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STATUS AND UPGRADE OF THE VISIBLE LIGHT DIAGNOSTICS PORT FOR ENERGY SPREAD MEASUREMENTS AT KARA

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Abstract

At the visible light diagnostic (VLD) port at the Karlsruhe Research Accelerator (KARA), it is possible to study the energy spread of electron bunches by measuring the horizontal bunch profile of the incoherent synchrotron radiation. KALYPSO, an MHz-rate line-array detector, has been employed to measure the bunch profile. Recently, the KALYPSO system has been upgraded to a version of a microstrip sensor based on TI-LGAD. The measurements have shown that the system's overall sensitivity was significant - at least by a factor of 20 improved, enabling the study of bunch profiles at low bunch charges. This contribution will present an overview of the upgraded setup and preliminary results.

INTRODUCTION

Several operation modes are implemented at the Karlsruhe Research Accelerator (KARA) for generating intense synchrotron radiation. One of which is the short-bunch, low-α_c mode. In this mode of operation, the electron bunches are squeezed to a bunch length of a few ps. Due to this, a self-interaction with the emitted radiation occurs, resulting in short bursts of THz radiation. The formation of microstructures on the longitudinal density profile of the electron bunch characterizes this self-interaction behaviour [1–3]. This phenomenon is called the *microbunching instability*. To study this instability at KARA, several diagnostic methods have been implemented, including streak camera, electro-optical spectral decoding (EOSD) for longitudinal bunch profile measurements [4, 5], THz detectors (e.g. Schottky diodes) for measuring the THz intensity [6] and measuring the transverse bunch profile of the electron bunch for energy spread studies [7].

The transverse bunch profile has been acquired by measuring the incoherent synchrotron radiation (ISR) emitted at a 5° port of a dipole-bending magnet at a dispersive section of the storage ring. As the radiation is emitted in a dispersive section, the horizontal bunch size is coupled with the relative energy spread of the electron bunch given by the Eq. (1). Measuring the ISR provides an opportunity to study the effect of the microbunching instability on the transverse bunch profile and hence the energy spread [8]. The horizontal profile is measured by a line array camera called KALYPSO. The following section describes the optical setup used to study the horizontal bunch profile.

$$\sigma_\delta = \frac{1}{D_x}\sqrt{\sigma_x^2 - \beta_x \epsilon_x}. \qquad (1)$$

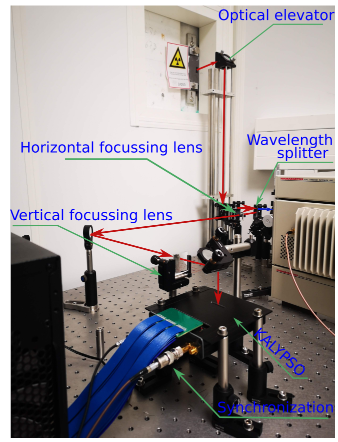

Figure 1: Optical setup for measuring the transverse bunch profile. Taken from Ref. [9].

The σ_δ is the relative energy spread, σ_x is the horizontal bunch size, D_x is the horizontal dispersion, ϵ_x is the horizontal emittance and β_x is the horizontal beta function of the electron bunch.

EXPERIMENTAL SETUP

The experimental setup used for studying the transverse bunch profile is shown in Fig. 1. A beam elevator aligns the ISR beam to the optical axis on the optical table. The beam is split using a wavelength splitter and the spectral range from 400 nm to 550 nm is focused onto a line array detector using cylindrical lenses. The previous measurement setup had a fast-gated camera (FGC) instead of KALYPSO [10]. Although the FGC had good sensitivity, it could resolve a bunch with a framerate of 450 kHz in a single-bunch operation mode, the sensor size only allowed for the acquisition of 80 bunch profiles. To overcome this limitation, KALYPSO has replaced the FGC. KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy) is an ultra-fast line array camera capable of framerates up to 12 MHz developed at KIT. KALYPSO uses microstrip sensors made of different semiconductor materials enabling it to measure radiation from 350 nm (near-UV) up to 5000 nm (mid-IR). Since the emitted ISR is in the visible region of the spectrum, a Si-based microstrip sensor is mounted on KALYPSO [11, 12]. This KALYPSO system has already been used in several measurement campaigns. However, through all these measurements, it could not measure at low light conditions, i.e. low bunch currents. The system's sensitivity had been too low to measure the ISR at bunch currents below 0.71 mA (260 pC). This is a significant disadvantage since

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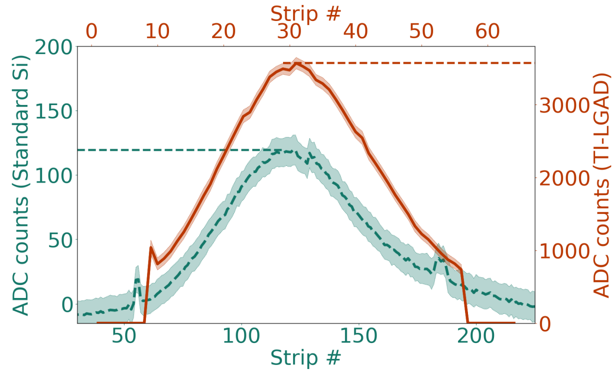

Figure 2: Comparison between the transverse profile measured using standard Si microstrip versus TI-LGAD based KALYPSO at the same bunch current of 1 mA.

the onset of microbunching has been recorded at a threshold of around 0.2 mA (73 pC) [1]. Hence, it has not been possible to study this region of interest with the previous detector systems.

Recently, the detector within the KALYPSO system has been upgraded by using a TI-LGAD (Trench Isolated Low Gain Avalanche Detector), designed and fabricated at FBK, Trento [13]. LGADs are similar to the conventional PN-junction microstrip, except they feature one additional dopant layer introduced by diffusion under the standard implant - called the gain layer. This results in a highly localized electric field region around 300 kV cm^{-1}. When biased, this results in a controlled avalanche mechanism in the sensor, thus accounting for its internal gain of a few tens (typically 10-30). Moreover, LGADs are thin sensors with a thickness of around 45 µm, hence having a short rise time of the order of around 50 ps when combined with suitable readout electronics. The trench isolation technique used in the fabrication of this sensor allows it to have a strip pitch down to 50 µm. Hence, due to its internal gain characteristic, this sensor is a wholesome combination of timing resolution, spatial resolution, and sensitivity. The measurements performed by this detector have shown an immense improvement in sensitivity, with the system having a dynamic range of 63.23 dB and SNR (signal-to-noise ratio) by a factor of at least 20. Combing this sensor with the KALYPSO front-end chip makes an ultra-fast detector with a high dynamic range. Figure 2 shows a comparison of the bunch profile of the ISR at a bunch current of 1 mA acquired with two KALYPSO families at a framerate of 2.7 MHz.

KALYPSO enables single-shot measurements to be acquired continuously for a long acquisition time. This allows to study ultra-fast bunch dynamics. A clear signature of the microbunching instability (MBI) are short bursts of THz radiation called THz bursting. One example of such measurements is shown in Fig. 3. The machine parameters during the measurement are reported in Table. 1.

The evolution of 80 000 consecutive transverse bunch profiles were measured each in single-shot, spanning a period of 29 ms. The transverse position and size of each bunch have been calculated by applying a Gaussian fit to the raw data. The sawtooth bursting seen during the THz bursting due to

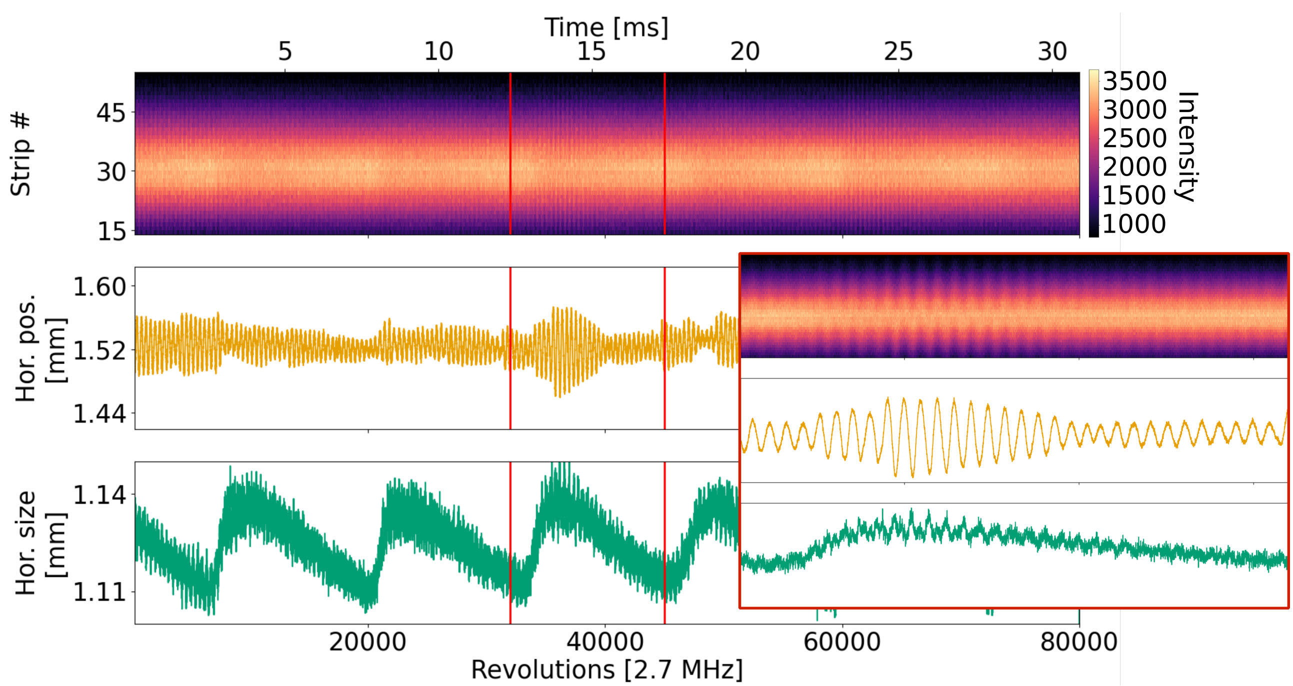

Figure 3: Incoherent synchrotron radiation measurement acquired with KALYPSO-LGAD. The first row corresponds to the raw data for 80 000 revolutions acquired. The second and third rows show the horizontal position and horizontal bunch size calculated from a Gaussian fit. The inset shows a zoomed-in perspective of the highlighted red window, depicting the coherent motion of the electron bunch.

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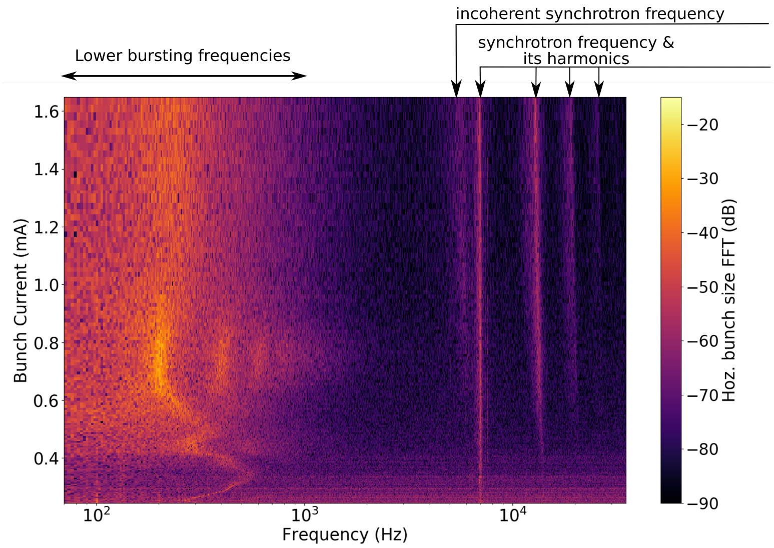

Figure 4: A spectrogram for transverse bunch size with logarithmic frequency axis, highlighting both the low frequencies corresponding to the bursting dynamics and high frequencies corresponding to the synchrotron oscillations and their harmonics.

Table 1: KARA Beam Parameters in Short Bunch Mode Used During the Transverse Profile Measurements in Fig. 3

Energy (E)	1.3 GeV
Bunch current (I_b)	0.1 to 3 mA
RF frequency (f_{RF})	499.744 MHz
Synchrotron frequency (f_s)	7.05 kHz
Momentum compaction factor (α_c)	3.4×10^{-4}
RF Voltage (V_{RF})	884.3 kV

the onset of the MBI can be seen in the calculated bunch profile. The coherent motion of the electron bunch along its center of mass, resulting in an oscillation in the longitudinal and transversal position, can also be seen. The frequency of this oscillation is the synchrotron frequency (f_s), which is here calculated from the Fast Fourier transform (FFT) of the bunch position and size leading to 7.05 kHz. The result agrees with the beam position monitor measurements (BPM).

One further advantage of the upgraded KALYPSO is the possibility to generate the so-called bursting spectrogram from the measured transverse profiles. A bursting spectrogram is generated by calculating the spectrum of the bunch size, individually for each bunch current and then combing them to form one spectrogram [14]. Previously, this has not been possible due to the low sensitivity of the detector. These spectrograms have been previously generated for the THz intensity measurements and have helped to study bursting dynamics, especially along the bursting threshold of the MBI [14, 15]. The transverse bunch profiles (dataset consists of at least 1 000 000 revolutions) are measured at regular intervals with a decaying bunch current to generate this spectrogram. A DCCT (Direct Current Current Transformer) is used to measure the bunch current.

The FFT of the calculated bunch size versus the corresponding bunch current is displayed in Fig. 4. The left section of the figure corresponds to the lower bursting frequencies. These frequencies follow a pattern similar to that observed in CSR intensity spectrograms. The low burst frequencies increase and decrease along with the range of the decaying bunch currents and vanish slightly at high bunch currents. Also visible is the constant synchrotron frequency of 7.05 kHz that does not vary with beam current. The incoherent synchrotron frequency, which corresponds to the incoherent motion of individual electrons, is lower than the coherent synchrotron frequency and deviates to lower frequency values with increasing bunch current. The data qualitatively agrees with the measurements performed with other detectors (e.g. Schottky diodes for THz intensity) [3].

OUTLOOK

The overall performance of KALYPSO-LGAD has been tested. It has been shown that the system can resolve the bunch profile of the incoherent synchrotron radiation even at very low bunch charges down to 0.05 mA (18 pC), even below the MBI threshold. The experiment has shown that LGAD is advantageous not only for HEP (High Energy Physics) where it is primarily used for their timing resolution but also for photon science.

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