INVESTIGATION OF EXTREMELY SHORT BEAM LONGITUDINAL MEASUREMENT WITH A STREAK CAMERA

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Abstract

During normal operation of synchrotron third generation light sources like Diamond, the measurement of the electron bunch profile, of the order of 10 ps, is perfectly done with a streak camera. However, in 'low alpha' operation, the shorter bunch length becomes extremely close to the resolution of the camera. In such a case, performing a good measurement and extracting the real information requires a good knowledge of the impulse response of the streak camera. We present analysis and measurement of the contributions to the point spread function (PSF) of the streak camera. The first contribution is the static PSF and is obtained by measuring a focussed beam without any sweep. The second contribution is the dynamic PSF, which is due to a chirp introduced by refractive optics. For pulse with large spectral bandwidth the dynamic PSF can be larger than 5 ps.

INTRODUCTION

Third generation synchrotron light sources are characterised by low emittance, small beam size, but also short bunch lengths. At Diamond we have been carrying out tests in the so-called low alpha mode, reducing the momentum compaction factor by up to a factor of 250, which gives a smallest theoretical bunch length of 0.7 ps, 15 times smaller than our 10.8 ps nominal bunch duration [1]. Measuring the real profile of such a short pulse is challenging. At Diamond, to measure bunch longitudinal profiles and length, we measure synchrotron radiation (SR) pulses with a dual sweep streak camera (SC) with a synchroscan at 250 MHz from Optronis GmbH. The manufacturer's specification of the camera gives 2 ps for the resolution with Rayleigh criterion and monochromatic light. This provides a good resolution for the normal operation mode of the camera but leads to extremely challenging measurement in low alpha mode.

We present measurement of the instrumental response of the streak camera that is decomposed into a static and dynamic response. The static response is measured as the point spread function of the image of a focussed photon beam on the SC, with no sweep from the electrodes. The dynamic response, as observed by previous authors [2, 3, 4], is the additional pulse lengthening measured while sweeping the electrodes of the SC, due to the dispersion in material traversed by the pulse. The decomposition of the PSF is firstly evidenced by means of spectral filters, and then measured with introduction of a spectrograph in the focussing optics of the SC.

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STREAK CAMERA RESOLUTION

The SC is composed of a photocathode, a streak tube in which the electrons undergo a longitudinal constant accelerating voltage, and then a transverse varying high voltage from two sweep electrode pairs. The images are obtained by a phosphor screen, coupled to a multi channel plate (MCP) and a CCD camera [5]. The best probe of the resolution is to measure known short pulses. Measurement of broadband synchrotron light pulses in low alpha mode allows to evidence not only the static PSF, but also the dynamic PSF induced by group velocity dispersion of optical materials.

Electron Bunch Length in Storage Rings

In storage rings, the r.m.s length of small charge bunches is proportional to the relative energy spread of the relativistic electrons, σ_ϵ, to the momentum compaction factor, α_c, and inversely proportional to the synchrotron frequency, f_s. The expression governing the bunch length at very low charge is given (in s) by:

$$\sigma_{bunch} = \frac{\alpha}{2\pi f_s}\sigma_\epsilon \quad (1)$$

For the Diamond storage ring in normal operation we have $\alpha = 1.7 \cdot 10^{-4}$, $f_s = 2.5$ kHz, and $\sigma_\epsilon = 10^{-3}$, which make the bunch length $\sigma_{bunch} \approx 10.8$ ps. In the low alpha mode reported here, we had $\alpha = 10^{-5}$, $f_s = 0.6$ kHz, and $\sigma_\epsilon = 10^{-3}$, which make the bunch length $\sigma_{bunch} \approx 2.6$ ps.

Setup and Measurements

Bunch length is measured with the SC using the visible part of the SR from a bending magnet. The spectrum from the diagnostics beamline is selected by the mirrors of the transport line and the vacuum-air sapphire window. It ranges from 200 nm to over 800 nm. Further filtering by UV absorption is introduced by the BK7 focussing lens.

In the low alpha mode operation the measurements of the electron bunch length were performed with white beam and with a series of spectral filters at the same current.

Preliminary, the static PSF has been measured for the white beam and also with 10 nm bandwidth filters at 490 nm and 560 nm, and with a 400-450 nm bandpass filter. As the static PSF is measured in pixels, it translates to a resolution in ps with the sweep unit scale calibration factor (0.1863, 0.3137 and 0.6374 ps/pixel for the 15, 25 and 50 ps/mm sweep speeds respectively). The results are reported in table 1. The smaller resolution, around 7.33 pixel, is for the narrow bandwidth filter at 560 nm. In all other cases, the PSF is larger at 10 pixels and even 11.66 pixels for the

Table 1: Bunch Length in Low Alpha mode. The measured bunch length, Σ, varies as function of the pulse bandwidth. This is shown by the corrected bunch length, Σ^*, after subtracting quadratically by the SC r.m.s PSF width, Δ_{PSF}, measured for each case, white beam (WB), with bandpass filter (BP) 400-450 nm, narrow band filters 490 ± 10 nm and 560 ± 10 nm. The PSF is measured in pixels and reported as , $\Delta_{PSF,ii}$ with the corresponding scales 50 ps / mm, 25 ps / mm and 15 ps / mm.

	WB	BP 400-450 nm	490 nm	560 nm
Δ_{PSF} (pixel)	9.88	11.66	9.81	7.33
$\Delta_{PSF,50}$ (ps)	6.23	7.44	6.25	4.67
$\Delta_{PSF,25}$ (ps)	3.1	3.66	3.0	2.3
$\Delta_{PSF,15}$ (ps)	1.85	2.17	1.83	1.36
Short bunch measurements at 25 ps/ mm				
Σ (ps)	6.53	5.92	5.14	4.88
Σ^* (ps)	5.72	4.62	4.1	4.2

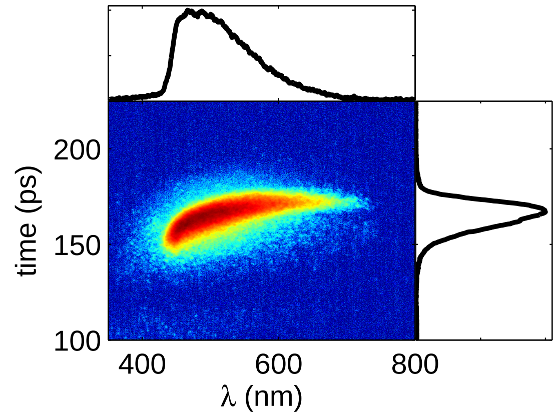

Figure 1: SC image presenting the pulse profile vs. wavelength. The chirp induced by the dispersion in the glass element traversed by the photon beam is clearly visible. The net result is a pulse broadening.

bandpass filter 400-450 nm. This suggests two effects: One and probably the main effect is the quality of the focussing system (BK7 singlet lens, slit and Nikkor achromat lens); and a possible additional effect of higher energy electrons spreading into the streak tube.

The bunch length has been measured in a short time, at 12 μA per bunch, varying less than 2 μA. This implies that the bunch length was the same for all measurements. The raw measurements vary with the bandwidth. However, the PSF largely contributes to the measurement as the bunch length is very close to the PSF width. In a first but good approximation, the contribution is quadratic, assuming the PSF and the measured pulses to be Gaussian. We then can write:

$$\Sigma^* = \sqrt{\Sigma^2 - \Delta^2_{PSF}} \qquad (2)$$

where Σ^* is the real r.m.s pulse duration, Σ is the measured r.m.s pulse duration, and Δ_{PSF} is the r.m.s static PSF of the SC.

Once the contribution of the PSF is removed, all the measurements should give the same bunch length. In fact, as described earlier in [2, 3], there is an additional broadening of pulses with wide spectral range due to the dispersion in the lenses' material and in the vacuum-air out-coupling window. We assume the broadening to be negligible for narrow bandwidth pulses, which is achieved with the 10 nm bandwidth filters. Consequently, the measurements with a pulse of large spectral band show a measurable broadening.

Direct Measurement with Spectrograph

A more accurate measurement of the pulse broadening due to the refractive materials is to measure a SR time resolved spectrum, i.e. the pulse profile vs. photon wavelength. For that we couple the SC with a spectrograph, keeping the same focussing optics as for the previous measurements. Figure 1 shows the results of such a time resolved spectrogram. The intensity spectrum is shown above the image, and on the right the profile of the integrated pulse over the spectrum. These measurement have been taken on a different day than the one in the previous section, so the machine parameter settings are different. For this measurements, we have $\alpha \approx -3 \cdot 10^{-6}$, $f_s \approx 340$ Hz, and the bunch current is $\approx 5.3\mu$A. Because the bunch has already some significant charge we expect to measure a larger pulse width than the 1.4 ps theoretically predicted.

Following the same approach as in the first section, we measured the static PSF of the spectrograms in the focussing mode. It is not fully optimised with a mean resolution of the order of 10 pixels r.m.s, but it is comparable with the previous experiment. In addition, the chromatic effects due to the first focussing lens make the optimisation of the static PSF difficult.

Figure 2 shows the centroid of the pulses vs. wavelength. The three curves presented are from the same pulses but at the three different sweep speeds offered by the synchroscan unit. The overlapping shows the independent calibration agreement. The quadratic polynomial fit (see figure caption) shows a higher order chirp probably due to the different glasses traversed by the photon beam, a sapphire window, a BK7 lens, and the achromatic Nikkor lens of the SC. The large chirp observed with the time resolved spectra explains the broadening measured with different spectral bandwidth pulses in the previous section (see table 1).

Figure 3 presents the pulse at 535 nm and the integrated pulse over the spectrum: the r.m.s width of the pulses are 3.3 ps and 6.7 ps respectively. The quadratic difference gives a first order estimate of the dynamic PSF of the order of 5.8 ps.

Finally we have measured with the 15 ps/mm sweep speed the pulse duration vs. wavelength as shown in Figure 4. In the range 400-600 nm, where the relative intensity is larger than 10% of the max, the corrected r.m.s width is on

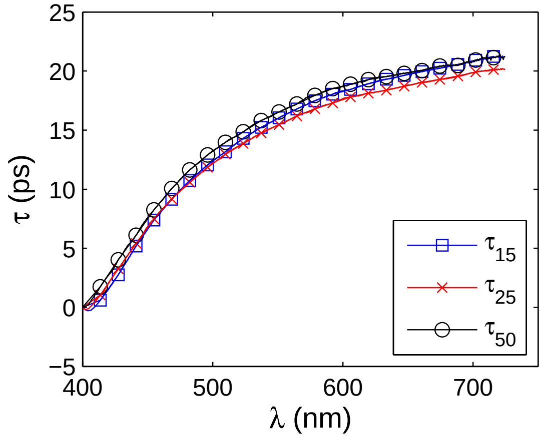

Figure 2: Centroid of the pulses vs. wavelength measured on Figure 1. τ_{ii} indicates the sweep speed. Fit of the curves converges to the second order polynomial: $y = -0.00026\,(\lambda - 400)^2 + 0.14\,(\lambda - 400) + 0.4$ (λ in nm and y in ps).

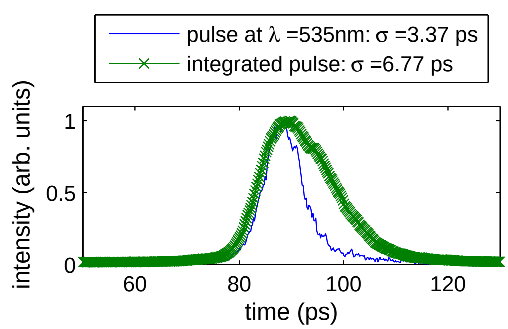

Figure 3: Pulse profile at 535nm compared to the integrated pulse over the spectrum.

average ≈ 3.5 ps with standard deviation 0.3 ps.

CONCLUDING REMARKS

We have characterised the instrument response of the SC. It is shown that the static PSF width is not uniform over the visible spectrum. This is due to mainly the chromatic effects of the lens system. However some spread due to the thermal energy of photons can also influence the width of the PSF. It is not measured here, and might be needed to further characterise the SC. We also presented the chirp induced by dispersion in glass materials and the effect on pulse width measurement. This is a well-known effect that is often forgotten. We associated this effect to a dynamic PSF introduced by the dispersion in the refractive optics of the SC. This leads to an additional spread in the pulse measurement that can be larger than 5 ps as shown by the time resolved spectra. Of course, this is unwanted and needs to be cured. The immediate solution is to use a narrow band filter so that the dispersion is negligible. However, this method also implies reducing the photon flux by more

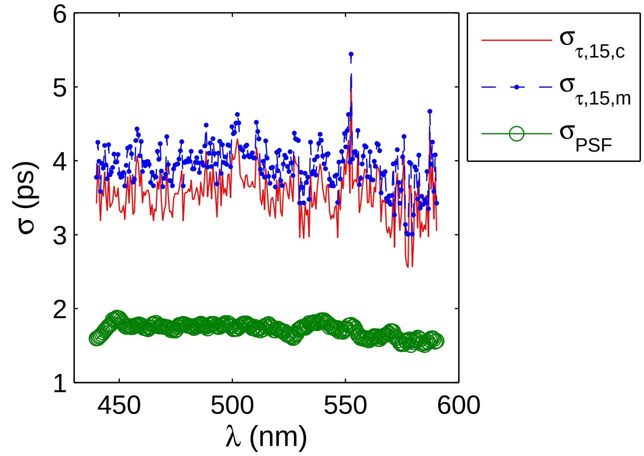

Figure 4: Pulse duration in the time-resolved spectrogram. The curves show measured and corrected r.m.s pulse width vs. wavelength. The relative spectrum intensity is shown in the inserted graph.

than 95%, which may prevent the ability to measure bunch length at very small current. Introducing a spectrograph in the measurement allows to measure precisely the induced chirp. In addition, it preserves the use of the full available power of the synchrotron radiation for the bunch length measurement. Thus, the low limit current for bunch length measurement should be pushed further down. Finally, the use of reflective focussing optics [4] presents the advantage of an almost dispersion free optical system. However, dispersion from the vacuum-air window still remains. In order to optimise the SC performance, we are currently designing a reflective focussing optics which includes a spectrograph. This should enable the SC to measure extremely short bunches closer to the manufacturer specification extended to the whole available SR spectral bandwidth, thus using at the same time all the available power. In addition, this new system keeps the ability to measure residual chirp.

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