency analysis is a new method for analyzing the stability of orbits in a conservative dynamical system. It was first devised in order to study the stability of the solar system [J. Laskar, Icarus 88 (1990) 266–291] and then applied to the 2D standard mapping [Laskar et al., Physica D 56 (1992) 253–269]. It is a powerful method for analyzing weakly chaotic motion in Hamiltonian systems or symplectic maps For regular motions, it yields an analytical representation of the solutions. The analysis of the regularity of the frequency map with respect to the action space and of its variations with respect to time gives rise to two criteria for the regularity of the motion which are valid for multi-dimensional systems. For a 4D symplectic map, plotting the frequency map in the frequency plane provides a clear representation of the global dynamics, and reveals that high order resonances are of great importance in understanding the diffusion of non-regular orbits through the invariant tori. In particular, it appears in several examples that diffusion along the resonance lines (Arnold diffusion), is of less importance than diffusion across the resonances lines, which can lead to large diffusion due to the phenomenonon of overlap of higher order resonances chaotic layers. Many fine features of the dynamics are also revealed by frequency analysis, which would require more theoretical study for a better understanding.

- Certain damping mechanisms can affect the precision of tune measurements
- Refined Fourier Methods as a remedy to this problem.
- The Numerical Analysis of Fundamental Frequencies (**NAFF**), allow for a fast convergence to the tunes at the order of **$1/N^4$**
- Can we accelerate this convergence?

Methodology I: Tune measurements





- Combining M BPMs together, which have an average sampling rate error δ, leads to an increase of the resolution by:

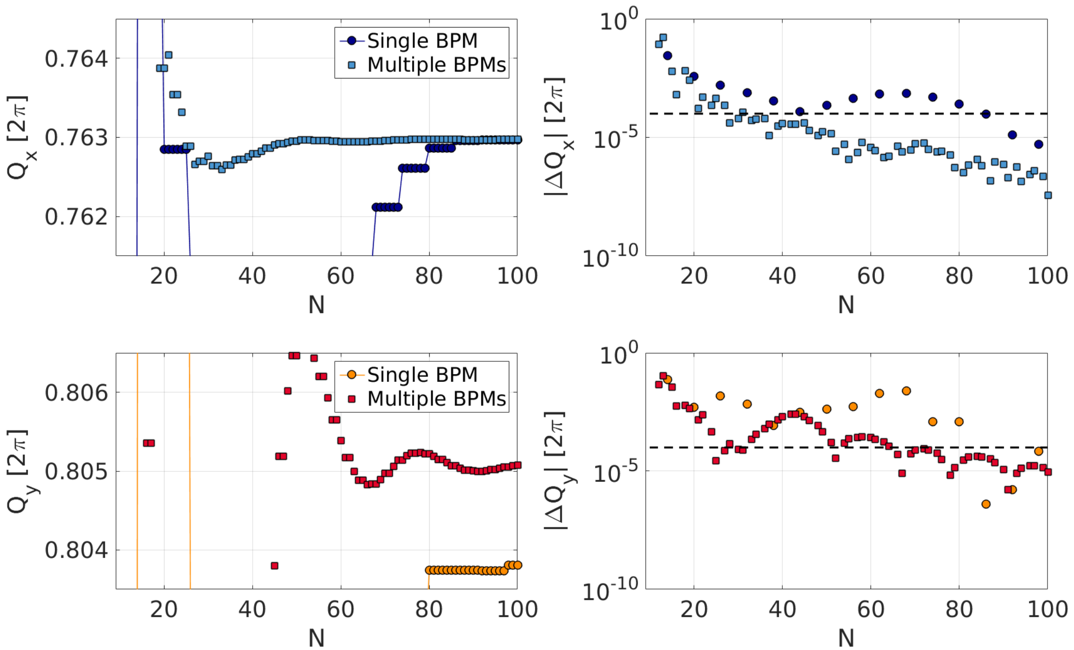
$$|Q_0\text{-}Q(N)| \sim \frac{1}{M^3 N^4}(1+\delta)$$

- <u>Recipe</u>: Gather the TbT in an array [**NxM**] and vectorize [**1xMN**]:

$$\begin{vmatrix} x_1[1] & x_2[1] & \dots & x_M[1] \\ x_1[2] & x_2[2] & \dots & x_M[2] \\ \dots & \dots & \dots & \dots \\ x_1[N] & x_2[N] & \cdots & x_M[N] \end{vmatrix}$$

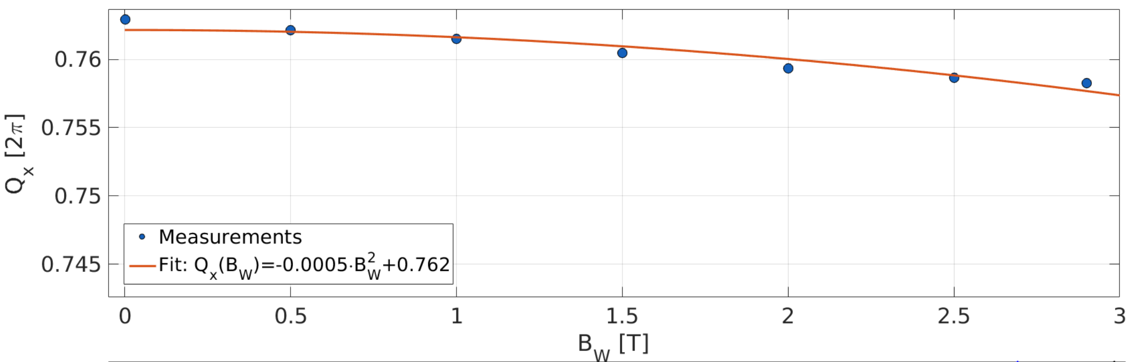
$$\tilde{x} = [\underbrace{x_1[1]x_2[1]\dots x_M[1]}_{\text{First Period}} \dots \underbrace{x_1[N]x_2[N]\dots x_M[N]}_{\text{M Period}}]$$

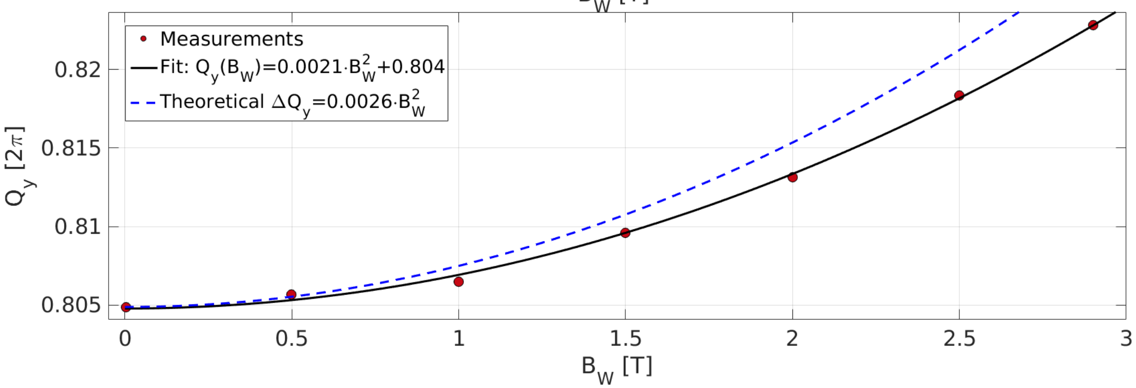
Results I: Tune Measurements



- By using the mixed BPMs scheme the tunes were also measured during each ramp of the wiggler with the beam at the nominal chromatic orbit.
- Precision is increased in both cases and it is at the level of 10^{-4} at around 30 turns.

Results I: Tune Measurements





- The measurements were fitted with quadratic models.
- The horizontal tune-shift is not expected but it is present, possibly due to sextupolar feed-downs.
- The expected vertical tune-shift is relatively close to the theoretical predicted value.
- ($\Delta Qx/Qx$, $\Delta Qy/Qy$) ~ (0.5%, 2%) at 2.9 T

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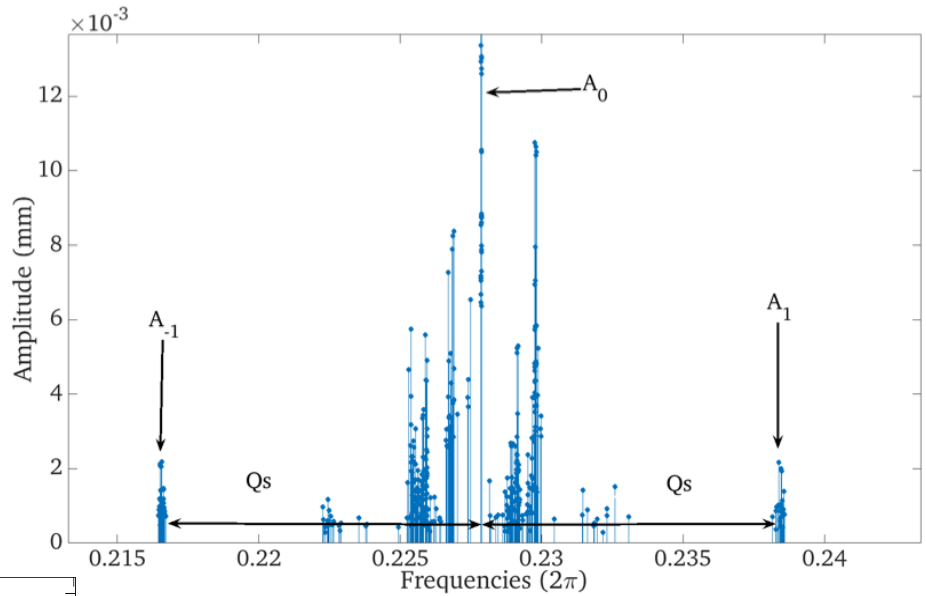
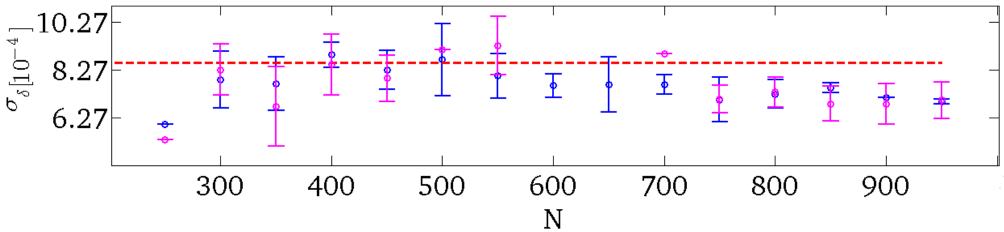
Methodology II :Chromaticity measurements

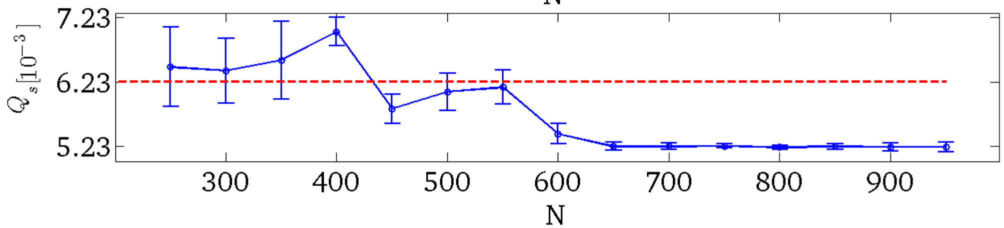
- It has been shown* that Fourier analysis can determine the linear chromaticity, which quite simply scales as : $Q' = \frac{Q_s}{\sigma_\delta}\sqrt{\frac{A_1+A_{-1}}{A_0}}$

- Precise knowledge of the RMS energy spread is important.

- Independent of BPM calibration factors

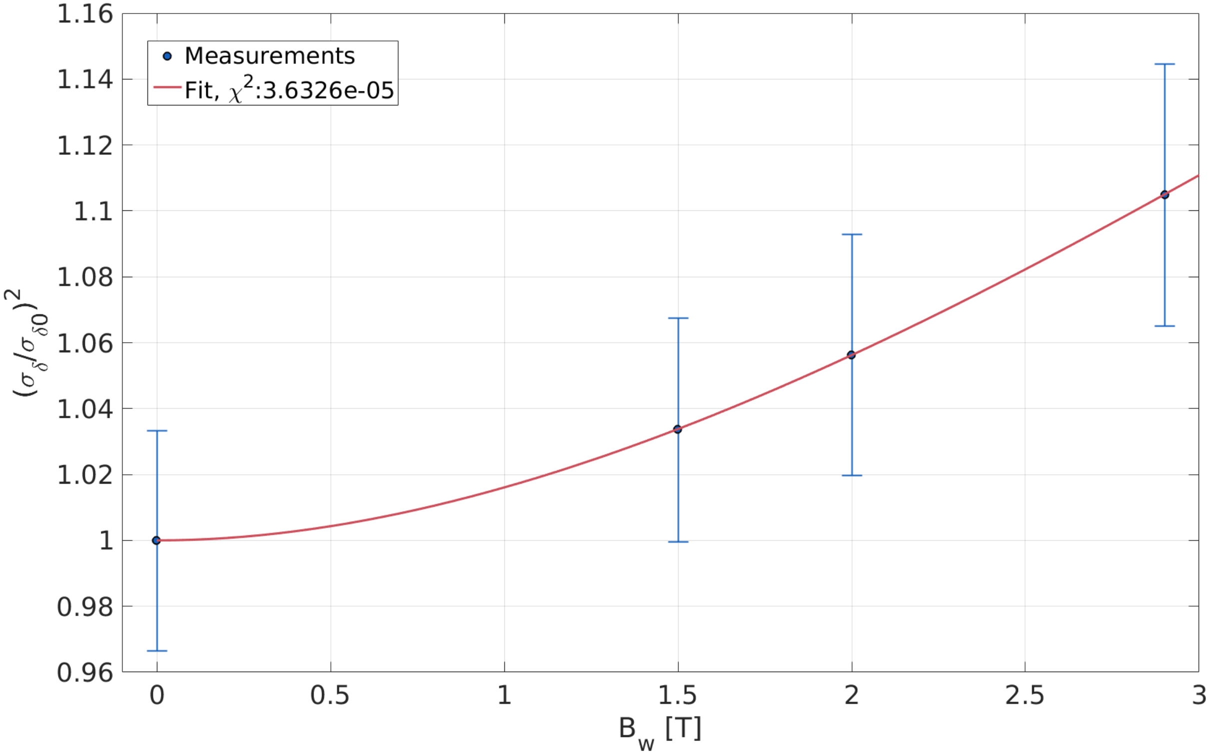






** P. Zisopoulos, Y. Papaphilippou, IPAC 2014, THPRO076, p. 3056-3058*

Results II: Chromaticity measurements

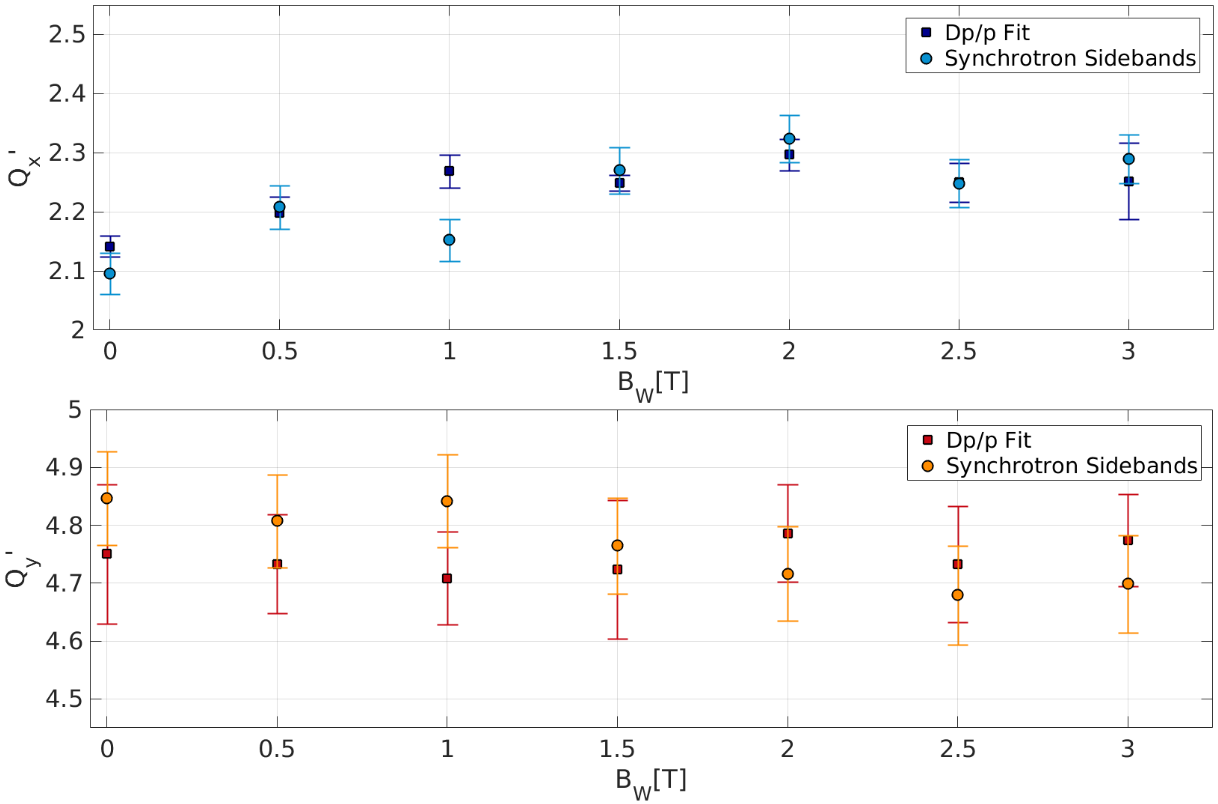


- RMS Energy spread measurements performed with a streak camera.
- The errorbars correspond to 1σ uncertainty of the measurement.
- To obtain the energy spread at intermediate points, the measurements are fitted to*:

$$y[x] = \frac{1 + c1\ x^3}{1 + c2\ x^2}$$

* with W3=I3w/I3o, W2=I2w/I2o, we have $(\sigma_\delta/\sigma_{\delta 0})^2 \sim \frac{1+W3}{1+W2}$

Results II: Chromaticity measurements



- The synchrotron period at KARA is about 80 turns.
- The chromaticity was extracted from the Fourier spectra of 4/Qs turns and from a fit with the dp/p.
- The measurements indicate a slight increase of Q'_x
- For Q'_y the uncertainty in the vertical plane is larger so a clear trend is not evident.

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Conclusions

- The first beam dynamic measurements with the CLIC SC Wiggler were carried out at KARA.
- The tune-shift with the wiggler's field was measured. The estimated vertical focusing agrees reasonably with the theoretical prediction. A slight horizontal defocusing is also reported.
- A novel method to measure chromaticity was introduced. The results agree well with the traditional chroma measurements.
- A slight increase in horizontal chromaticity is observed. The vertical chromaticity exhibits larger uncertainties due to the conditions of the machine while recording the TbT data.

Thank you for your attention !

Spare Slides

The NAFF Algorithm

- See J. Laskar, Frequency analysis for multi-dimensional systems. Global dynamics and diffusion)

- Outline of the method
  1. Given a numerical sequence f(t) i.e. BPM signal, perform standard FFT to locate approximately the maximum of power spectra
  2. Apply a window filter in order to reduce leakage effects.
  3. Use interpolation methods (quadratic, Hardy's integration) to find exactly the maximum of $\varphi(\omega)=\langle f(t), e^{i\omega t}\rangle$ in the vicinity of the previously found frequency. This gives the first frequency v_1.
  4. Perform orthogonalization of the basis function $e^{iv_1 t}$ so we can project f(t) on it . Substract the first term from f(t) and iterate until desired number of frequencies is obtained.

Normalized Intensity evolution