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PRESERVING INFORMATION OF THE THREE SPATIAL ELECTRON BEAM DIMENSIONS IN ONE STREAK CAMERA MEASUREMENT *

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Abstract

At the pulse stretcher and storage ring ELSA a streak camera is used for the analysis of visible synchrotron radiation. It functions as fast time resolving beam diagnostic apparatus, capable of visualizing dynamics down to the picosecond time regime. The optical beamline splits the photon beam into two parts and projects both electron beam images onto the streak camera, one of them with transversely perpendicular orientation and slight displacement. Thereby it provides simultaneous imaging of both transverse planes. Thus, the information of bunch and beam dynamics of all three dimensions is preserved and can be observed in slow sweep or synchroscan operation. Characteristics and exemplary measurements, demonstrating the capabilities and limits of this technique, are presented.

INTRODUCTION

Since commissioning of the ELSA streak camera beamline was completed in 2013 [1], the natural reduction of three-dimensional spatial information to two dimensions due to the streaking action turned out to be of hindrance as both, horizontal and vertical beam responses were of interest. In the initial setup the change of the observation plane was possible by insertion of a Dove prism. However, simultaneous observation of both transverse planes could not be performed. Therefore a dual imaging beamline was installed and initially tested [2] by coupling a horizontal and a vertical beam image onto the streak camera's input optics. Due to the promising results, attention was drawn to the addition of two beamline extensions. First, the possibility to adjust the difference of photon propagation time between the two imaging beams was added. Secondly, independent remote positioning of both photon beams enabled to account for transverse electron beam orbit displacements. The remote positioning capability also ensures optimum utilization of the available space on the CCD matrix, especially in synchroscan mode.

THE OPTICAL SYSTEM

The evacuated synchrotron radiation (SR) beamline frontend is approximately 12 m long and serves as differential vacuum pumping section in order to achieve a pressure 1-2 orders of magnitude below synchrotron vacuum. As the primary reflecting mirror is fully exposed to the x-ray beam, mirror surface reactions with residual gas are suppressed [3]. The mirror couples the visible part of the SR spectrum out of the accelerator's plane through a vertical chicane onto an optical table housing the optical components. An overview of the beam optics assembly is given in Fig. 1.

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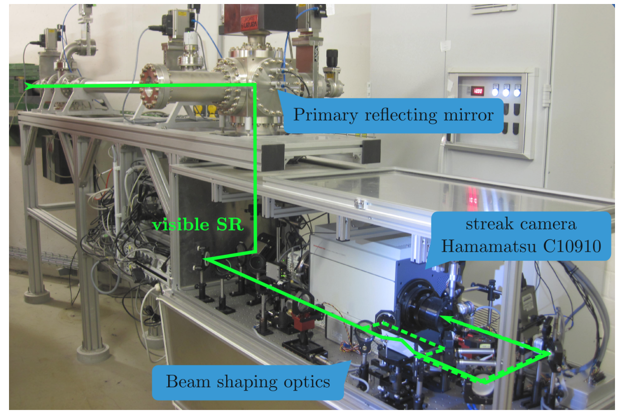

Figure 1: Photograph of the optical diagnostics beamline's back-end including the vertical chicane and the optical setup. The optical path (green) is guided through beam shaping optical elements half-way around the streak camera.

Table 1: ELSA & Source Point Parameters

Parameter	Value
Beam energy E	0.5–3.5 GeV
Revolution period T_{rev}	548 ns
Cavity RF frequency f_{RF}	499.67 MHz
Natural emittance ϵ_x	18–900 nm· rad
Bunch length σ_s	14–91 ps
Beam size ($8\sigma_x$ at source point)	3.1–21.9 mm

Requirements for Image Magnification

ELSA's electron beam dimensions are in the order of millimeters transversely and several ten picoseconds longitudinally. The accelerator properties and the resulting source point parameters are listed in Table 1.

Since longitudinal resolution capabilities are intrinsic properties of any streak camera, the aforegoing beamline is designed to provide sufficient resolution of transverse beam dynamics. The optics therefore match the expected electron beam size with the smallest field stop aperture which is identified as the photocathode of the operating streak camera Hamamatsu C10910 with a size of $0.15 \times 4.41\,\mathrm{mm}^2$ [4]. The requirement for minimum beam demagnification at the photocathode is therefore

$$M_{\mathrm{cathode}} \lesssim h_i/h_o \approx 10^{-2},$$

where $h_i = 150\ \mu$m is the maximum allowable field size due to the aperture and $h_o \approx 22$ mm the maximum expected source size. The inequation takes into account that transverse beam oscillations enlarge the effective source size.

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In comparison to previous beamline designs, a 3" primary focusing lens (f_1=500 mm) was installed which increased the effective aperture and freed up space on the back-end of the optical table. This lens forms an initial image with magnification

$$M_1 = f_1/(d_o - f_1) \approx 4{,}2 \cdot 10^{-2},$$

where $d_o \approx 12.41$ m is the distance from the lens to the source point. A pair of interchangeable lenses $f_2 = 200$ or 65 mm and $f_3 = 100$ or 50 mm forms a relay line of parallel light bundles which enables further adjustable demagnification $0.25 \leq M_{\text{relay}} = f_3/f_2 \leq 1.54$, where the product $M_1 \cdot M_{\text{relay}} = M_{\text{cathode}} \geq 0.01$ sufficiently satisfies the condition above at equality.

In addition, the interchangeable lenses allow close-up views of the electron beam which increases the spatial resolution on the 672×512 effective pixel matrix of the streak camera's CCD chip[1]. On the other hand, further demagnification of initially small beam sizes increases the available intensity on small spots. For single-shot measurements at short time scales, as in synchroscan operation, this is usually required in order to obtain a sufficient signal-to-noise ratio.

Dual Transverse Projection

In order to couple two images onto the input optics, a 50 % beamsplitter divides the light bundle within the relay line. One image is bypassing the Dove prism, whereas the second bundle passes through it and is rotated transversely by 90°. The two bundles are recombined onto a common optical path with initial displacement of ≈ 2.5 cm and angular deviation of ≈ 30 mrad. The setup is illustrated in Fig. 2.

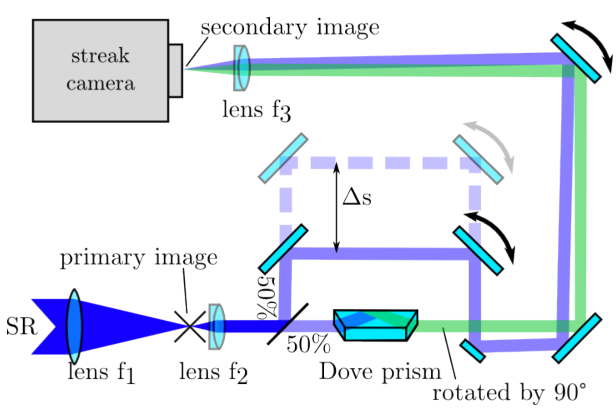

Figure 2: Schematic of the optical path including beam splitting and recombination. The bypassing branch is variable in length Δs in order to adjust the photon propagation time.

The assembly allows to adjust the photon propagation time difference for both beams as in

$$\Delta t_{\text{ph}} = \frac{2\Delta s}{c} - \frac{d_{\text{Dove}} \cdot (n-1)}{c},$$

where $0 < \Delta s < 5$ cm is the adjustable travel distance of the motorized linear stage, $d_{\text{Dove}} \approx 8.6$ cm the mean length of the Dove prism, $n \approx 1.52$ its refractive index at 587 nm (N-BK7 glass) and c the vacuum speed of light. The travel distance allows for a time adjustment range of $0 < \Delta t_{\text{ph}} < 200$ ps, which is useful in synchroscan operation.

In order to utilize maximum available intensity of the visible spectrum range, broad-band optical components are used. The consequent signal dispersion is estimated to be

$$\Delta t_{\text{disp}} \leq d/c \cdot \Delta n \approx 7 \text{ ps},$$

where $d \approx 12$ cm is the estimated total glass material thickness and $\Delta n = n(400\text{ nm}) - n(700\text{ nm}) \approx 1.77 \cdot 10^{-2}$. For typical bunch lengths at ELSA (>1.2 GeV) this broadening is considered negligible.

IMAGING PERFORMANCE

The dual transverse imaging capability requires the usage of multiple optical components, each contributing to the reduction of image transfer quality. The impact on slow sweep and synchroscan measurements are noticeable, but of minor concern.

Transverse Imaging Quality

Fig. 3 demonstrates the transverse image quality for two different magnification settings. The streak camera is set to focus mode and observes a stable electron beam at 1.2 GeV.

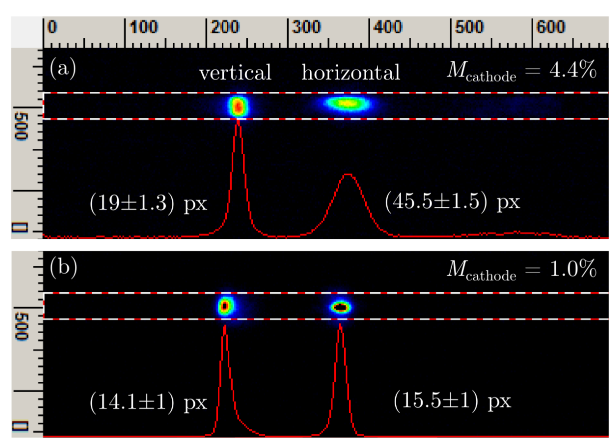

Figure 3: Vertical and horizontal 1.2 GeV beam image in focus mode. The horizontal lines mark the vertical aperture of the streak camera.

The image quality is satisfactory at $M_{\text{cathode}} = 4.4$ % and agrees well with previous measurements taken with a diagnostic CCD camera [5]. It is apparent that good pixel resolution is only obtained for large images, whose field size is consequently limited or cropped by the photocathode aperture.

The image broadening effect plays a major role at large demagnification as shown for $M_{\text{cathode}} = 1.0$ %. The smaller the image, the more impact have imperfect optical element materials, surfaces or placements. As relative measurements of bunch dynamics are mostly of interest, this circumstance is tolerable.

[1] The CCD camera operates in 2×2 binning mode.

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Slow Sweep Operation

Fig. 4 demonstrates the impact of the particular image size from Fig. 3 (a) in *slow sweep* operation. During studies of ion effects on the stored beam, sudden horizontal coherent oscillations were captured by the streak camera.

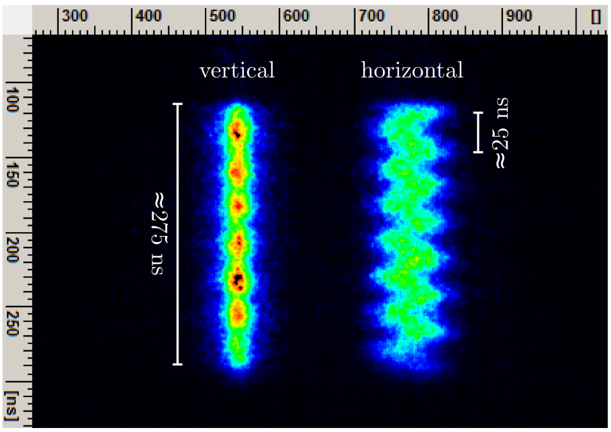

Figure 4: Slow sweep view of the vertical and horizontal bunch train. Coherent horizontal oscillations are observable. The vertical image responds with intensity fluctuations due to the narrow photocathode aperture.

The vertical bunch train fluctuates in intensity because its elliptical, upright spot image sweeps vertically across the photocathode's aperture. With the dual imaging technique this behavior can be identified as imaging artifact instead of a filling inhomogeneity. The exact cause of the 40 MHz oscillation is yet subject of investigation.

Synchroscan Operation

In synchroscan mode, the fast vertical sweeping axis is operated at 125 MHz, being the fourth submultiple of the master RF. The minimum horizontal linear sweeping time is 59.7 ns. This yields a sufficient horizontal spatial image separation of ≤ 90 px/bunch since only every 4th bunch is displayed in one row. Since the fast vertical sweeping field oscillates sinusoidally, every second bunch is displayed at an up or down streak around the streak's zero-crossing. This generally divides the available space on the CCD camera into two halfs, each for one fast-sweeping direction. An exemplary image is shown in Fig. 5, where all bunch signals could be separated. The corresponding vertical and horizontal image pairs are horizontally shifted due to spatial separation on the photocathode and vertically separated by the time of flight adjustment $\Delta t_{\mathrm{ph}} \approx 190$ ps. It must be noted that the intensity difference of vertical and horizontal images are caused by the Dove prism's transmission coefficient < 1 which only affects the horizontal image.

In order to test the imaging quality in dual transverse synchroscan operation, a beam instability was risen by increasing the defocussing sextupole component at a stored beam current of 80 mA. At > 10 times of the regular chromaticity value instabilities were observed with impact on particular bunches, such as the bunch labeled as #1, whereas

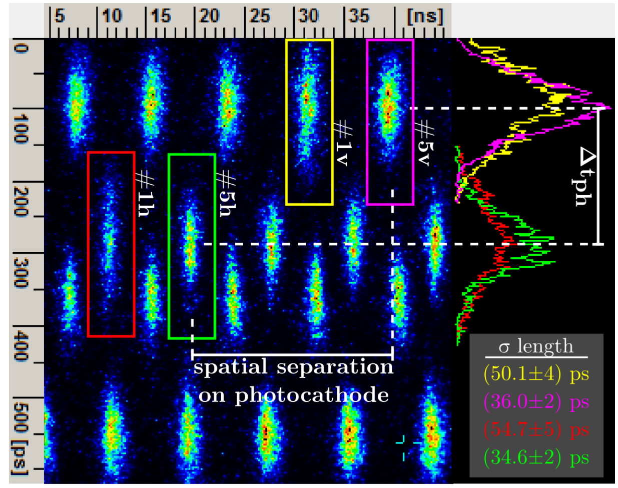

Figure 5: Single shot synchroscan image comparing vertical and horizontal perspectives on single bunches. Bunch #1 is deformed in length as indicated by the side-profiles. The corresponding bunch pairs are shifted horizontally due to spatial separation on the photocathode and vertically by Δt_{ph}.

the neighboring bunches were seemingly unaffected. The instability resulted in bunch lengthening as indicated by the side-profile widths, taken with [6]. Further increase of the sextupole component sporadically affected more observed bunches in the same way and eventually resulted in complete beam loss. Potential head-tail instabilities could not be observed. However, the system's detection capability for such instabilities in both transverse planes is evident.

CONCLUSION

The preservation of three-dimensional image information is of particular value when beam responses are occurring unexpectedly in the transverse plane. The beamline's aperture extension and image magnification optimization have enabled simultaneous transverse beam profile monitoring down to single-bunch, single-shot measurements in synchroscan mode.

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