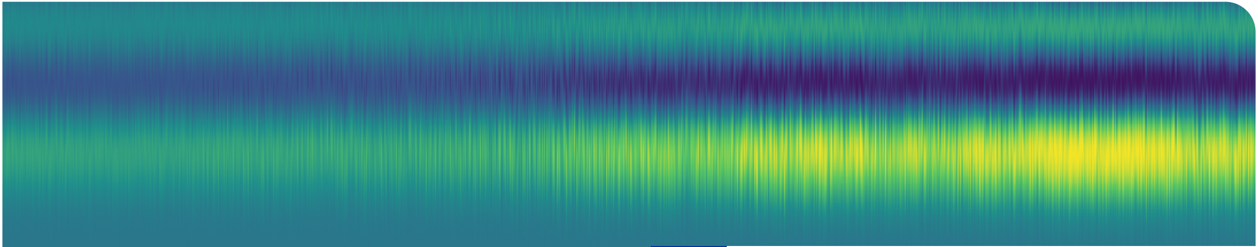
Experiences on Implementation and Collective Effects during Negative Momentum Compaction Operation at KARA

Patrick Schreiber, M. Brosi, B. Härer, A. Mochihashi, A. Papash, R. Ruprecht, M. Schuh, A.-S. Müller | I.FAST Workshop 2022



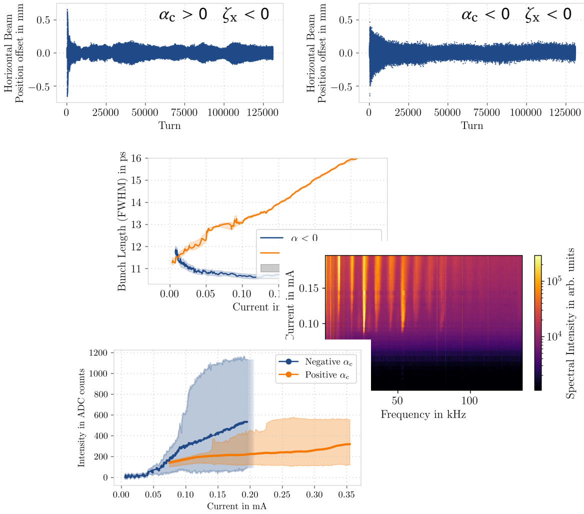
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

Motivation

- Synchrotron light sources are continuously under development
- Future machines on the verge of feasibility
- New schemes necessary
- Special magnet configurations considered
  - ⇒ Side effects are high nonlinearities and hard operation conditions
  - ⇒ Could be compensated using negative momentum compaction $\alpha_c < 0$
- KARA as accelerator test facility allows studies
  - Implementation of negative momentum compaction optics possible
  - Provides multitude of diagnostic tools

Contents

- Momentum Compaction Factor
- Implementation & Strategy
- Transverse Stability
- Bunch Length
- Longitudinal Instability



Momentum Compaction Factor

- Radius in magnetic field dependent on momentum

  $$\rho = \frac{p}{qB}$$

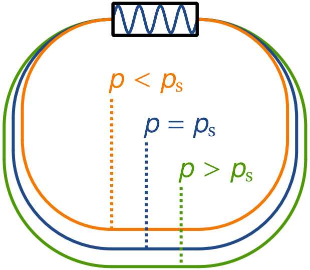
⇒ Path length dependent on momentum

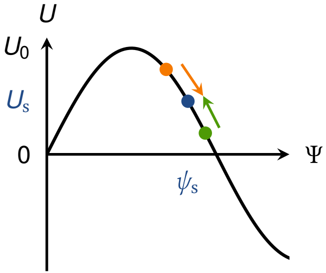
$$\alpha_c = \frac{\Delta L / L}{\Delta p / p} = \frac{1}{L} \oint \frac{D(s)}{\rho(s)} ds$$

⇒ Circulation time dependent on momentum

- ⇒ Higher momentum -> later
- ⇒ Lower momentum -> earlier

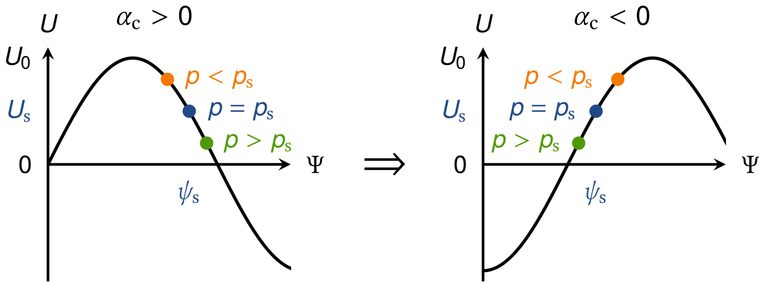
⇒ Phase focusing on falling slope of RF

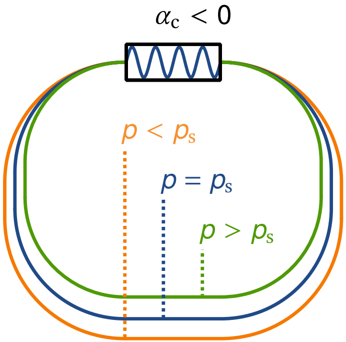




Negative Momentum Compaction Factor

- When $\alpha_c < 0$ higher energetic particles gain more energy
  - $\Rightarrow$ Phase defocusing
- Necessary to shift the acceleration phase
  - $\Rightarrow$ Regain phase focusing





KARA

- **KA**rlsruhe **R**esearch **A**ccelerator
- Electron storage ring of the KIT synchrotron light source

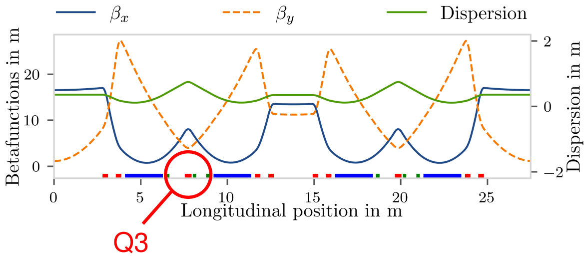
Location	KIT-Campus North
Circumference	110.4 m
Maximum Energy	2.5 GeV
Accelerating Frequency	500 MHz

Source: ibpt.kit.edu

Implementation

- KARA consists of DBA cells
- Dispersion controlled with Q3 (centre quadrupole)
- Increasing strength of Q3 increases dispersion span into also negative areas

User Optics $\alpha_c \approx 8 \times 10^{-3}$



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

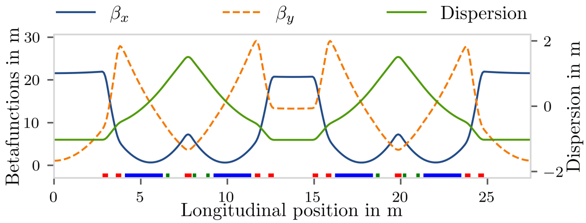
Schreiber et al., DOI: 10.23732/CYRCP-2020-009.297

Implementation

Karlsruhe Institute of Technology

- Increasing strength of Q3 increases dispersion span into also negative areas
- Existing low α_c 1.3 GeV mode
- First, low α_c injection optics established
- Changes necessary extrapolated for negative α_c
- OPA[1] simulations used for simulation of new optics

Low α_c Optics $\alpha_c \approx 1 \times 10^{-4}$



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

[1] Streun, OPA, https://ados.web.psi.ch/opa

Schreiber et al., DOI: 10.23732/CYRCP-2020-009.297

Implementation

- OPA[1] simulations used for simulation of new optics
- Settings for direct injection into negative α_c implemented

⇒ Only a few turns beam storage

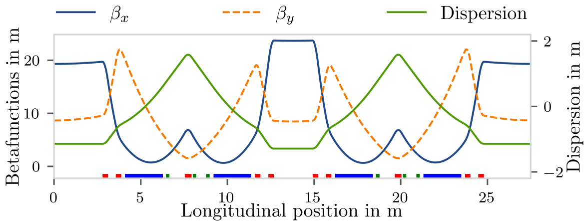
- Manual tuning of quadrupoles, kicker, septum and corrector magnets

⇒ Accumulation possible

- Unexpected working point

⇒ Tunes moved to usual injection tunes

Negative α_c Optics $\alpha_c \approx -2 \times 10^{-3}$



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

[1] Streun, OPA, https://ados.web.psi.ch/opa
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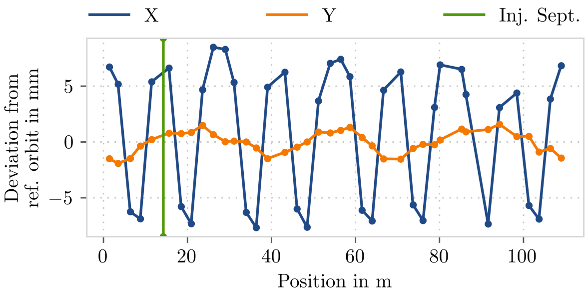
Implementation

Karlsruhe Institute of Technology

- Large orbit deviations necessary for injection
- Can be reduced after injection
- Due to higher beam stability sub-mm orbit deviations possible at 1.3 GeV



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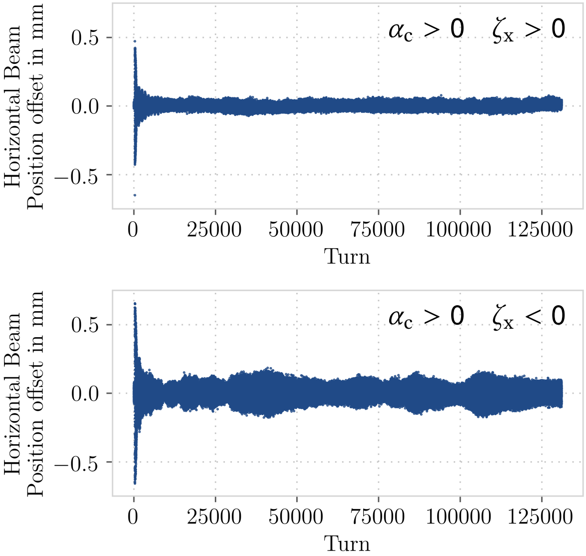
Status of Implementation

- ✓ Negative momentum compaction operation established
  - → Found correct magnet configuration
- ✓ Multiple energies available
- ✓ Momentum compaction factor variable
- ✗ Limited beam current (low compared to positive α_c)
- Now we can investigate differences in dynamics

Schreiber et al., DOI: 10.23732/CYRCP-2020-009.297

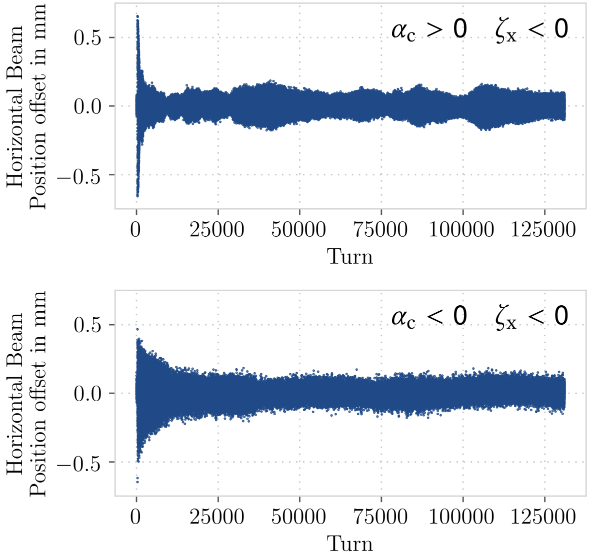
Transverse Stability

- Transverse position after kick at positive α_c and positive and negative chromaticities
- Strong residual oscillations at $\zeta_x < 0$
- Frequency of oscillations not corresponding to synchrotron frequency



Transverse Stability

- Transverse position after kick at positive and negative α_c and negative chromaticities
- Strong oscillations at positive α_c
- Some steady oscillations at negative α_c due to increased dispersion

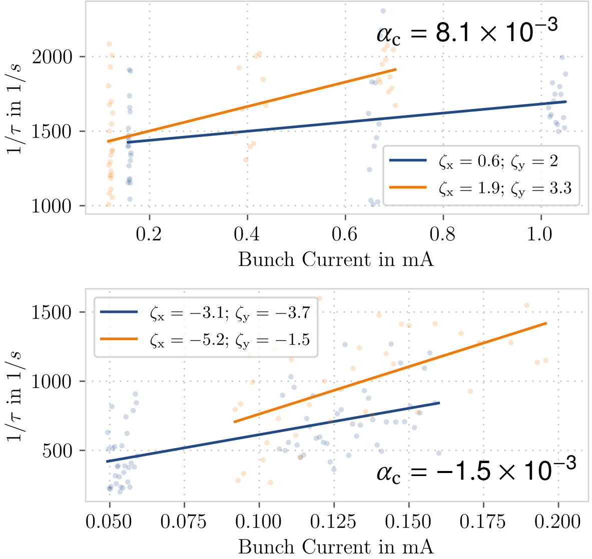


Transverse Stability

- Effects could be caused by head-tail effects
- Supported by current dependency of head-tail damping time

$$\frac{1}{\tau} \propto N_b \frac{\zeta}{\alpha_c}$$

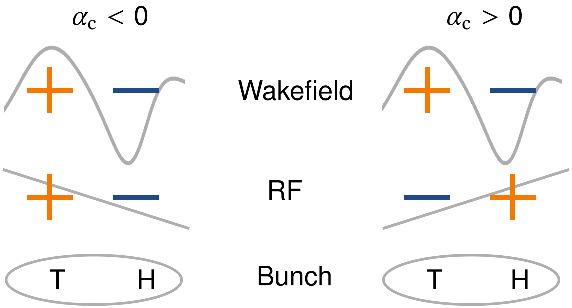
⇒ Negative α_c allows $\zeta < 0$ while avoiding head-tail instability



Bunch Length

- Determined by effective potential
- Effective potential: Sum between RF and wake potential $U_{\mathrm{eff}} = U_{\mathrm{RF}} + U_{\mathrm{Wake}}$
- For $\alpha_c < 0$ the RF potential is reversed

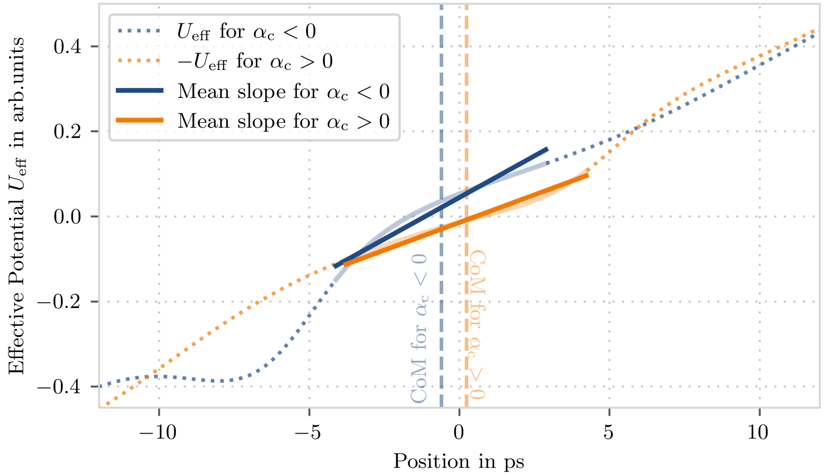
  $\Rightarrow$ Sum is different



Exemplary sketch with CSR Parallel-Plates Wake

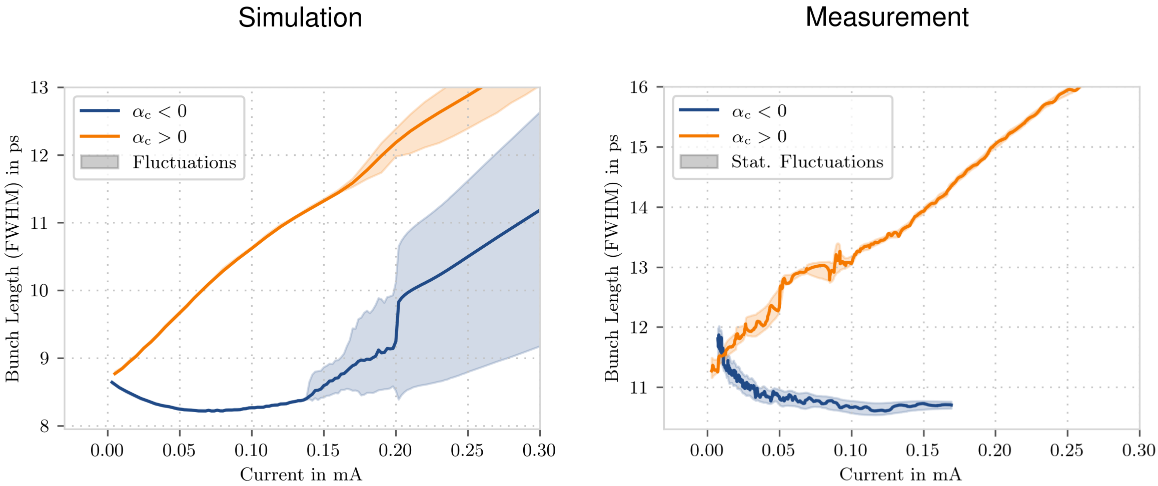
Schreiber et al., DOI: 10.18429/JACoW-IPAC2021-WEPAB083

Bunch Length - Effective Potential



Schreiber et al., DOI: 10.18429/JACoW-IPAC2021-WEPAB083

Bunch Length



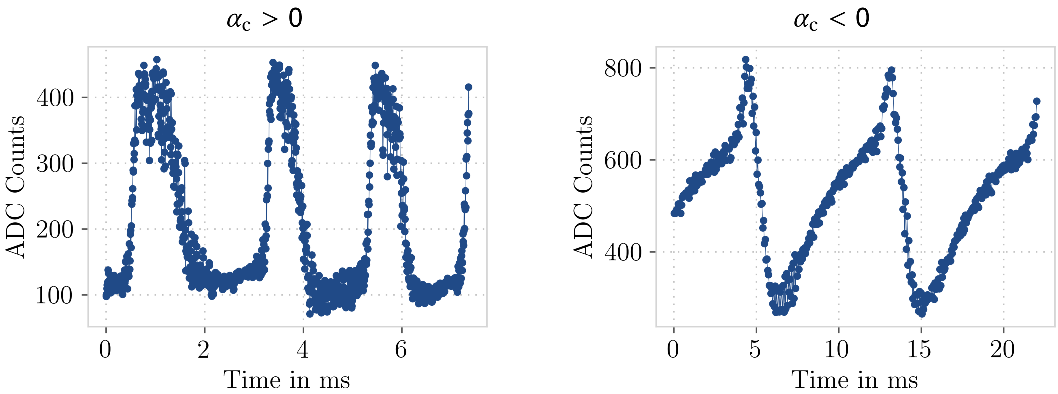
Schreiber et al., DOI: 10.18429/JACoW-IPAC2021-WEPAB083

Longitudinal Instability

- Longitudinal instability observed at low $|\alpha_c|$
- Rises when bunch radiates coherently (CSR) (for short bunches)
- Due to interaction of a bunch with its own emitted radiation
- Intensely studied for positive α_c
- Bursts of coherent THz radiation that could be used by some experiments
- Detrimental to other experiments (no stable beam size etc)

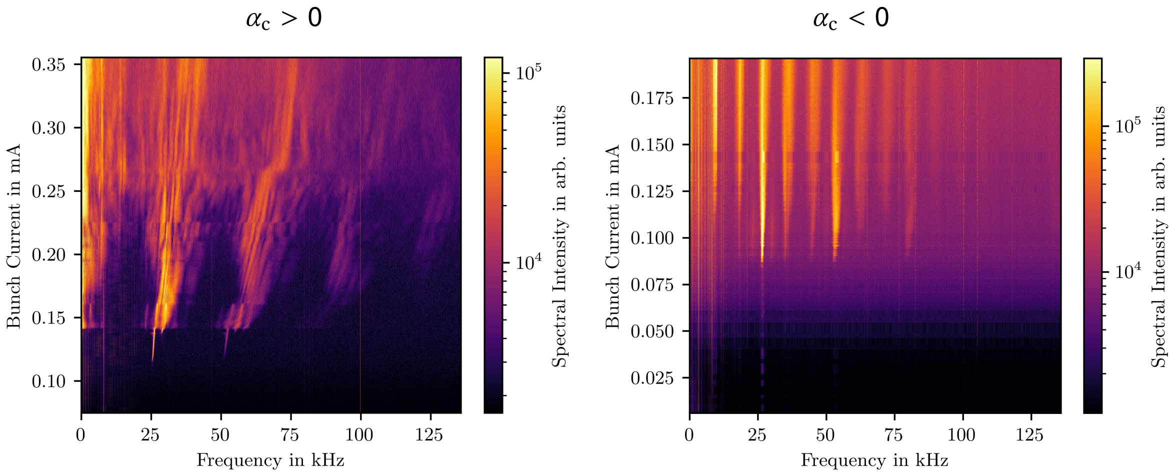
Longitudinal Instability

- Intensity of emitted CSR varies



- Temporal properties of intensity variation differ between positive α_c and negative α_c

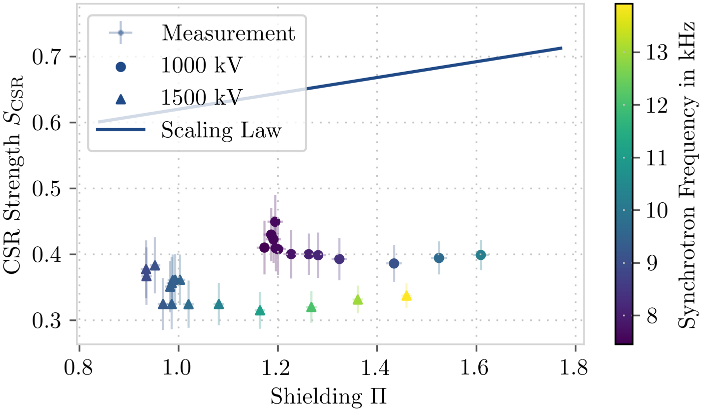
Longitudinal Instability



Longitudinal Instability

Threshold Current

- Scaling law[2] for positive α_c fits measurements[3]
- Significantly lower threshold at negative α_c
- Additional dependency on acceleration voltage



$$\Pi = \sigma_{z,0} \cdot \frac{R^{1/2}}{h^{3/2}} \qquad S_{\mathrm{CSR}} = I_b \cdot \frac{cR^{1/3}}{2\pi\gamma f_s \sigma_{\delta,0} I_A \sigma_{z,0}^{4/3}}$$

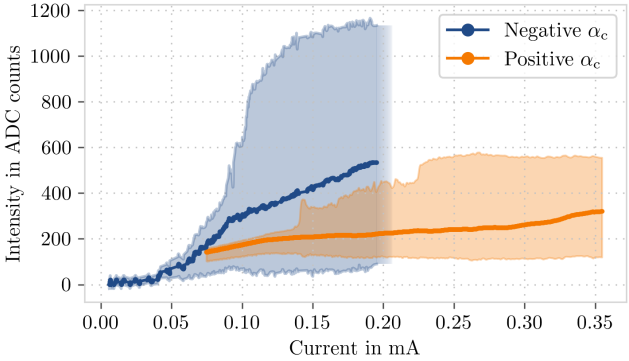
[2]Bane et al., DOI: 10.1103/PhysRevSTAB.13.104402

[3]Brosi et al., DOI: 10.1103/PhysRevAccelBeams.22.020701

Longitudinal Instability

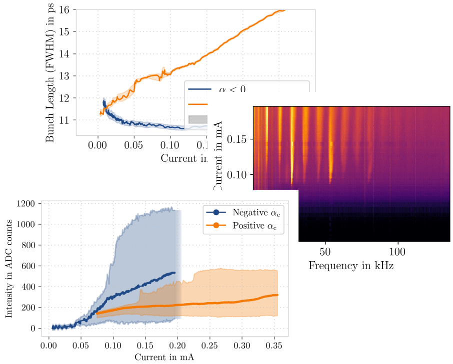
CSR Intensity

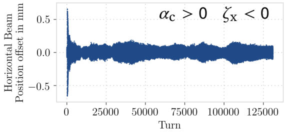
- Intensity measured with identical setup at positive and negative α_c
- Higher peak intensity at negative α_c
- Higher mean intensity at negative α_c
  - ⇒ Corresponds to the observed shorter bunch length
- Stabilisation could result in high intensity yield

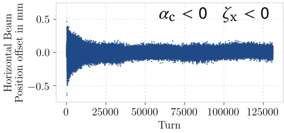


Summary

- Negative momentum compaction operation on shifted phase
- Successful implementation at KARA
- Transversal stability for $\zeta < 0$ and $\alpha_c < 0$
- Bunch shortening for $\alpha_c < 0$ at low currents
- Shorter bunches in general for $\alpha_c < 0$
- Longitudinal instability differs for $\alpha_c > 0$ and $\alpha_c < 0$
- Lower instability threshold for $\alpha_c < 0$
- Higher CSR intensity for $\alpha_c < 0$







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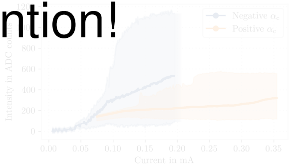
Thank you for your attention!



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