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TIME-RESOLVED MEASUREMENTS OF TRANSVERSE BEAM EXCITATION IN AN ELECTRON STORAGE RING

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Abstract

In the Karlsruhe Research Accelerator (KARA), electron beams of up to 200 mA are stored with an energy of 2.5 GeV, while injection is performed at 500 MeV. At the injection energy, the beam life time and the injection efficiency depend largely on Touschek scattering. As a counter-measure, the beam size can be enlarged transversally by an exciting modulation, e.g. applied via a strip-line. In an existing setup, the vertical beam size is measured with a double-slit interferometer. Here, we examine different detectors for this setup. A different choice from the conventional CMOS camera is the ultra-fast line camera KALYPSO, which can not only measure on a turn-by-turn basis, but can also stream frames to a computer and thus can capture larger time frames than, for example, a fast-gated camera.

INTRODUCTION

To improve the injection efficiency and life-time of the electron beam in the KARA storage ring, one area of research is artificially blowing up the beam size by transversal modulation with a strip-line. Since the vertical beam size is smaller than the diffraction limit, techniques such as double-slit interferometry are employed to measure the vertical beam size. Conventionally, the interferogram is digitized with an industrial CMOS camera [1]. Its integration time in the order of microseconds to milliseconds prevents the system from discriminating fast modulations of merely the beam position from the desired beam size increase.

BEAM SIZE MEASUREMENT

In a double-slit interferometer, the interference pattern at the detector has a sinc^2 shape [2] (see Fig. 1) with a global intensity maximum $I_{\max}$ and the first intensity minimum $I_{\min}$ adjacent to the peak. The visibility, or contrast ratio, V is related to the intensities I_1 and I_2 at the slits by the magnitude of the complex coherence γ and is given by

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} |\gamma| . \tag{1}$$

Hence, without an intensity imbalance at the slits, V and $|\gamma|$ are identical.

With the distance L from source to the double-slit, the slit separation d and the source wavelength λ, the van Cittert-Zernike theorem states the complex coherence is given by the Fourier transform of the light source's spatial profile $f(x)$ as

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

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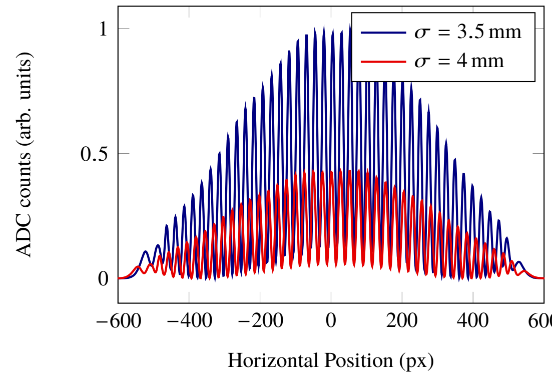

Figure 1: Ray optics simulation showing the interference pattern for a Gaussian beam at the detector plane. The inverse relation between beam size σ and visibility V is apparent.

The profile $f(x)$ can be assumed as a Gaussian beam [3] with width σ. The visibility then becomes

$$V = |\gamma| = \exp\left[-2\left(\frac{\pi\sigma d}{\lambda L}\right)^2\right], \tag{3}$$

and can be rearranged to

$$\sigma = \frac{\lambda L}{\pi d}\sqrt{0.5 \ln \frac{1}{V}}. \tag{4}$$

By measuring the intensities $I_{\max}$ and $I_{\min}$, the beam size σ can be computed [4, 5].

The conventional CMOS camera setup has a limited time resolution in the order of microseconds to milliseconds set by the integration time and the lack of hardware trigger. A fast-gated camera can be used, but commercial devices are limited to one acquisition every few hundred turns [1,6]. The frame-buffer of commercial cameras is also often limited. Furthermore, to measure the visibility V of a double-slit setup in one orientation, the second dimension of conventional and fast-gated cameras is not necessary. To measure coupling between the x and the y planes, the CMOS setup will still be used.

Therefore, the fast line camera KALYPSO is employed to get turn-by-turn profiles of the interferogram and thus turn-resolved beam sizes. With its streaming mode, the beam size evolution can be measured for several seconds.

EXPERIMENTAL SETUP

The experimental setup is located approximately 4 m after a dipole magnet of the KARA storage ring. The synchrotron radiation is guided upwards with an aluminum-coated copper mirror and leaves the vacuum through a sapphire window. A

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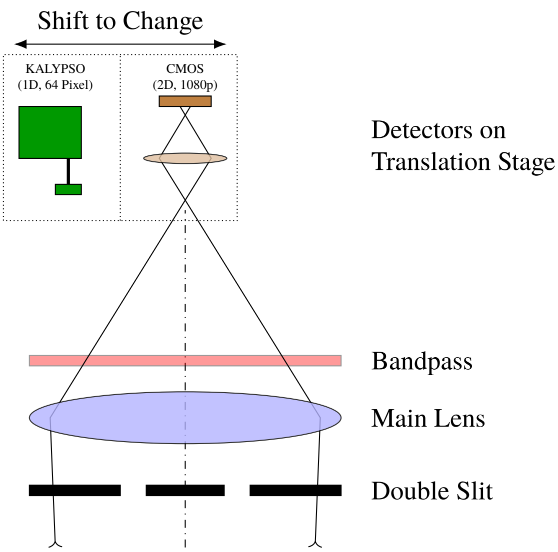

Figure 2: Optical experimental setup near a synchrotron radiation port at the KARA storage ring.

pneumatically movable double-slit is used for interference-based measurements in the vertical plane. A plano-convex main lens with 300 mm focal length is then used to create an intermediate image. An optical bandpass filter is used to remedy chromatic aberrations of the lenses and to avoid smearing the interference image.

For two-dimensional analysis of the interference pattern, a 1920 by 1080 pixel grayscale CMOS camera with a macro lens is used. Integration times in the order of milliseconds yield averages over several thousand turns of the storage ring. In order to perform turn-by-turn analysis, KALYPSO is used. Its TI-LGAD (Trench-Isolated Low-Gain Avalanche Diode) sensor features 64 pixels and can be read out every revolution [7].

Both detector systems are mounted next to each other on the movable platform of a dimensional translation stage. It is used to remotely align the detectors and also to switch between them, see Fig. 2.

KALYPSO CHARACTERIZATION

The KIT in-house developed KALYPSO uses a novel TI-LGAD detector, which spectral properties are not entirely known. For comparison with the existing CMOS camera setup, its spectral properties are examined and the modulation scheme is tested by imaging the synchrotron radiation beam *without* the double-slit setup.

The spectral responsivity of the TI-LGAD sensor is determined with a tungsten calibration light source (Thorlabs SLS201), a fly-eye spatial homogenizer and a set of 10 nm wide optical bandpass filters. For each gain setting, the mean over all pixels is calculated. This is repeated 1000 times and the average is drawn versus the filters' center wavelengths in Fig. 3. The spectral response closely resembles the characteristic of a silicon photodetector, such as the CMOS camera used in this experiment. Since the highest signal is achieved for wavelengths around 800 nm, the optical bandpass used

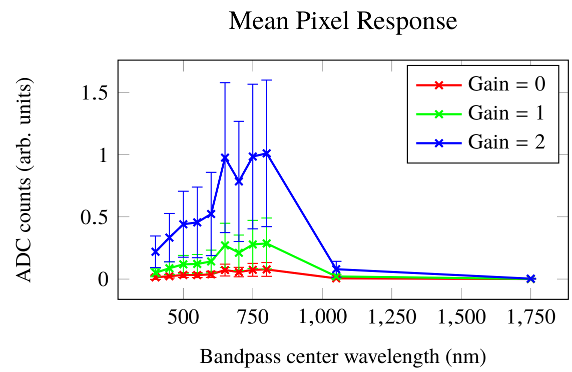

Figure 3: Spectral response of the KALYPSO TI-LGAD for different gain settings G, measured with a bias voltage of $V_{\text{bias}} = -42\,\text{V}$.

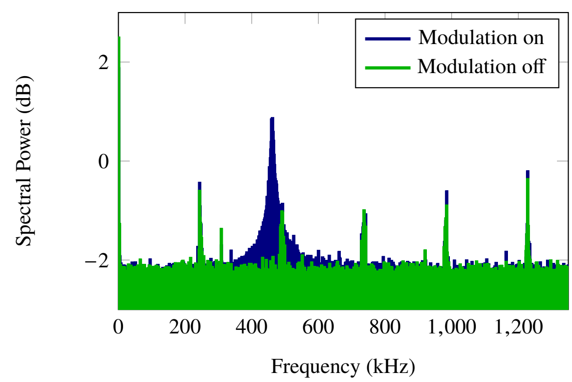

Figure 4: Periodogram of one KALYPSO pixel for 10 000 revolutions.

should also be in that regime. However the current setup uses a green bandpass filter, which was likely chosen for a color CMOS camera using a Bayer color filter (two green, one red, and one blue pixel).

For the modulation test, a 250 MHz stripline is driven with a 460 kHz, 11 W sine wave. KALYPSO is aligned such that two pixels in the center are illuminated. In Fig. 4, the periodogram of a single pixel signal is then computed with and without the modulation switched on.

FIRST RESULTS

For the prototype setup, the two detectors are evaluated separately at the synchrotron light monitor near the KARA storage ring and on the IR2 beam line.

The (re)assembled setup with double-slit and CMOS camera performed as expected and resulted in interferograms shown in Fig. 5. However, with the current setup, it was not possible to measure any interferogram with KALYPSO.

FUTURE UPGRADES

In the current experimental setup, the signal-to-noise ratio (SNR) achieved at KALYPSO is too low for any interference pattern measurements. Therefore, the following improvements will be implemented.

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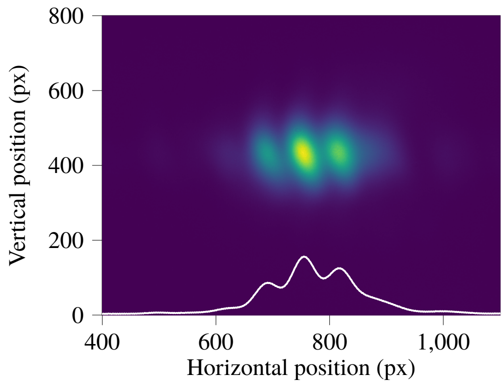

Figure 5: Measured interferogram at the IR2 beamline of KARA. The horizontal profile is shown in white.

The green optical bandpass filter will be switched for a NIR (near-infrared) filter, as the spectral response around 800 nm is highest for both sensors in that regime.

The in-vacuum mirror and optical window are over ten years old and both show signs of radiation damage, see Fig. 6. Without removing the components from the storage ring assembly, the damage is likely due to oxide formation and carbon adsorption on the sapphire window. Both the mirror and the window will be be replaced. The old components will be examined using a spectrometer to determine their detrimental effects on synchrotron radiation transport.

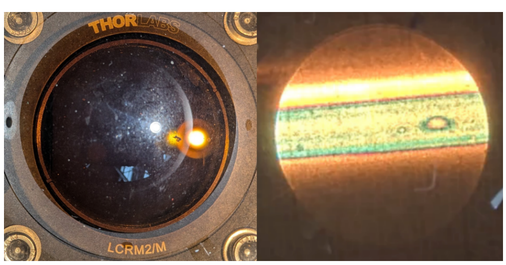

Figure 6: Radiation-damaged optical window (left) and radiation-damaged in-vacuum mirror (with synchrotron radiation present).

The plano-convex main lens ($f = 300$ mm) suffers from spherical aberrations and Fresnel reflections on the surface, and will be switched to an antireflection-coated achromatic lens.

To increase the optical power at the detectors, different double-slit geometries or totally different mask geometries are also studied. One example is the inverted double-slit, where the slits are replaced by light blocking wires, and the rest of the mask is transparent. The first result in Fig. 7 is produced by two 1 mm hex keys placed about 5 mm apart. A more precisely manufactured second version is needed to make conclusions about beneficial effects.

OUTLOOK

After replacing damaged components and upgrading the experimental setup, both detectors shall be operational and an in-depth measurement campaign will be carried out to study the effects of stripline modulation on the beam size

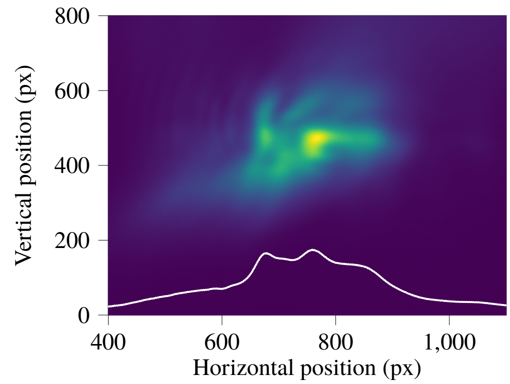

Figure 7: Interference pattern generated from the same setup as in Fig. 5 but with an inverted double-slit mask. The horizontal profile is shown in white.

for different operating modes and with different modulation sources.

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