DETERMINING THE INFLUENCE OF TRANSVERSAL BEAM EXCITATION ON BEAM SIZE AND DYNAMICS AT KARA

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Abstract

Significant beam dynamics parameters, such as energy spread or transversal beam size, can be calculated from the transversal bunch profile. At the Karlsruhe Research Accelerator (KARA), located at the Karlsruhe Institute of Technology (KIT), the beam size in the storage ring is being investigated using the KArlsruhe Linear arraY detector for MHz rePetition rate SpectrOscopy (KALYPSO), a line array that examines the synchrotron radiation emitted at a five-degree port of a dipole magnet. Trench-Isolated Low-Gain Avalanche Diode (TI-LGAD) technology provides superior sensitivity compared to conventional silicon detectors, thereby facilitating the study of low-charge bunches. As the KALYPSO system can be triggered at several megahertz, turn-by-turn analysis can be performed at KARA, which has a revolution frequency of 2.7 MHz. In addition to the study of the energy spread, the analysis of beam size and position modulations can be performed. These can either occur naturally or be induced by a white noise signal on a strip line. In this contribution, the influence of transversal beam excitation on beam size and time-resolved dynamics at KARA is investigated.

INTRODUCTION

To investigate the influence of beam excitation on the machine dynamics of the research accelerator, the vertical beam size is monitored. However, direct imaging of the synchrotron radiation is insufficient, since the measurement is limited by the diffraction limit due to the crotch absorber. Therefore, an interferometric setup is used at the Synchrotron-Light-Monitor-2 (SLM-2) station at KARA to overcome this limitation. In conventional interferometric setups, the interference pattern is typically recorded using an industrial CMOS camera. Such a setup was implemented by Michael Holz [1, 2]. However, the temporal resolution was limited to the millisecond range by the integration time of the CMOS cameras, preventing the observation of fast beam dynamics during excitation. To enable a higher temporal resolution of up to turn-by-turn measurements, the fast line-array detector KALYPSO [3] is used instead. The setup was recently significantly improved by replacing a damaged mirror and a deteriorated vacuum window. This substantially increased the detectable light intensity and enabled single-bunch, single-turn measurements. In addition, a new remotely adjustable mounting system enables rapid alignment in all three spatial dimensions, allowing optimized focusing onto the detector. The use of a macro lens further broadened the interference pattern on the detector, increasing the number of usable pixels and improving the quality of the beam size reconstruction.

BEAM SIZE MEASUREMENT

The intensity observed in a double slit interferometry experiment can be described as a sinc^2 envelope [4].

$$I(x) = (I_1 + I_2)\ \mathrm{sinc}^2\left(\frac{\pi a}{\lambda f}x\right)\left[1 + V\cos\left(\frac{2\pi d}{\lambda f}x + \psi\right)\right]. \tag{1}$$

Here I_1 and I_2 are the intensities of the synchrotron radiation at the slits, a is the single slit width, d the slit distance, x the position at the detector, f the distance between the lens and the detector screen, ψ is the phase difference between the light arriving from the two slits, λ is the wavelength and V denotes the visibility. The relationship between the complex coherence factor γ and visibility V is given by:

$$V = \frac{I_{\mathrm{max}} - I_{\mathrm{min}}}{I_{\mathrm{max}} + I_{\mathrm{min}}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}|\gamma|. \tag{2}$$

In this case I_{max} and I_{min} denote the local maximum and minimum intensities of the interference pattern, respectively. With evenly lit slits, V and $|\gamma|$ are identical.
According to the van Cittert–Zernike theorem, the complex coherence factor γ is given by the Fourier transform of the spatial light-source distribution:

$$\gamma = \int f(x)\ \exp\left(-i\,\frac{2\pi d}{\lambda L}x\right)\,\mathrm{d}x. \tag{3}$$

where L denotes the distance between the source point and the double slit [5]. Assuming a Gaussian beam profile results in:

$$V = |\gamma| = \exp\left[-2\left(\frac{\pi w d}{\lambda L}\right)^2\right]. \tag{4}$$

Solving for the beam size w leads to:

$$w = \frac{\lambda L}{\pi d}\sqrt{\frac{1}{2}\ln\left(\frac{1}{V}\right)}. \tag{5}$$

The visibility is reconstructed by fitting

$$y(x) = \alpha_0 \cdot \mathrm{sinc}^2((x - b_1)\,\alpha_1)\,\left[1 + \mathrm{V}\cos((x + b_2)\,\alpha_2.)\right]. \tag{6}$$

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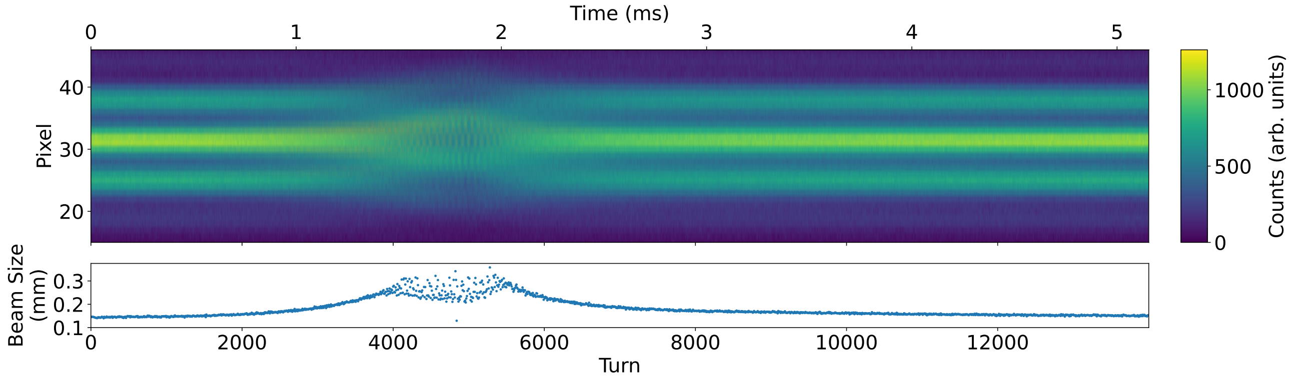

Figure 1: Turn-resolved KALYPSO interference pattern during a grow-damp measurement with shorter excitation time. The lower plot shows the reconstructed beam size obtained from an eight turn average.

to the measured intensity profile. Here, α_0 corresponds to the overall intensity scaling factor $(I_1 + I_2)$. The parameter α_1 accounts for the scaling factor $\frac{\pi a}{\lambda f}$ of the sinc envelope, while α_2 represents the interference scaling term $\frac{2\pi d}{\lambda f}$. The parameters b_1 and b_2 describe offsets caused by detector alignment and b_2 also the phase shifts, compensating for the fact that the center of the interference pattern is generally not located at the pixel with index zero.

EXPERIMENTAL SETUP

The synchrotron radiation was extracted through the five-degree port of a bending magnet and passed through a crotch absorber, resulting in a diffraction limit of 174 µm. Since the equilibrium vertical beam size of the unexcited beam is 143 µm, an interferometric setup was installed. The setup used a double slit with a slit separation of $d = 2.4$ mm positioned at $L = 3.35$ m from the source point. An optical bandpass filter with center wavelength $\lambda = 520$ nm and a 200 mm focusing lens were used. In addition, a macro extension tube was used to maximize the usable width of the line-array detector. The detector provides 64 pixels and is capable of recording several million turns in a single measurement at megahertz frame rates, enabling long-duration measurements for fitting the interference pattern and reconstructing the visibility. The measurements were performed at KARA using low-beta optics at a beam energy of 2.5 GeV [6]. The machine was operated in single-bunch mode at a beam current of 4.5 mA. In addition, reference beam-size measurements using a slower diagnostic system were performed to enable future comparison with the fast KALYPSO measurements and calibration of the reconstructed values to absolute beam-size units [7]. The beam was excited using vertical grow-damp measurements via a bunch-by-bunch (BBB) feedback system [8]. Excitation was applied via a strip line connected to the BBB system. During the excitation interval, the signs of the vertical feedback coefficients were inverted, causing the feedback system to drive the transverse oscillation instead of damping it [9].

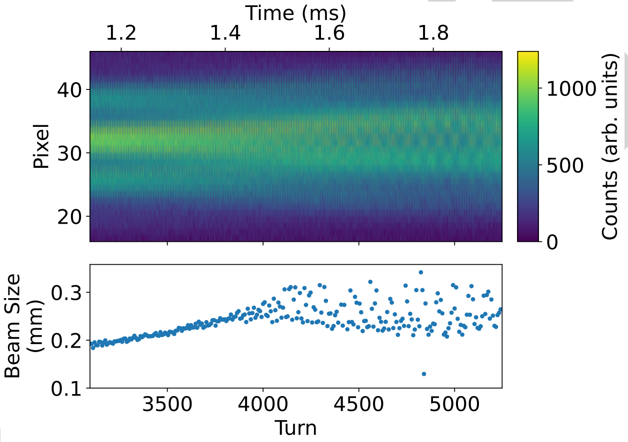

Figure 2: Turn-resolved KALYPSO interference pattern during excitation. The lower plot shows the reconstructed beam size obtained from an eight turn average.

EXPERIMENTAL RESULTS

Figure 1 shows the evolution of the interference pattern during the grow-damp measurement. During excitation, the outer interference peaks broaden, while the central peak appears to split, as shown in Fig. 2. This behavior may be caused by the beam moving away from the optical focus position, thereby changing the observed orbit projection. In addition, a modulation of the interference pattern can be observed, which may indicate oscillatory beam motion. The resulting motion reduces the fringe contrast and therefore deteriorates the visibility reconstruction. Starting at approximately turn 4100, the visibility could no longer be reconstructed reliably using the fit function. After approximately[1] 2 ms, the excitation is switched off and the feedback damping becomes dominant. The number of averaged turns has a significant influence on the stability of the visibility reconstruction. Averaging over four turns was found to provide stable and reproducible reconstruction results. This reduces the mean relative statistical uncertainty from $\sigma(V)/V = 0.043$ for single-turn evaluation to $\sigma(V)/V = 0.022$ for four-turn averaging. Single-turn evaluation leads to distorted beam-

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[1] In this dataset the start of the grow-damp measurement and the KALYPSO readout were not synchronized.

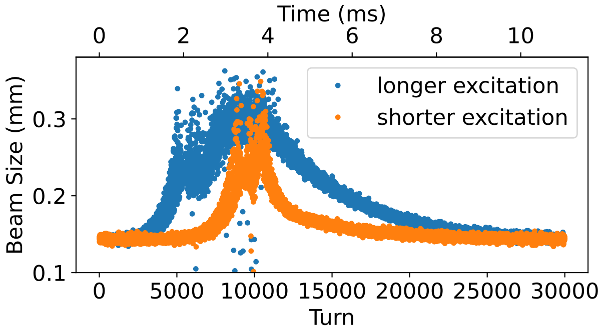

Figure 3: Comparison of the damping behavior for shorter and longer excitation time using the reconstructed beam size from a four-turn average. The shorter excitation measurement was offset in time such that the onset of the damping phase overlaps with that of the longer excitation.

size dynamics, where the excitation appears delayed and significantly reduced in amplitude. Four-turn averaging therefore provides a suitable compromise between statistical precision and temporal resolution, while averaging over more turns does not significantly improve the reconstruction quality.

Although the beam size growth rate is comparable for both excitation durations, the damping time after the longer excitation is significantly increased, as shown in Fig. 3. The recovery time increases from approximately 4 ms to 6 ms. The observed damping originates from the bunch-by-bunch feedback system rather than from the natural radiation damping of the storage ring. This behavior suggests a nonlinear response of the beam dynamics under prolonged excitation and requires further investigation.

The relative systematic error of this method can be calculated using the following equation:

$$\frac{\sigma(w)}{w} = \sqrt{\left(\frac{\sigma(\lambda)}{\lambda}\right)^2 + \left(\frac{\sigma(l)}{l}\right)^2 + \left(\frac{\sigma(d)}{d}\right)^2} = 0.0189 \tag{7}$$

The systematic uncertainty of the reconstruction is therefore comparable to the statistical uncertainty, indicating that further improvements require optimization of both contributions.

LIMITATIONS

The main limitation of the current setup is a five-degree misalignment between the KALYPSO detector axis and the interferometric axis caused by the detector mounting. This angular offset degrades the interference pattern quality and leads to uneven illumination of the detector pixels. Taking the geometric projection of the slit separation into account would increase the relative systematic uncertainty from 0.018 to 0.048. This will be adressed in the next shutdown period. In addition, uniform slit illumination is not guaranteed due to polarization effects. These effects may lead to asymmetric intensities of the secondary interference peaks, thereby complicating the visibility reconstruction.

Another important limitation is the assumption of a Gaussian beam profile during excitation. The visibility reconstruction relies on a Gaussian transverse beam distribution, which is generally expected due to damping effects in equilibrium operation. However, under strong excitation and large amplitude oscillations, deviations from a Gaussian beam profile are expected and could influence the reconstruction accuracy.

CONCLUSION AND OUTLOOK

The recent improvements enabled single-bunch, single-turn beam-size measurements with KALYPSO. Using the upgraded setup, proof-of-concept measurements of time-resolved transverse beam dynamics during grow-damp excitation were successfully performed, demonstrating the suitability of the system for studies of fast transverse beam dynamics in storage rings. The achieved performance enables investigations of different excitation schemes, short-timescale beam instabilities, and injection optimization studies at KARA. The influence of non-Gaussian beam profiles and polarization effects on the visibility reconstruction will be determined and the results compared with different methods.

ACKNOWLEDGEMENT

S. B. would like to thank the IBPT for providing the opportunity to conduct this master's thesis at a large-scale research facility, as well as the team for inspiring discussions.
M. N. acknowledges the support by the Doctoral School ”Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology” and by the German Federal Ministry of Research, Technology and Space (BMFTR) ErUM-Data project FASTER (05D25VK5).

REFERENCES

[1] M. Holz, “Determination of the transversal electron beam size at the ANKA storage ring”, MA thesis, Karlsruhe University of Applied Sciences, Karlsruhe, Germany, 2014.

[2] B. Kehrer *et al.*, “Visible light diagnostics at the ANKA storage ring”, in *Proc. IPAC'15*, May 2015. `doi:10.18429/JACoW-IPAC2015-MOPHA037`

[3] M. M. Patil *et al.*, “KALYPSO LGAD: a MHz repetition rate line camera based on trench-isolated low gain avalanche detector”, *J. Instrum.*, vol. 20, no. 01, p. C01006, 2025. `doi:10.1088/1748-0221/20/01/C01006`

[4] M. Koopmans, P. Goslawski, J. G. Hwang, M. Ries, M. Ruprecht, and A. Schälicke, “Status of a double slit interferometer for transverse beam size measurements at BESSY II”, in *Proc. IPAC'17*, pp. 149–152, May 2017. `doi:10.18429/JACoW-IPAC2017-MOPAB032`

[5] T. Mitsuhashi, “Beam profile and size measurement by SR interferometers”, in in *Beam Measurement*, World Scientific, 1999, pp. 399–427, `doi:10.1142/9789812818003_0018`,

[6] A. I. Papash *et al.*, “Different operation regimes at the KIT storage ring KARA (Karlsruhe research accelerator)”, in *Proc. IPAC’21*, pp. 163–166, Aug. 2021. doi:10.18429/JACoW-IPAC2021-MOPAB036

[7] A.-S. Müller, I. Birkel, E. Hüttel, K. B. Scheidt, and P. Wesolowski, “Precise measurements of the vertical beam size in the ANKA storage ring with an in-air x-ray detector”, 2006, https://cds.cern.ch/record/1078623,

[8] E. Blomley, A.-S. Müller, and M. Schedler, “Beam studies with a new longitudinal feedback system at the ANKA storage ring”, in *Proc. IPAC’16*, pp. 2658–2660, Jun. 2016. doi:10.18429/JACoW-IPAC2016-WEPOR001

[9] M. Noll *et al.*, “Time-resolved measurements of transverse beam excitation in an electron storage ring”, in *Proc. IBIC’25*, pp. 578–580, Sep. 2025. doi:10.18429/JACoW-IBIC2025-TUPMO43