Experimental studies for the high field wiggler at KIT-ANKA

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Outline

• The CLIC DR SC Wiggler prototype at ANKA
• Theoretical impact of the wiggler on beam dynamics
• Description of the experiment
• Methodology I & Results I: Tune measurements
• Methodology II & Results II: Chromaticity measurements
• Conclusions
• Future Plans
The CLIC SC Wiggler prototype at ANKA

- ANKA (recently renamed KARA) 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-ANKA 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.

Parameters ANKA

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

J. Gethmann et al, IPAC 2017, WEPIK068, p.3087-3089
A. Bernhard et al, IPAC 2016, WEPMW002, p.2412-2415

8/12/2017 7th Low Emittance Rings Workshop
The impact of the CLIC SC Wiggler on beam dynamics

- The ANKA storage ring 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’≠0 at LSS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (0 T / 3 T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(l_1) [m]</td>
<td>1.058 / 1.058</td>
</tr>
<tr>
<td>(l_2) [m(^{-1})]</td>
<td>1.140 / 1.258</td>
</tr>
<tr>
<td>(l_3) [10(^{-1}) m(^{-2})]</td>
<td>2.069 / 2.427</td>
</tr>
<tr>
<td>(l_4) [10(^{-2}) m(^{-1})]</td>
<td>-1.488 / -1.488</td>
</tr>
<tr>
<td>(l_5) [10(^{-3}) m(^{-1})]</td>
<td>6.830 / 7.125</td>
</tr>
</tbody>
</table>

*J. Gethmann, simulations with ELEGANT*
Scaling laws for the radiation integrals

- \( I_{1w} = -\frac{L_w}{2k_w^2} \frac{1}{\rho_w^2} \approx 5.0 \cdot 10^{-4} \)

- \( I_{2w} = \frac{L_w}{2} \frac{1}{\rho_w^2} \approx 1.2 \cdot 10^{-1} \)

- \( I_{3w} = \frac{4L_w}{3\pi} \frac{1}{\rho_w^3} \approx 3.7 \cdot 10^{-2} \)

- \( I_{5w} = \frac{8N_w}{15\rho_w^3 k_w} \left( \frac{\beta_x}{\rho_w^2 k_w^2} + \frac{5\eta^2}{\beta_x} \right) \approx 2.4 \cdot 10^{-4} \)

with \( \rho_w = \frac{B_w}{B_p} \), \( L_w \) the length of the wiggler, \( N_w \) the number of periods, \( \eta \) and \( \beta_x \) the dispersion and beta functions at the wiggler.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length ( \lambda_w )</td>
<td>mm</td>
<td>51.4</td>
</tr>
<tr>
<td>Total length ( L_w )</td>
<td>m</td>
<td>1.8504</td>
</tr>
<tr>
<td>On-axis field amplitude ( B )</td>
<td>T</td>
<td>2.9</td>
</tr>
<tr>
<td>( \beta_x ) at the position of the wiggler</td>
<td>m</td>
<td>18.96</td>
</tr>
<tr>
<td>( \beta_y ) at the position of the wiggler</td>
<td>m</td>
<td>2.17</td>
</tr>
</tbody>
</table>
The outline of the experiment at ANKA

- Turn by turn data were recorded from the 39 BPMs at ANKA 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 kick horizontally and vertical oscillations were possible through betatron coupling.
Preparation of the 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.
Methodology I: Tune measurements

- Certain damping mechanisms can affect the precision of tune measurements
- Powerful refined Fourier methods gave the solution to this problem
- The Numerical Analysis of Fundamental Frequencies (NAFF) give a precision of $1/N^4$
- Can we accelerate this convergence?
Mixing the BPMs together for precision

- Combining $M$ BPMs together leads to an increase of the sampling rate
  $\frac{1}{M^3N^4} + \text{periodic error}$

- Recipe: Vectorize a given a matrix $B$, with dimensions $N \times M$, with data for $N$ turns from $M$ BPMs.

\[
\tilde{x} = [x_1[1] \ x_2[1] \ \ldots \ x_M[1] \ 
\ x_1[2] \ x_2[2] \ \ldots \ x_M[2] \ 
\ 
\ 
\ \ldots \ \ldots \ \ldots \ \ldots \ 
\ x_1[N] \ x_2[N] \ \ldots \ x_M[N]]
\]

\[
\tilde{x} = [\underbrace{x_1[1]}_{\text{First Period}} \underbrace{x_2[1]}_{\text{M Period}} \ldots \underbrace{x_M[1]}_{\text{First Period}} \ldots \underbrace{x_1[N]}_{\text{M Period}} \underbrace{x_2[N]}_{\text{M Period}} \ldots \underbrace{x_M[N]}_{\text{M Period}}]
\]
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.
- \((\Delta Q_x/Q_x, \Delta Q_y/Q_y) \sim (0.5\%, 2\%)\) at 2.9 T
Methodology II: Chromaticity measurements

- It has been shown* that Fourier analysis can determine the linear chromaticity, which quite simply scales as:

\[ Q' = \frac{Q_0}{\sigma_\delta} \sqrt{\frac{A_1 + A_{-1}}{A_0}} \]

- The knowledge of the RMS energy spread and the quality of the data are rather important.

- Independent of BPM calibration factors.

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* 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 1-σ uncertainty of the measurement.

• To obtain the energy spread at intermediate points, the measurements are fitted to*:

\[ y[x] = \frac{1 + c_1 x^3}{1 + c_2 x^2} \]

* with \( W_3 = \frac{I_3}{I_0} \), \( W_2 = \frac{I_2}{I_0} \), we have \( \frac{\sigma_\delta}{\sigma_{\delta 0}} \sim \frac{1 + W_3}{1 + W_2} \)
Results II: Chromaticity measurements

- The synchrotron tune at ANKA is $Q_s = 0.013$.

- The chromaticity was extracted from the Fourier spectra of $4/Q_s$ 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.
Conclusions

- The first beam dynamic measurements with the CLIC SC Wiggler were carried out at ANKA.

- 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 demonstrated. The results agree well with the RF frequency ramping measurements.

- A slight increase in horizontal chromaticity is reported. The vertical chromaticity exhibits larger uncertainties due to the conditions of the machine while recording the TbT data.
Future Plans

• Explore the possibility of recording larger vertical oscillations to improve the quality of the data

• Measure the contribution of the wiggler to the linear beta-beating.

• Measure contribution of the wiggler to non-linear dynamics.

• Studies with beam dynamics simulations to observe the response of the linear and non-linear model under the influence of the CLIC wiggler.

• Measurement of the damping times and emittance.

• Try the same measurements in low-alpha mode
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. Use interpolation methods (quadratic, Hardy’s integration) to find exactly the maximum of $\phi(\omega) = <f(t), e^{i\omega t}>$ in the vicinity of the previously found frequency. This gives the first frequency $v_1$. Applying a window filter also increases precision.
  3. Perform orthogonalization of the basis function $e^{iv_1t}$ so we can project $f(t)$ on it. Subtract the first term from $f(t)$ and iterate until desired number of frequencies is obtained.
Normalized Intensity evolution

![Normalized Intensity evolution graph](image)