Karlsruhe Institute of Technology

Accelerator Technology Platform @ KIT

First Experiences with Negative Momentum Compaction at KARA

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Motivation

- Understanding of collective effects and instabilities critical to a successful operation of a synchrotron light source
- Most efforts focus on a positive value of the momentum compaction factor α_c
- Negative α_c regime important for a thorough understanding of collective effects
- KARA used as accelerator test facility ⇒ possibility to study these effects at a negative value of α_c

$$\alpha_c = \frac{\Delta L/L}{\Delta p/p} = \frac{1}{L}\oint \frac{D(s)}{\rho(s)}\mathrm{d}s$$

Lattice and Optics

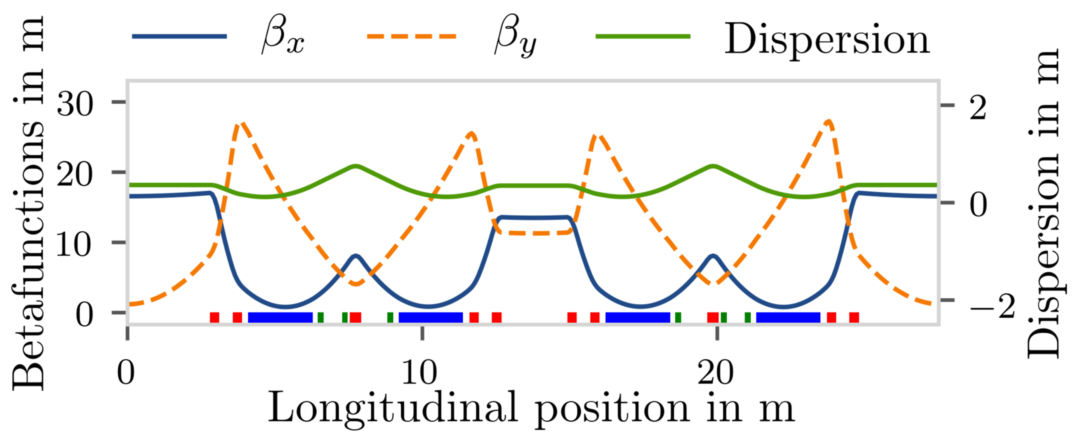
KARA

- 4 fold symmetry
- 2 double bend achromats per cell
- 5 quadrupole magnets per DBA (Q1-5)
- Straight sections are filled with insertion devices, RF stations and injection magnets

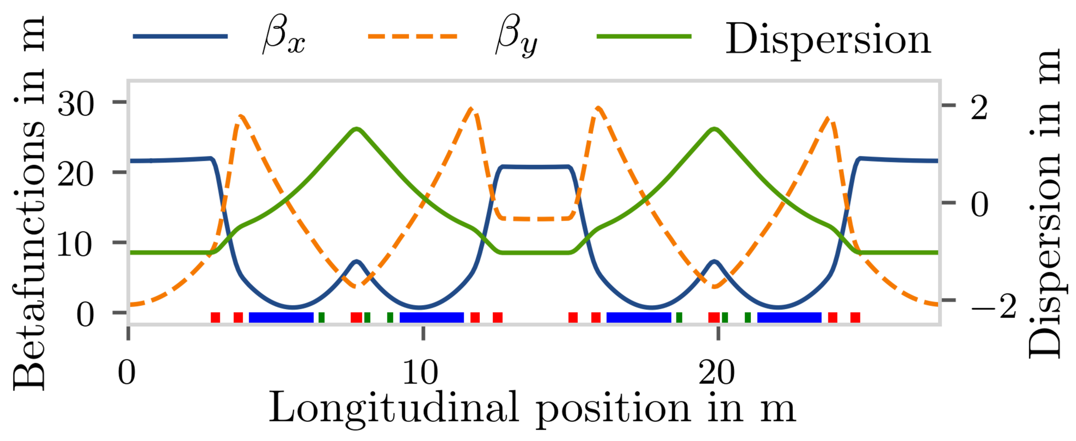
Parameter	Value
Energy	0.5-2.5 GeV
Circumference	110.4 m
RF frequency	500 MHz
Revolution frequency	2.715 MHz
$\sigma_{z,\,\mathrm{RMS}}$ (standard operation, 2.5 GeV)	45 ps
$\sigma_{z,\,\mathrm{RMS}}$ (short bunch mode, 1.3 GeV)	few ps

Operation Modes

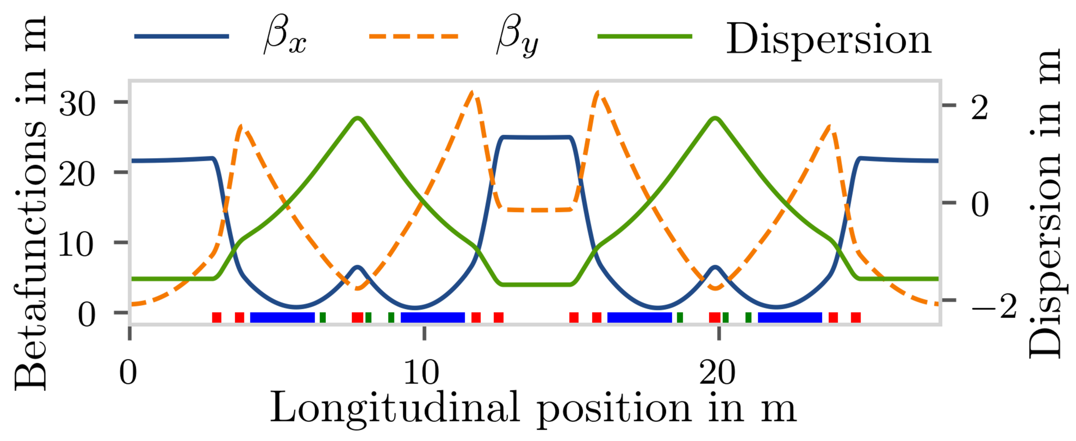
- Two operation modes already established
- Standard operation at 2.5 GeV and $\alpha_c \approx 9\times10^{-3}$
- Short bunch mode at 1.3 GeV and $\alpha_c \approx 1\times10^{-4}$
- New mode: negative α_c at 0.5 GeV
- Lower α_c requires stretched dispersion, including negative parts



Calculated lattice used for user operation at $\alpha_c = 9\times10^{-3}$ and 0.5 GeV. The bottom depicts the magnets, quadrupoles in red, sextupoles in green and bends in blue.



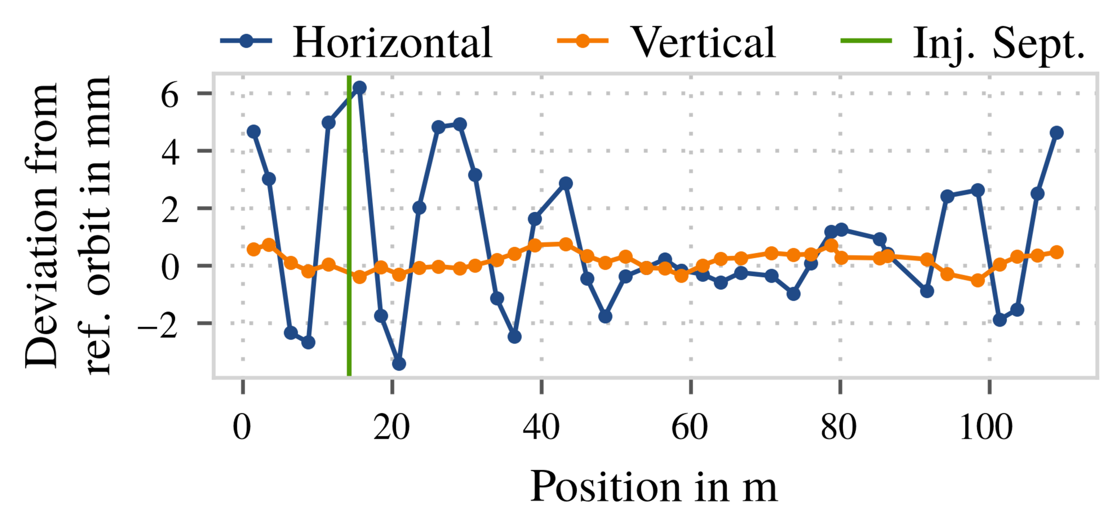
Calculated lattice for $\alpha_c = 1\times10^{-4}$ at 0.5 GeV. In large parts the dispersion is negative.



Calculated lattice for a negative value of $\alpha_c = -8\times10^{-3}$. In large parts the dispersion is negative.

Status of Operation

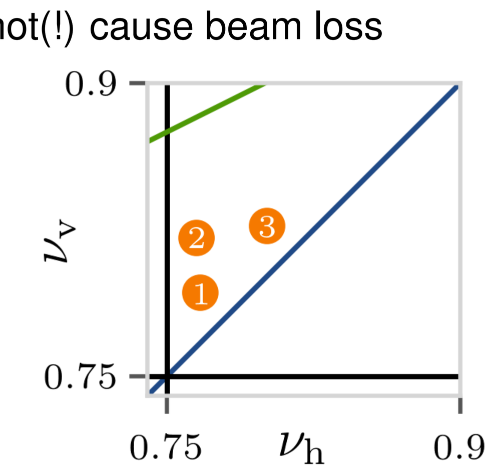
- Injection into different optics with negative values of α_c has been established at 500 MeV
- Maximum beam and bunch current is limited, highest achieved current is 17 mA distributed over 30 bunches and 1 mA for single-bunch operation
- Multiple factors affecting the current limit were identified
  - High orbit deviations seem to be beneficial
  - Reduced absolute value of α_c seem to result in higher beam currents
  - Reduced sextupole strengths and therefore reduced chromaticities seemed beneficial
- High orbit deviations lead to acentrical crossing of quadrupoles and sextupoles



Orbit deviations during injection into an optics with $\alpha_c \approx -8\times10^{-3}$

Working Point & Chromaticity

- Tunes ν and Chromaticity ξ for optics with different values of α_c has been measured
  - At $\alpha_c \approx -1.2\times10^{-2}$: $\nu_h \approx 0.76$ $\nu_v \approx 0.79$ $\xi_h \approx -1.89$ $\xi_v \approx -7.14$
  - At $\alpha_c \approx -8\times10^{-3}$: $\nu_h \approx 0.76$ $\nu_v \approx 0.78$ $\xi_h \approx -2.24$ $\xi_v \approx -4.93$
  - At $\alpha_c \approx -4\times10^{-3}$: $\nu_h \approx 0.76$ $\nu_v \approx 0.80$ $\xi_h \approx -3.27$ $\xi_v \approx -4.22$
  - At $\alpha_c \approx -1.6\times10^{-3}$: $\nu_h \approx 0.76$ $\nu_v \approx 0.82$ $\xi_h \approx -3.75$ $\xi_v \approx -1.51$
- Changing chromaticities is relatively easy, injection and storing possible
- Shifted chromaticities: Vertical from ≈ −7.1 to ≈ 1.49 and horizontal from ≈ −4 to ≈ 0.8
  - Horizontal chromaticity had almost no effect, even a change of sign
  - Positive vertical chromaticity resulted in a sub mA injection limit
  - Moving to positive vertical chromaticity with stored beam did not(!) cause beam loss
- Working point was moved ① → ② → ③
  - ①: Starting point, quite good injection rate and current limit
  - ②: Almost same behaviour as at ①
  - ③: Low current limit and lower injection rate than at ①
  - Between ① and ② the behaviour is almost the same as at ①
  - Between ② and ③ part of the beam was lost and injection rate got worse closer to ③
  - From ③ to ① injection rate and current limit increased again



Collective Effects

Head-Tail Instability

- Dependent on ξ_v and α_c [1]

$$\tau_{\pm}^{-1} = \mp\frac{N r_0 W_0 c \xi_v \hat{z}}{2\pi\gamma C\eta},$$

W_0: Wake field $\hat{z}$: Ampl. of sync. osci.
η: slip factor $\eta = \alpha_c - 1/\gamma$

- ξ_v/η ⇒ for $\alpha_c < 0$ and $\xi_v < 0$ a bigger $|\xi_v|$ decreases growth rate

TMCI

- Multiple threshold approximations exist
- Version adapted from [2]:

$$N_{\mathrm{b,thr}}^{\mathrm{TMC}} \propto \frac{|\eta|}{|Z_y^{\mathrm{BB}}|}\left(1+\frac{\xi_v\omega_0}{\eta\omega_r}\right)$$

Z_y^{BB}: broadband impedance ω_0: revolution frequency
ω_r: resonant freq. of impedance

- ξ_v/η ⇒ for $\alpha_c < 0$ and $\xi_v < 0$ a bigger $|\xi_v|$ increases threshold

⇒ ξ_v could influence maximum bunch current

Micro-Bunching Instability

- Using equation from [3] the predicted threshold for $\alpha_c = +1.8\times10^{-3}$ is $I_{\mathrm{thr}} = 0.038$ mA
- THz emission has been measured above and below this threshold Measurements suggest a significantly higher threshold
- More systematic tests planned, above and below threshold
- Applicability of Inovesa [4] under investigation

Open Questions

- Are textbook equations still valid for negative α_c, any experience?
- What is limiting the total beam current in multi-bunch operation?
- What is limiting the bunch current in single-bunch operation and why is it higher than in multi-bunch operation?
- How can we identify which effect causes low beam current limits/high loss rate?
- Which diagnostics is necessary to identify these effects?
- Why does positive vertical chromaticity result in low injection limit, but beam can still be stored?
- Does operation with negative α_c influence the micro-bunching instability?

You have answers? Email me:

Summary and Outlook

- Optics with negative values of α_c have been successfully established at KARA
- Maximum beam and bunch current is limited
- Multiple factors with influence on this limit were identified (orbit deviations, $|\alpha_c|$, chromaticity)
- Head-Tail and Micro-Bunching instabilities will be investigated more closely
- Applicability of simulations using Inovesa is under investigation

[1] A. W. Chao *Physics of Collective Beam Instabilities in High Energy Accelerators*, Wiley, 1993, ISBN: 978-0-471-55184-3
[2] W. Herr, CAS - CERN Accelerator School: Advanced Accelerator Physics Course, 2014
[3] K. L. F. Bane, Y. Cai, and G. Stupakov, *Threshold studies of the microwave instability in electron storage rings*, PhysRevSTAB, 2010, DOI: 10.1103/ PhysRevSTAB.13.104402
[4] P. Schönfeldt et al., *Inovesa/Inovesa: Gamma Three* DOI: 10.5281/zenodo.2653504

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