PERFORMANCE OF A STREAK CAMERA USING REFLECTIVE INPUT OPTICS

Cyrille Thomas*, Guenther Rehm, Diamond, Oxfordshire, UK
Ian Martin, Diamond, Oxfordshire and JAI, Oxford, UK

Abstract

Electron bunch profile and length measurement from large bandwidth synchrotron radiation with a streak camera can be strongly limited by the chirp introduced by the length of material present in the input refractive optics of streak cameras. Elimination of the chirp can be done either by filtering the bandwidth of the synchrotron radiation pulses, by measuring time resolved spectra with the streak camera, or by replacing the front optics lenses by focusing mirrors. The first solution reduces the power available, thus limiting measurements to a minimum bunch current that can be too high to assess the 'zero' current bunch length. The second elegant solution allows measurement of the bunch length with the whole bandwidth and available power but with loss of the second sweep axis in the camera, so that no beam dynamics can be observed. In order to prevent any pulse chirp, keep all the available power and capability of beam dynamics observation, we designed new input optics exclusively with mirrors. We present here our design and the results of the system with our streak camera, measuring picosecond bunch profile in the new Diamond low-alpha lattice.

INTRODUCTION

Measurement of electron bunch length of third generation light sources like Diamond is essential for characterisation of the lattice and of the impedance of the machine. At Diamond, the nominal operation mode with a momentum compaction factor $\alpha = 1.7 \times 10^{-4}$, the bunch length is 10 ps. Therefore, the quoted 2 ps resolution of the streak camera (SC) is enough to measure the nominal bunch length. However, Diamond can be also operated with a much smaller α so that the bunch length can be less than 1 ps [1]. This represents a real challenge for the SC, not only because of the resolution of the camera, but also because the measurement has to be done at a very small bunch charge, so the photon flux entering the camera is very low, and because the large chirp introduced by refractive front optics (FO) imposes either the use of filters that further reduce the available power or the use of a spectrograph at the expense of losing the beam dynamics [2]. In order to remove the chirp and use all the available photon flux we designed and built a new FO using only reflective optics. This new FO has comparable resolution to the refractive FO. In this paper we present this design and the performance of the SC with this new FO.

* cyrille.thomas@diamond.ac.uk

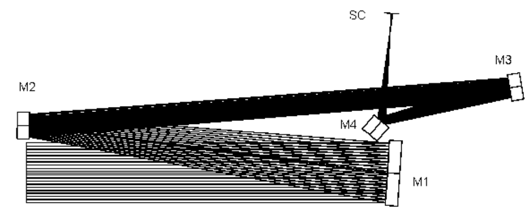

Figure 1: Reflective FO assembly. Mirrors 1 to 4 are shown as M1..4 and SC stands for streak camera. The lines are ray tracing from ZEMAX.

Table 1: ZEMAX study of the performance of the new FO of the SC. The source is the Diamond bending magnet source, 50×25 μm^2.

Diffraction limit spot size (μm)	3
Optical path difference for all wavelengths (ps)	0.05
Gaussian beam horizontal size (μm)	10
Gaussian beam vertical size (μm)	20

REFRACTIVE FRONT OPTICS DESIGN

The design of the FO assembly has been done using ZEMAX [1]. A schematic of the assembly is shown in figure 1. In order to replace the refractive FO the new optics must focus the synchrotron radiation into a spot smaller than 50 μm for all wavelengths. Also, aware of any effect that could lengthen the pulses we had a close look at the optical path difference for extreme paths across the optical system aperture. Finally, we also evaluated the image of a Gaussian beam propagating through the optical system, taking into account the natural astigmatism of the bending magnet synchrotron beam. Table 1 shows the most relevant parameters of the study. They show all the requirements for the new FO are matched, so the new FO are able to focus a spectrally broad band pulse onto the SC, matching the focusing of the refractive FO but without introducing any chirp.

Comparison with Reflective Front Optics

The refractive FO induce a large chirp in very broadband pulses [2] like the bending magnet synchrotron radiation pulses. Yet, such a system coupled with a spectrograph allows measuring the pulse duration, thus the bunch length, for all wavelengths in the spectrum and consequently re-

[1] Software For Optical System Design (http://www.zemax.com/)

Table 2: Static PSF of the SC with the refractive and the reflective optics.

	Reflective Optics	Refractive Optics
σ (pixel)	9.2	9.8
σ at 15 ps/mm (ps)	1.6	1.7
σ at 25 ps/mm (ps)	2.85	3.0
σ at 50 ps/mm (ps)	5.75	6.2

moving the chirp from the measurement. However, this is done at the cost of disabling the second sweep axis of the SC which means any information on beam dynamics which is lost. The reflective FO realise two advantages: no induced chirp and a larger spectral bandwidth than the BK-7-glass used in the previous system (filtering out all UV photons). The new system with UV enhanced Al coating focuses a larger power on the SC, resulting in bunch length measurements accessible at smaller bunch currents.

The first step in the comparison of the two FO is to measure the static point spread function (PSF) of the SC for the two optical systems. In the fast sweep axis, the PSF of the two systems is quasi identical. The measurement is summarised in table 2 giving the PSF that corresponds to each of the three sweep speeds of the synchroscan units.

Time Resolved Spectra

Although the reflective FO does not induce any measurable chirp, the pulse measured with the SC are chirped because there is still a sapphire window out-coupling the beam from vacuum to air. In order to measure this chirp, we replaced the fourth mirror in the reflective FO by a grating, and used a 350-550 nm band pass filter to suppress the diffracted higher orders modes from the grating. The stored current was 1.5 mA irregularly filled in 400 bunches, $\alpha \approx -6 \cdot 10^{-6}$, and the RF cavity voltage $V_{RF} = 2.2$ MV. Figure 2 presents a time-resolved spectrum image from the SC, with the synchroscan axis sweeping at 250 MHz on the 15 ps/mm scale, and wavelengths on the other axis. We also measured the PSF spectrum. The chirp from the sapphire window is extracted by measuring the centroid of the pulses for each wavelength. This is shown in figure 3. In comparison with the refractive FO, the reduction of the chirp is clearly visible. A first order comparison of the slope of the chirp shows a reduction by a factor 4.5. However, for measuring very small bunch lengths of typically less than 2 ps, the residual chirp might still be a limiting factor.

The net effect of the chirp is a pulse broadening as can be seen in the top figure 2. The profile of the integrated spectrum is broader than the profile integrated across a narrow band around 490 nm. For a non-chirped pulse the r.m.s width should be identical after quadratic subtraction of the PSF in all cases. The difference measured here is due to the chirp, which broadens the large spectral band pulses. A first order estimation of the broadening due to the chirp can be done by the quadratic difference of the two pulse widths. In this case, a pulse with a 380 nm

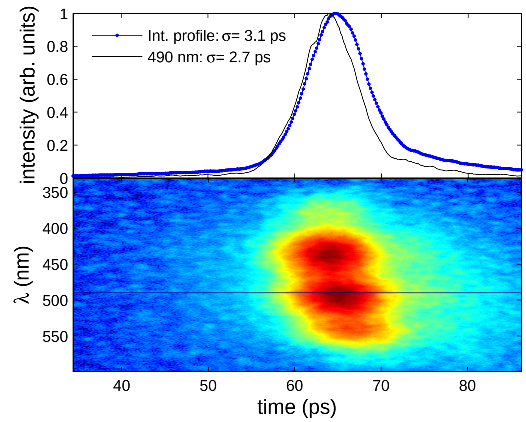

Figure 2: Bottom: SC image showing a time resolved spectra of the synchrotron radiation. Top: Integrated spectrum profile showing a pulse r.m.s width $\sigma = 3.1$ ps, and a spectral line profile at 490 ± 5 nm showing a pulse width $\sigma = 2.7$ ps .

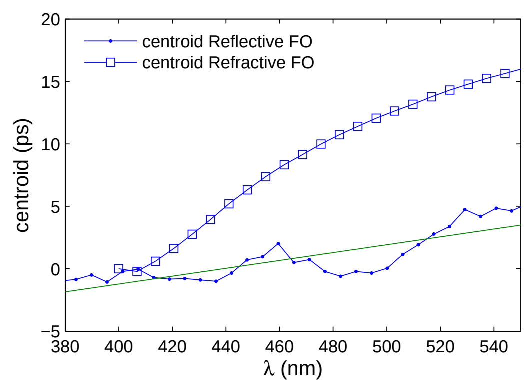

Figure 3: Chirp across the spectrum and compared with the chirp induced by the refractive FO. The linear slope component is 30 fs/nm and 140 fs/nm for the reflective and refractive FO respectively.

to 550 nm spectral band is lengthened by approximatively $\sqrt{\sigma^2_{broadband} - \sigma^2_\lambda} \approx 1.5$ ps.

SHORT BUNCH MEASUREMENTS

Measurement of r.m.s width which is close to the PSF of the SC requires a very good knowledge of the instrument. Measuring the PSF and also the time-resolved spectra, shows the additional broadening due to the chirp of the pulses. Figure 4 presents the bunch length measured as function of the wavelength, corrected by quadratic subtraction of the spectral PSF. The lines show the mean values of the spectrum of the r.m.s width, and the value of the r.m.s width of the integrated spectrum. The difference shows the broadening of the pulse due to its chirp.

Looking at the spectral PSF, one notes a difference of 20% between the shorter and the longer wavelength. This was already observed with the refractive FO. We are still

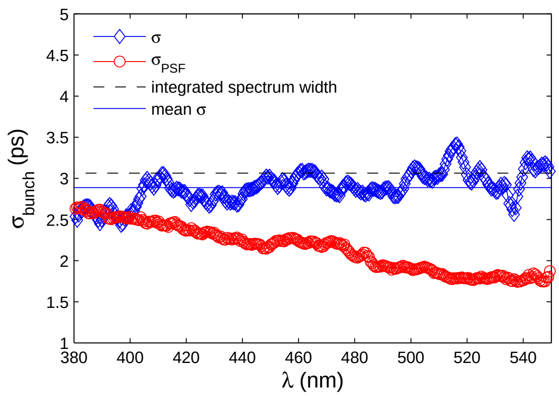

Figure 4: Bunch length and PSF measured across the spectrum. The lines indicate the mean values of the r.m.s width and also the fitted value of the integrated spectrum. Quadratic correction using the PSF is included.

investigating this effect and we observe this to be a typical instrument response. A possible explanation could be that higher energy photons might induce a higher spread in the electron cloud they generate in the photocathode. There also appears to be a tendency for the longer wavelength photons to produce a slightly longer bunch length measurement. Again, this effect is still under investigation. It might be caused by a non-uniformity of the electron optics and not related to the wavelength of the photons.

Having measured and characterised the two components of the SC response, the static PSF, measured with the sweep units at rest, and the dynamic PSF introduced by large broadband chirped pulses, one can measure electron bunch length using synchrotron radiation in so-called 'low alpha' mode. An example of such a measurement is shown in figure 5, where the bunch length is measured as function of the current. In this measurement, $\alpha = -6 \times 10^{-6}$ and we varied the RF cavity voltage to 1.5 MV and 2.2 MV. The measured bunch length has been corrected with the measured static PSF $\sigma_{PSF} = 2$ ps (on the day of the measurement), and the dynamic PSF, $\sigma_{PSF,dyn} = 1.5$ ps estimated in the previous section. However, for these measurements the band pass filter used for the time resolved spectra measurement was not in place. Therefore the broadening induced by the very large spectral band pulses is expected to be larger than 1.5 ps. The total PSF taken into account is $\sqrt{\sigma_{PSF}^2 + \sigma_{PSF,dyn}^2} = 2.5$ ps. This implies that any bunch length less than 2.5 ps will be measured with a large uncertainty due to the quadratic correction.

The theoretical bunch length expected at near zero current for the measurement shown in figure 5 is 3.0 ps and 2.3 ps for 1.5 MV and 2.2 MV respectively. In comparison with the measurement, one can see that it comes very close in both cases. However, we also note that the total PSF is of the same order as the near zero current bunch length for 2.2 MV . Therefore, the information shown by this measurement is that the bunch length at near zero current is less than 2.6 ps, and the uncertainty on the measurement is equal or less than $0.5 \cdot \frac{\sigma^2_{PSF,total}}{\sigma^2} \approx 0.5$.

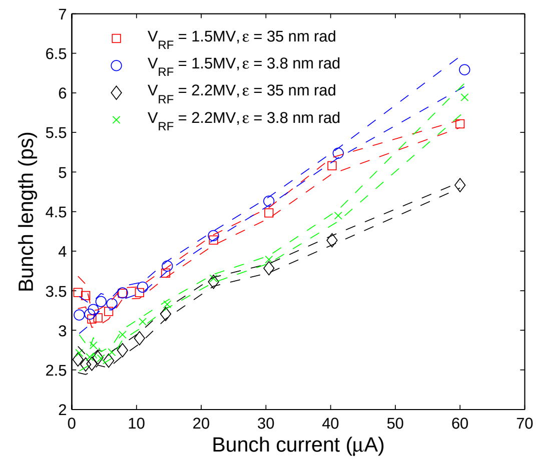

Figure 5: Bunch length, with quadratic subtraction of the total PSF vs. current for $\alpha = -6 \times 10^{-6}$ for two different RF cavity voltages and for two different lattices with 35 nm rad and 3.8 nm rad emittance. The dash lines indicate the standard deviation over 2000 measurements for each measurement point.

CONCLUDING REMARKS

We have successfully designed and built new front optics for the streak camera, which allows measurements of a larger spectral bandwidth, thus focusing more of the available photon flux onto the streak camera. In addition, the induced chirp on spectrally broad pulses by the refractive FO has been eliminated. However, there is still a remaining chirp resulting from the vacuum-air window of the beamline, causing pulse broadening which needs to be considered for measuring picosecond bunch lengths. For measurement of less than 2 ps, a reduction of the bandwidth typically to 50-100 nm has to be considered for a more precise measurement. However, this bandwidth reduction is still a factor 5-10 larger than the 10 nm FWHM band-pass we had to use with refractive FO for the same measurement. In summary, the modifications have enabled to measurements of shorter bunch lengths at lower beam currents, which agree well with theoretical predictions.

REFERENCES

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