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Reconstruction of sub-femtosecond longitudinal bunch profile measurement data

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Abstract. With a current trend towards shorter electron beams with lengths on the order of few femtoseconds (fs) to sub-femtoseconds both in conventional and novel accelerator communities, the need for diagnostics with equivalent attosecond resolution is increasing. The proposed design for a sub-femtosecond diagnostic by Andonian et al. (2011, Phys. Rev. ST Accel. Beams 14 072802) is one such example that combines a laser deflector with an RF deflecting cavity to streak the electron beam in the horizontal and vertical direction. In this paper, we present a tool for the reconstruction of the longitudinal beam profile from this diagnostic data, which can be used both for the analysis of planned experiments and testing of different beam scenarios with respect to their specific setup requirements. Applying this method, the usefulness of the device for measurements in a number of example scenarios, including plasma-accelerated and ultrashort RF-accelerated electron beams, is discussed.

1. Introduction

Both the need for short, high current electron beams for application in advanced radiation generation schemes, like Free-Electron Lasers (FELs), and the natural bunch length reduction to femtoseconds in novel accelerators, such as plasma- and dielectric-based devices [1, 2], have led to an increased interest in ultrashort electron beams and their measurement in the accelerator community. The current standard for bunch length diagnostics comprises a wide range of setups including electro-optical detectors, devices based on coherent and incoherent transition radiation and transverse deflecting cavities. Most of them can resolve electron beams on the order of few to tens of femtoseconds [3, 4, 5] and are thus not suitable as diagnostics in the attosecond regime.

In this paper, we discuss a device proposed by Andonian et al. [6] which promises both sub-femtosecond resolution and a large dynamic range for the measurement of longitudinal beam profiles. The setup of this diagnostic is a combination of a laser modulator, i.e. a high power laser pulse in the TEM_{10}-mode co-propagating with the electron beam in a few-period undulator, and a transverse deflecting RF cavity (RF-TDS), followed by a drift space and a screen for measuring the transverse beam profile. While the laser pulse provides a transverse kick to the electron beam in the undulator, the strength of which has a sinusoidal dependence on the longitudinal position within the beam, the deflecting cavity behind additionally streaks the beam in the orthogonal direction. In the following drift space, the transverse kicks are converted into offsets in the horizontal and vertical directions, respectively, and the longitudinal beam profile is imprinted in the trace of the signal on the screen.

As derived in [6], the angular modulation of the beam by the laser modulator in x and the deflector in y based on the longitudinal beam coordinate s_0 is given by

$$\begin{aligned} x' &= x'_0 + S_{LM} \sin(ks_0) \\ y' &= y'_0 + S_{rf} k_{rf} s_0 \end{aligned} \tag{1}$$

where $k = 2\pi/\lambda$, $k_{rf} = 2\pi/\lambda_{rf}$ are the laser and RF wavenumbers, respectively, and $S_{LM} \propto B\lambda_u\sqrt{P_L}/\gamma^2$ and $S_{rf} \propto eV_{rf}/\gamma$ are the streaking strengths of the laser modulator and deflecting cavity. B and λ_u are the undulator peak magnetic field and period, P_L is the laser power, V_{rf} the deflecting voltage and γ is the Lorentz factor of the electron beam. The temporal resolution of the measurement is determined by the laser modulator and can be estimated based on the strength of this streaking:

$$\Delta t = \frac{\epsilon}{\sigma_x c S_{LM} k} \tag{2}$$

with ϵ the beam geometric emittance and σ_x its rms size in x. In comparison to the RF-TDS alone, the resolution of the full diagnostic hence benefits from streaking at optical instead of radio frequencies, while the second deflector acts to avoid signal overlaps due to the shorter streaking wavelength.

2. Bunch profile reconstruction

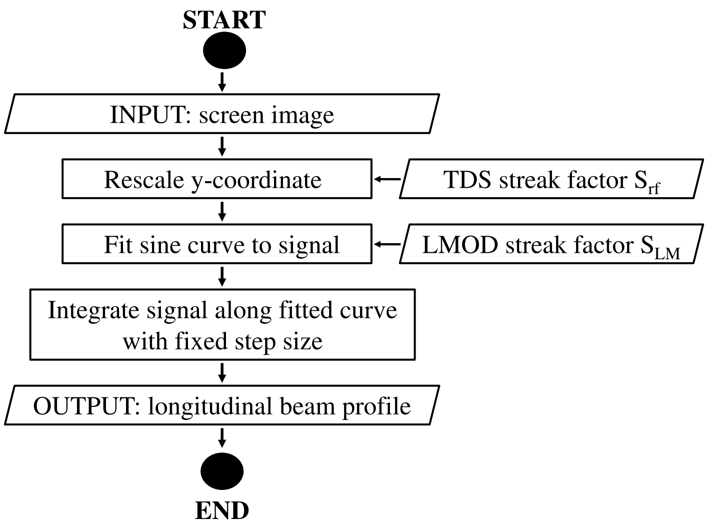

Figure 1. Flow chart of the algorithm used to reconstruct the longitudinal electron beam profile from a screen image of the sub-fs diagnostic.

In order to recover information about the longitudinal bunch length and profile from the screen image measured behind the sub-fs diagnostic setup, a reconstruction tool was developed, the algorithm for which is described in Figure 1. After re-calibrating the image vertically with the streaking strength of the deflecting cavity, a sinusoidal curve is fit to the screen signal and the longitudinal beam profile is calculated based on integration of the data along this fit.

The resolution calculated in Equation (2) is, due to the sinusoidal dependence of the streaking effect, only valid for the linear sections of the signal, whereas around the turning points it is limited to that of the RF-TDS and hence difficult to reconstruct correctly at the sub-femtosecond level. The recovery mechanism thus also includes a feature to combine multiple screen images; if taken at a slightly different phase in the laser modulator, as would naturally occur in an experiment due to jitter, the position of the beam along the sinusoidal screen pattern changes and so the high resolution reconstructions of different parts of the beam can be combined to an overall higher quality beam profile.

Figure 2 provides an example of the reconstruction options of the developed tool: while subfigure a) depicts a measurement example of the screen image, Figure 2 b) presents the application of the algorithm with the original beam shape as the black dotted line and the reconstructed profile based on multiple (single) shots at random phase as the blue solid (red dotted) line. Not only is the error in length and distance of the microbunches around 3 % and less, one can also clearly see the improvement in the reconstructed profile, particularly the shape of the microbunches, using multiple shots.

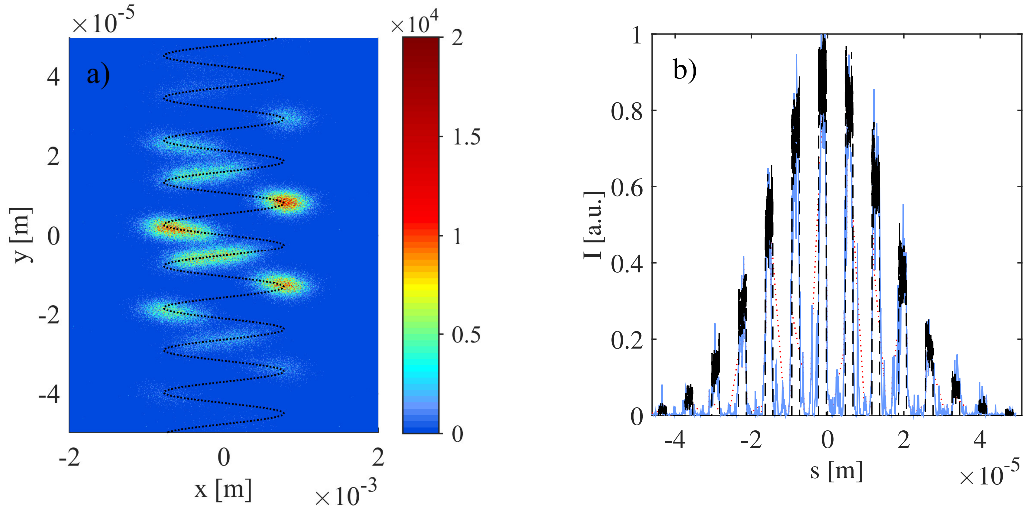

Figure 2. Reconstruction of an electron beam of 15 µm rms length consisting of 2 µm long microbunches at 5 µm distance. The reconstructed values are 15.55 µm for the full rms beam length, 1.94 µm for the microbunch length and 5.00 µm for the average microbunch distance. a): transverse beam distribution at the imaging screen with a sinusoidal fit overlaid; b): original beam distribution (dashed black) and recovered profiles based on a single sub-fs diagnostic measurement (dotted red) and five measurements with slightly varying laser phase (solid blue).

3. Application to ultrashort electron beams

Whereas previous studies have focused on applying the sub-fs diagnostic scheme to electron beams with longer overall pulse duration, but very fine substructures [6, 7], such as produced for example in FELs, in the following an application of this diagnostic to ultrashort beams in the sub-femtosecond regime is discussed. To this effect, simulations with the particle-tracking code ELEGANT [8] were performed to create sample diagnostic images that could then be analysed with the newly developed beam profile reconstruction routine.

The test case that has been simulated here is that of an RF-accelerated electron bunch from the planned SINBAD facility [9] with around 200 attoseconds rms duration, the exact properties of which are shown in Table 3. The latter also describes the design parameters for the diagnostic setup which have been chosen in order to fulfill the laser modulator resonance condition, while minimising the theoretical device resolution based on Equation (2). Note that due to the electron bunch length being shorter than half a laser wavelength in this setup, the beam is resolved over a single turn on the screen and the streaking in y is thus in principle not necessarily required. Moreover, the profile can be reconstructed in a single shot without loss in resolution.

Table 1. Design parameters for a test analysis of an ultrashort sample beam from the SINBAD facility at DESY with the sub-fs diagnostic.

Beam energy	(150.70 ± 0.38) MeV
Beam rms duration	6.32×10^{-8} m
Beam geometric emittance in x,y	0.72 nm, 0.66 nm
Laser power	350 GW
Laser wavelength	10.3 µm
Undulator peak field	1.354 T
Undulator period, no. of periods	6 cm, 3
Deflector voltage, wavelength	12 MV, 2.6 cm

Despite an expected resolution on the order of 1.48×10^{-8} m, a large error above 50 % was found in the reconstructed beam duration. This is likely due to the large initial beam size and divergence on the order of 100 µm and 10 µrad, respectively. As the final transverse beam distribution on the screen is composed of contributions from the initial transverse beam profile as well as the streaked longitudinal profile, a smearing effect of the pattern on the screen and hence an increased reconstruction error are observed if the initial beam distribution is too large. By using a collimator (radius 50 µm) in front of the laser modulator, though, the transverse beam properties can be improved. The results of the bunch profile simulation with the collimator are shown in Figure 3. The rms beam length in this case can be recovered with an error of 4.6 % improving upon the results gained from reconstruction with the deflecting cavity alone by a factor of around 20. One drawback of using a collimator is the significant reduction of the propagated beam charge to about 9 % of the initial value of 2.8 pC. Considering this charge loss as well as the relatively small size of the beam at the final measurement point, a high resolution imaging setup is necessary to resolve the beam.

A more challenging application for the diagnostic setup could be for plasma-accelerated electron beams which typically have bunch lengths on the order of one to few femtoseconds, yet a large correlated energy spread and geometric emittance of a few nanometers. While in theory the required resolution should be achievable with a medium strong streaking effect and smearing of the screen signal could be controllable through beam collimation, an important limitation in this case is likely the energy spread. Detailed simulations with a test beam show that an increased energy spread up to a few percent leads to a deterioration of the reconstructed beam quality. For a spread above around 5 %, the screen signal further becomes strongly distorted and unrecoverable. The cause for this effect is two-fold: on the one hand, the dependence of the streaking strength in x and y on electron energy, as shown in Equation (1), also results in smearing of the screen profile features with increasing spread. On the other hand, the momentum compaction effect of the undulator, quantified as $R_{56} = 2N_u\lambda$ (with N_u the number of undulator periods and λ the laser wavelength), causes a change in the length of the bunch during propagation in the laser modulator which can affect the final recovered beam profile. For ultrashort beams the latter is particularly dominant and can occur already at low values of energy spread. In order to avoid significant compression or stretching of a plasma-accelerated beam in the undulator, possible solutions could be the use of an extremely short, single period undulator in order to minimise the undulator R_{56} effect or a tapering of the undulator in order to

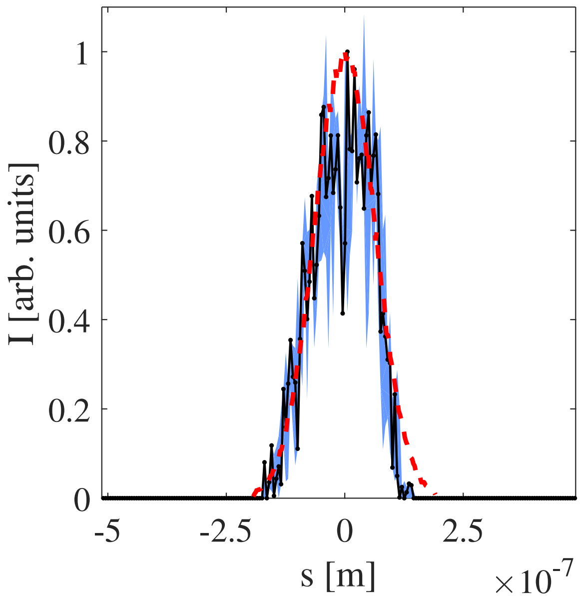

Figure 3. Reconstructed SINBAD beam with an rms beam length of 6.03×10^{-8} m (solid black) overlaid by the normalised initial beam profile (dashed red). The blue, shaded region shows the profile error, estimated based on the uncertainty in the fitting coefficients of the reconstruction algorithm.

compensate the energy chirp. Both options, however, require further study and will be reported on in the future.

4. Summary

A beam profile reconstruction tool for a sub-femtosecond longitudinal beam diagnostic based on streaking with a laser modulator and deflecting cavity was presented and its capability demonstrated, among others with improved performance due to the combination of data from multiple shots. It was further applied to the study of ultrashort beams in the attosecond regime with the sub-fs diagnostic setup. While the required design parameters are at the edge of currently available technology, possible example cases of high resolution bunch profile measurements with RF- and plasma-accelerated beams were presented. Initial beam transverse properties and energy spread were defined as two main limiting factors in reconstruction quality in the ultrashort regime. Future studies will extend the application of this diagnostic device to more challenging ultrashort electron beam accelerator setups, in particular also for the AXSIS (Frontiers in Attosecond X-Ray Science: Imaging and Spectroscopy) project at SINBAD [2].

Acknowledgments

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