Beam Image Analysis Script for a Combined Longitudinal Bunch Profile Diagnostic with Sub-Fs Resolution: Attoscope_Analysis_GUI_v5_4_5.m

The combined longitudinal bunch profile diagnostic consists of two stages of streaking, first within a laser modulator and second within an RF transverse deflecting cavity (TDS). Further information on the concept as well as numerical studies of this method and a short introduction to this reconstruction tool can be found in the following references:

- Andonian, G. et al. Longitudinal Profile Diagnostic Scheme with Subfemtosecond Resolution for High-Brightness Electron Beams. Phys. Rev. Spec. Top. - Accel. Beams 14, 072802 (2011). https://link.aps.org/doi/10.1103/PhysRevSTAB.14.072802

- Weikum, M., Andonian, G., Assmann, R., Dorda, U. & Sheng, Z. Reconstruction of sub-femtosecond longitudinal bunch profile measurement data. J. Phys. Conf. Ser. 874, 012079 (2017). https://doi.org/10.1088/1742-6596/874/1/012079

- Weikum M K, Andonian G, Sudar N S, Fedurin M G, Polyanskiy M N, Swinson C, Ovodenko A, O'Shea F, Harrison M, Sheng Z M, Assmann R W. Preliminary measurements for a sub-femtosecond electron bunch length diagnostic. Nucl. Instrum. Meth. A. 2018 (accepted).

This reconstruction program provides a GUI that converts an image of the transverse electron beam distribution from a measurement with this diagnostic device, or with an RF deflecting cavity alone, into an image of the longitudinal beam profile. It also allows, among others, to calculate the RMS longitudinal beam size, find microbunching structures and measure the distance between features within the beam.

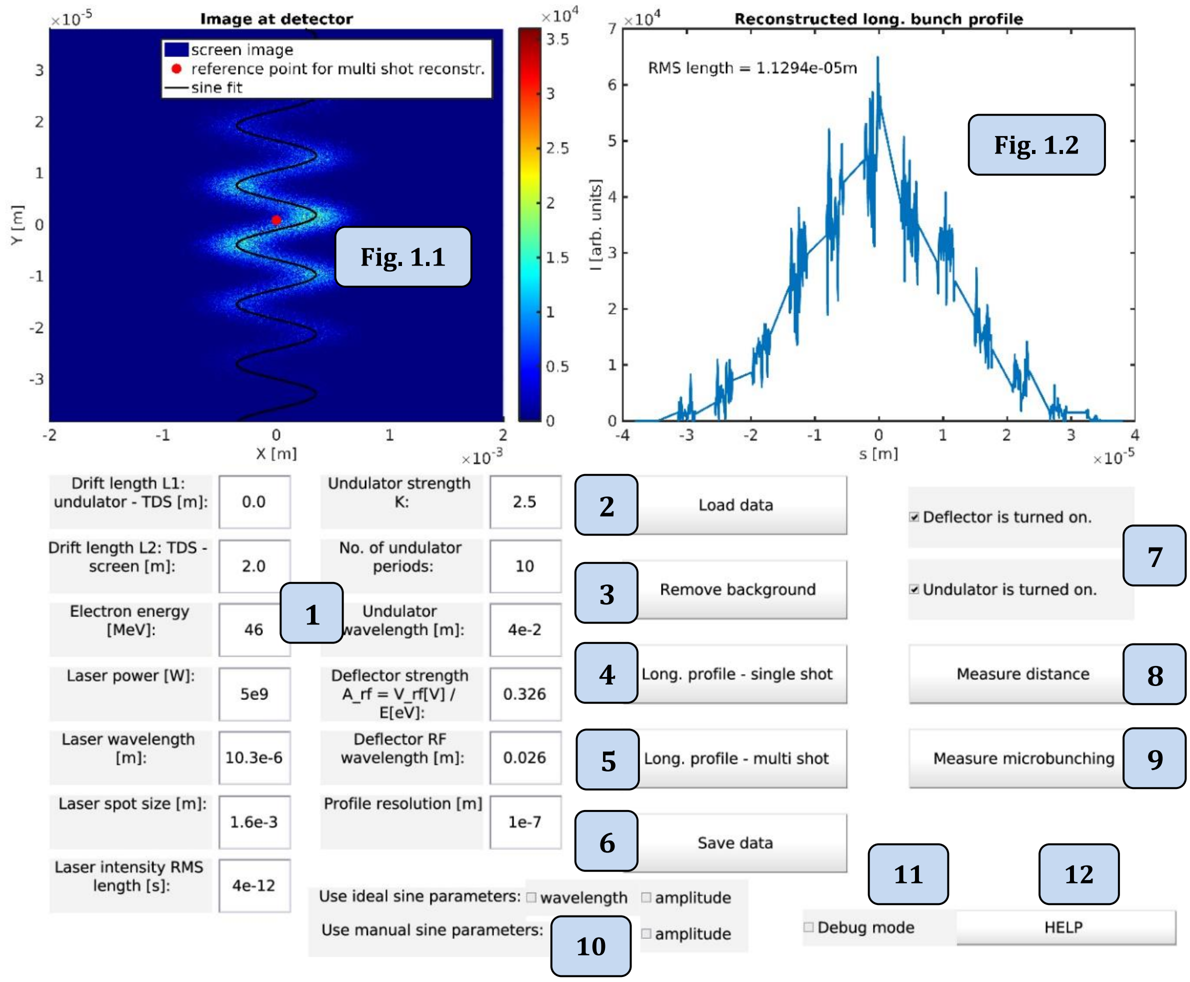

Figure 1: Screenshot of the analysis GUI with individual components marked.

Figure 1 shows the layout of the program GUI. In the following, its main functions are described:

1: Input fields for different setup parameters for the undulator, laser and deflector (see below for details): the values put into these fields are used in the reconstruction algorithm for characterising the sinusoidal beam shape within the screen image.
2: Load data-button: opens a dialog box to choose a file as input data; it also prompts the user to specify the image screen size to calculate the x- and y-dimensions of the image; the image is plotted in Fig. 1.1.
3: Remove background-button: opens a dialog box to choose a file as the image background; this is then subtracted from the input image and an updated screen image is replotted in Fig. 1.1.
4: Longitudinal profile – single shot-button: runs the image data in Fig. 1.1 through a reconstruction algorithm to calculate the longitudinal beam profile from it (for the algorithm see below); the result is plotted in Fig. 1.2 as a lineout of intensity vs. the relative position in the bunch, s_0, respectively; furthermore, the calculated RMS longitudinal beam size is displayed.
5: Longitudinal profile – multi shot-button: loads and combines the output from multiple saved single-shot analyses into a reconstruction with higher resolution in all beam sections.
6: Save data-button: saves a log file with various input and output parameter values ('log-Attoscope_BeamImage_[date-time].txt'); also saves the image data from Fig. 1.2 as an output file ('output-Attoscope_BeamImage_[date-time]-lineout.txt') in the local folder.
7: Checkboxes for undulator and deflector: check / uncheck to indicate if the undulator / laser and deflector are turned on or off; this is then considered in the reconstruction algorithm.
8: Measure distance-button: prompts the user to choose two points on one of the graphs by clicking with the cursor on it (before pressing OK in each case); the distance between these two points is then measured and displayed.
9: Measure microbunching-button: prompts the user to choose a region in Fig. 1.2 across which the FWHM width and distance of microbunches is calculated; the mean width and distance is displayed in Fig. 1.2.
10: Checkboxes for choice of sine fitting parameters: defines with what input parameters a sinusoidal fit is found to the signal in the measured screen image in Fig. 1.1, considering the following choices:
1) Use ideal sine parameters:
a) wavelength: the wavelength of the sine fit is considered fixed and equal to the laser wavelength provided as an input parameter;
b) amplitude: the amplitude of the sine fit is considered fixed and equal to the theoretical signal amplitude of $|A|(L_1 + L_2)$ where all variables are calculated from input parameters, as defined below;
2) Use manual sine parameters:
c) amplitude: the amplitude of the sine fit is considered fixed and determined in one of two ways: if the signal is clear enough, the amplitude is calculated from the positioning of the highest intensity regions within the signal (with intensity equal or higher than 75% of the maximum intensity) being located at the sinusoidal turning points; if the signal is not clear or bright enough, a manual input is requested to define the amplitude as a certain distance from the y=0 axis
11: Debug-mode: if checked, additional data is displayed in the form of extra figures to allow easier debugging of the script; a detailed list of this additional information is given below.
12: HELP-button: opens this documentation document for further information on the program.

Necessary input:

- Input parameters:
    - Distances between the undulator and the TDS (L_1) as well as the TDS and the imaging screen (L_2)
    - Mean electron beam energy at the diagnostic device
    - Streaking laser power (in TEM_{10} mode) (set to zero, if only TDS was used)
    - Streaking laser wavelength, spot size and pulse length

- Undulator strength value K (set to zero, if only TDS was used), number of undulator periods and undulator period (wavelength)
- TDS streaking strength A_{rf} defined by the deflecting voltage in the TDS (V_{rf}) and the electron beam mean energy (E) (note that this definition provided in the input box description is only valid assuming operation of the TDS at the zero-crossing as well as a simple drift space between the TDS and imaging screen)
- TDS RF-wavelength

Single-shot profile reconstruction ("Long. profile – single shot"):

- Measured screen image of the transverse distribution of the streaked beam after the diagnostic device
- (optional) Background signal of measurement screen for background noise subtraction
- Value of the unstreaked RMS beam size in the vertical direction / screen image of the transverse distribution of the unstreaked beam after the diagnostic device

Multi-shot profile reconstruction ("Long. profile – multi shot"):

- Two or more reconstructed profile files obtained from the analysis with this tool of multiple screen images taken with the same setup

Additional Information:

- **Input parameters and constants used in calculations:**
- <u>Deflector strength</u>: $A_{rf} = \frac{eV_{rf}}{\gamma mc^2} cos(\varphi) \frac{R_{34}}{L_2}$ with V_{rf}= deflector voltage, R_{34} = transport matrix element describing the conversion of the applied kick in the TDS into a transverse offset at the imaging screen, γmc^2 = electron beam mean energy, φ = phase of the RF in the deflector; note that the program automatically assumes a simple drift space between TDS and imaging screen, so that the effect of a more complex beam transport line needs to be included directly in the value of A_{rf} through the formula above
- <u>Undulator-laser interaction strength parameter</u> (calculated automatically from input values): $A = \frac{2K}{\gamma^2}\sqrt{\frac{P_L}{P_0}}[JJ]f(q,\nu,\tau_{RMS})$ with $K = \frac{eB_0\lambda_u}{2\pi mc}$ = undulator parameter, γ = electron beam energy, P_L = laser pulse power, $P_0 = \frac{4\pi\varepsilon_0 m^2 c^5}{e^2}$, $[JJ] = J_0\left(\frac{K^2}{4+2K^2}\right) - J_0(\frac{K^2}{4+2K^2})$ with $J_{0,1}$ Bessel functions and $f(q,\nu,\tau_{RMS})$ a function depending on undulator and laser properties (see Zholents, Zolotorev, New Journal of Physics, 10 (2): 025005, 2008 for more detail)
- <u>Profile resolution</u>: determines the step size for the reconstructed bunch profile; a resolution of $5x10^{-7}$m is usually sufficient for a first check of the profile, although for a better measurement of microbunching features smaller resolution is helpful; note that run time of the reconstruction algorithm increases with smaller step size and that the effective minimum resolution value depends on the actual resolution in the diagnostic measurement.
- **Image format requirements:**
- Input images must be in Tagged Image File Format (.tif) or ASCII Format (.asc) with the data in the form of an m-by-n array where m gives the number of y-coordinate points and n the number of x-coordinate points.
- For the multi-shot reconstruction, two or more profiles need to be loaded that have been reconstructed before from different screen images measured in multiple shots of the same beam setup; the files should thus be in the .txt-format that is the output with the "Save data" button of the tool ("output-Attoscope_BeamImage_[date+time]-lineout.txt").
- **Additional plots with debugging function:**
  The following additional plots are displayed, if the "Debug mode"-checkbox is checked during the actions "Long. profile – single shot", "Long. profile – multi shot" and "Measure microbunching":
- <u>"Long. profile – single shot":</u> signal intensity along the y-direction, integrated over x with the automatically proposed position of a central reference point (necessary for multi-shot

reconstruction) marked; the reference point is chosen as the maximum value of this integrated distribution and should mark a fixed reference recoverable from multiple shots of a beam profile

- <u>“Long. profile – single shot”:</u> figure with two subplots: 1) measured screen signal with an overlay of a) signal data points with an intensity equal or higher than 75% of the maximum intensity, b) a sine fit to the screen image signal, c) defined regions where the fitted sine curve turns (“turning point regions”), d) the start and end positions of each turning point region along the sine fit; 2) the reconstructed longitudinal beam profile with the signal at the turning point regions of the sine fit marked, as these are reconstructed differently from the rest of the profile
- <u>“Long. profile – multi shot”:</u> figure with two subplots: 1) the loaded reconstructed longitudinal profiles before adjusting their position relative to each other based on their previously defined reference points (synchronization), 2) the loaded reconstructed longitudinal profiles after synchronization
- <u>“Long. profile – multi shot”:</u> Comparison of a) the newly calculated longitudinal profile based on reconstruction of multiple screen images, b) the reconstructed longitudinal profile from a single screen image, c) if defined, a reference longitudinal profile
- <u>“Measure microbunching”:</u> figure with two subplots: 1) definition of the positions on the reconstructed profile used to define the peak and FWHM of one or multiple microbunches as well as the distance between them, 2) overview over the calculated FWHM widths and distances for each microbunch found in the defined region of interest

• **Tips for microbunching detection:**

- Two different modes are available to identify microbunches: 1) automatic: a region of interest needs to be specified within which microbunches are automatically detected and measured; 2) manual: individual peaks and troughs need to be identified manually within the reconstructed profile the distance and width of which is then calculated; in each of these two cases, the output values for FWHM width and distance provided are denoting a mean value across all identified microbunches.
- If the microbunching structure is not very clear, the automatic detection may not be successful, in which case using manual microbunch detection can be used to identify the sub-structure of a reconstructed profile more accurately.
- It is possible that microbunching is detected falsely due to artificial structures created by the reconstruction of the turning point regions of the sinusoidal signal fit; this may be the case if the microbunching coincides completely with the position of the marked turning point regions (in “debug mode”), particularly for multiple images taken at different phases

• **Possible future features:**

The tool contains a number of features to manipulate the input and output data, which are currently not in use and deactivated (visible as comments in the code). Once additional experimental data for the diagnostic device becomes available, which can define the nature of the measured signal more accurately than current initial tests, these features may be found to be useful and can be re-activated again. The following functions are included in this:

- Possibility to re-center the input screen image in the x- and y-direction before the reconstruction is started (not suitable for diagnostics of ultrashort beams as the signal is distorted)
- Vertical flipping of the input data structure (may become necessary depending on the input format)
- Possibility to subtract any remaining background noise from the reconstructed profile to calculate the profile RMS width more accurately

Main reconstruction algorithm:

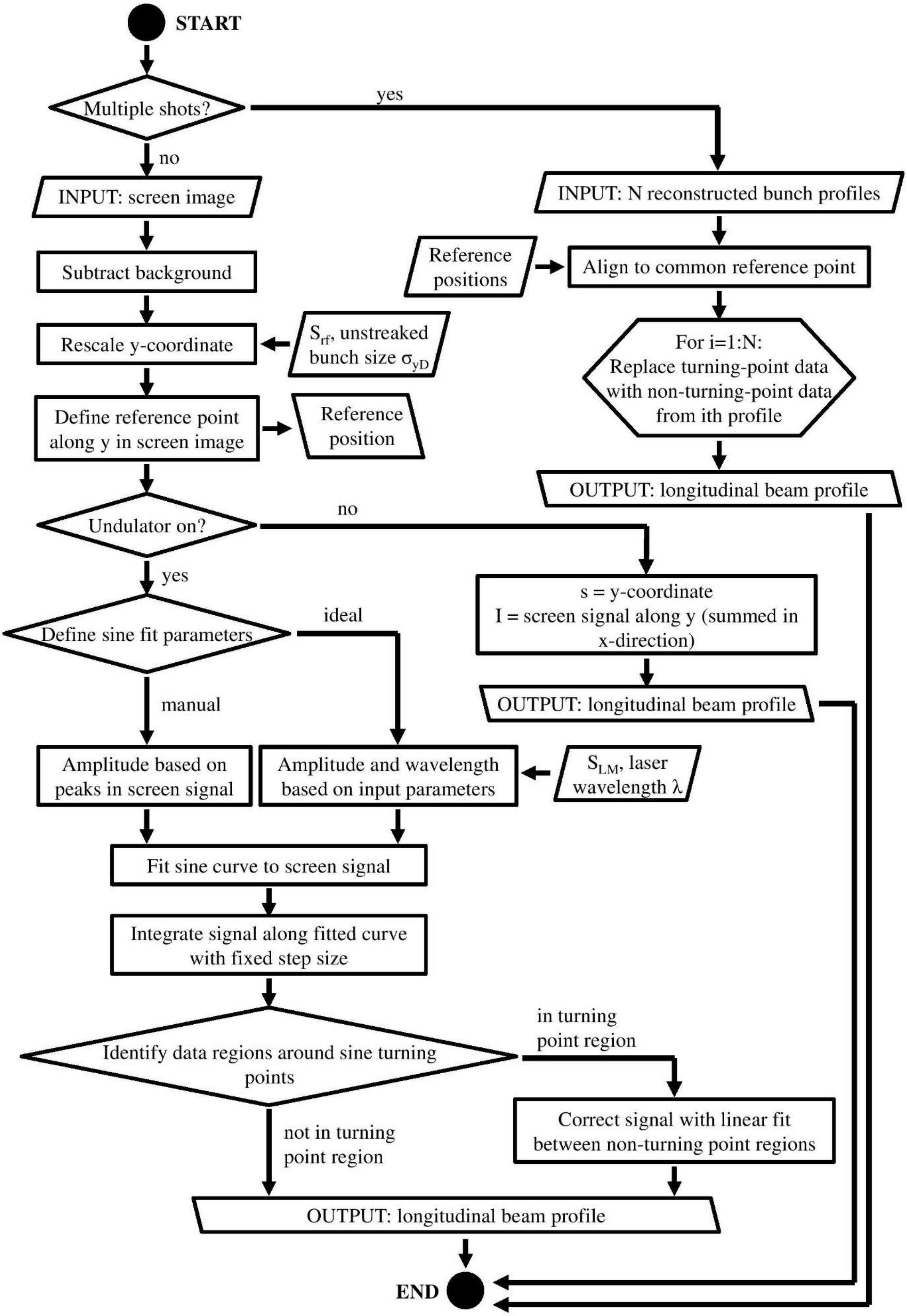

Figure 2: Main algorithm applied in the reconstruction tool.

Examples for recovered bunch profiles from the analysis tool:

Note that the files used for this example can be found with this documentation labelled as SampleDistribution1. In each case, the physical dimensions of the screen images are provided in the title of the .tif images following the expressions “xdim” and “ydim”; these are required as input into the analysis tool for loading the images. No background is assumed in this simulation, so that the loading of a background file to subtract this source of noise is not required.

The attached files include :

- Simulated screen images of the streaked beam distribution as main input for three different phases of the electron beam relative to the laser in the undulator
- Simulated screen image of the unstreaked beam distribution (with laser modulator, no TDS) to determine the unstreaked beam size
- Log-files for each image containing the input parameters for laser modulator and TDS used in the simulation of the diagnostic measurement

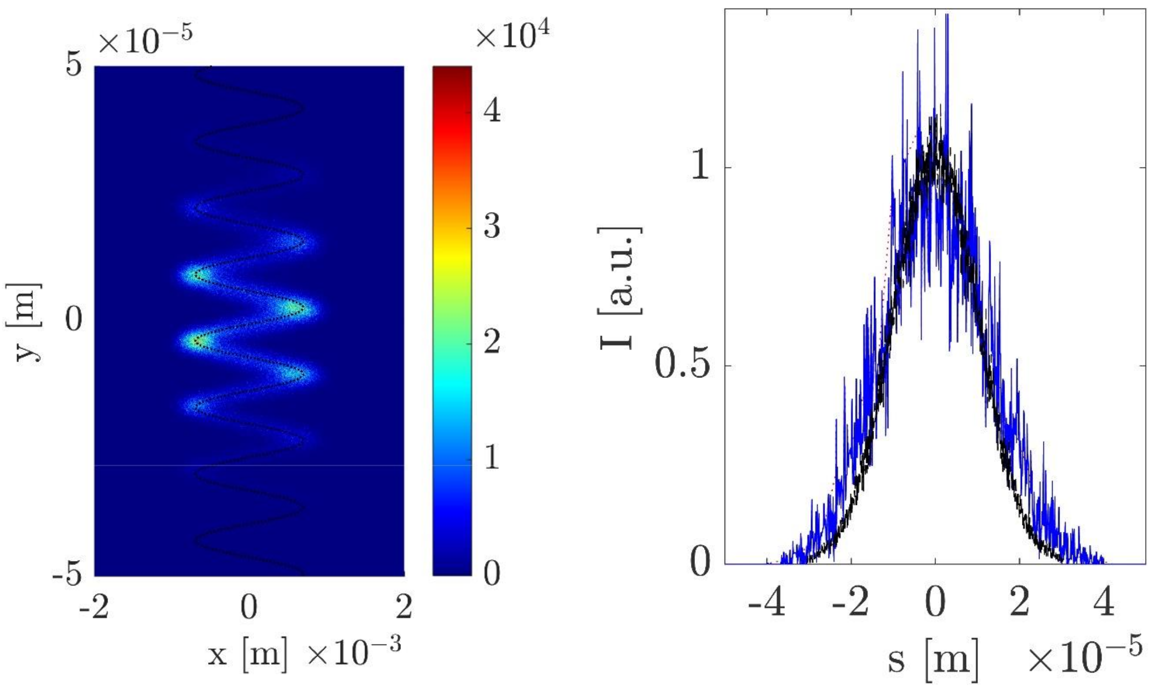

Figure 3: Reconstruction of a Gaussian electron beam with an RMS length of 10µm. Left: Simulation of a measured screen image as input to the reconstruction tool; the black line shows the sinusoidal fit that is applied to the signal during reconstruction. Right: Original longitudinal beam profile (black curve) together with two recovered longitudinal beam profiles based on reconstruction with a single screen image (dotted red curve) as well as with three screen images (blue curve). In the latter case, a reconstructed value for the RMS beam length of 12.33 µm is found.