

FAST IMAGE ANALYSIS FOR BEAM PROFILE MEASUREMENT AT THE EUROPEAN XFEL

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Abstract

At the European XFEL, images of scintillator screens are processed at a rate of 10 Hz. Dedicated image analysis servers are used for transversal beam profile analysis as well as for longitudinal profile and slice emittance measurement. This contribution describes the setup and the algorithms used for image analysis.

INTRODUCTION

The European X-Ray Free Electron Laser Facility (XFEL) consists of a 2.1 km long, superconducting linear accelerator which accelerates particles up to 17.5 GeV, followed by three undulator sections into which portions of the beam are distributed. Behind each undulator section, the photon beam is divided into multiple beamlines.

The electron beam consists of trains with up to 2700 bunches at a repetition rate of 10 Hz. With an inter-bunch repetition rate of 4.5 MHz, each bunch train is up to 600 μ s long [1].

Emittance Measurements

For beam size measurements, scintillator screens and wire scanners are available [2]. Different methods are applied for screen-based emittance measurements [3, 4]:

- On-axis measurement: Four screens are moved into and out of the beam one by one. This method has been well established at the FLASH linac [5], but is destructive and takes considerable time (several minutes).
- Off-axis measurement: Single bunches are extracted from the pulse train by fast kickers onto four off-axis screens. This measurement can be performed during the FEL operation and takes less than 10 seconds (including statistics over multiple images taken at 10Hz).
- Multi-quadrupole scans: The beam size is measured on a single screen, dependent on the strengths of multiple quadrupoles. This makes it possible to measure with a higher precision since more measuring points are available, and the beam size can be magnified. The duration of a measurement is several minutes.
- Slice emittance measurement: By a transverse deflecting structure (TDS), a bunch is streaked in one transversal direction and then deflected by a fast kicker onto an off-axis screen [6]. The longitudinal profile can then be measured in the streaked plane, while slices can be analyzed in the perpendicular plane.

Camera Servers

Cameras are controlled by DOOCS servers [7] which expose camera and processing parameters to control system clients. Client programs also read the produced images via DOOCS over the network. The camera images have a resolution of max. 1750x2330 with a 12 bit depth, resulting in 16 bit grayscale images. Each camera server runs on a μ TCA crate with 4 hyper-threaded CPUs and up to 6 cameras attached.

FAST IMAGE ANALYSIS

Traditional implementations of transversal beam profile measurement as used in FLASH operated as central servers which read images from the distributed camera servers. Off-Axis measurement at the XFEL requires to process up to 4 different screens simultaneously. With a rate of 10 Hz and an image size of 8 MB, even a single camera would already use up the available network bandwidth. Besides that, the analysis of such big images is quite CPU intensive. This situation suggests to consider local processing directly on the μ TCA crates in order to eliminate network traffic, and to look for optimized algorithms which reduce the CPU utilization.

Image Analysis Server

The image analysis server is implemented in C++ as a DOOCS server. It runs directly on the μ TCA crates and supplements the camera server. Image data are exchanged asynchronously through ZeroMQ [8] channels. Each image is processed in a separate thread. Fig. 1 illustrates the setup.

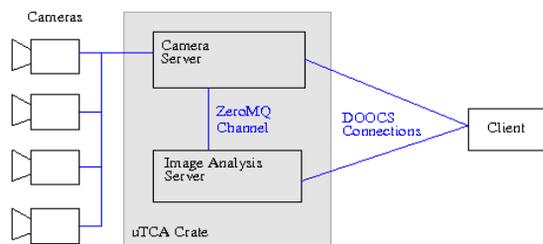


Figure 1: Setup of camera and image analysis servers.

Performance Improvements

The analysis needs to be fast and reliable. It is performed entirely on x and y axis projections in order to make the processing as fast as possible. It mainly consists of Gaussian fits and RMS calculations, making use of the OpenCV [9], GSL [10], and armadillo [11] libraries.

An obvious question is how image size reduction could improve the performance and how this would affect the accuracy of the results.

Figure 2 shows how size reduction effects the processing time and accuracy of the calculated values of sigma as a result of the Gaussian fit. These measurements were made with test images of 2000x2000 pixels with simulated Gaussian-distributed beam spots, sigmas of 10, 20, and 50 pixels, and added noise with an amplitude of 5% of the maximal intensity. The downscaling size is the length of each side of the reduced image.

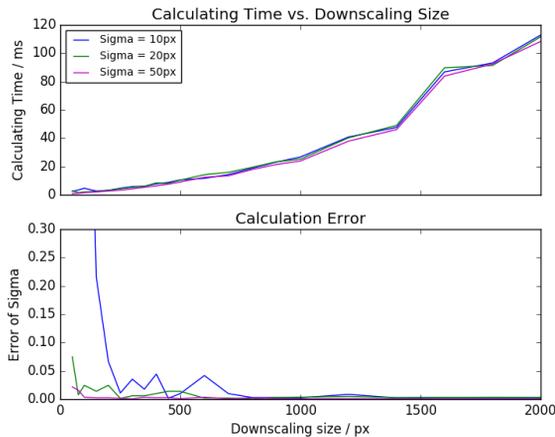


Figure 2: Processing time and calculation error versus downscaling size for different beam sizes.

As it can be expected, downscaling drastically reduces the processing time for the analysis. The OpenCV library scales images very efficiently. The computing time needed for the downscaling turns out to be small compared to the gained processing time so that it does not compensate the advantage.

It shows that the accuracy of the results is only slightly affected by the downsizing as long as the size of the beam spot is large enough compared to the downscaling size. For small beams however, the error increases significantly when the downscaling size becomes too small.

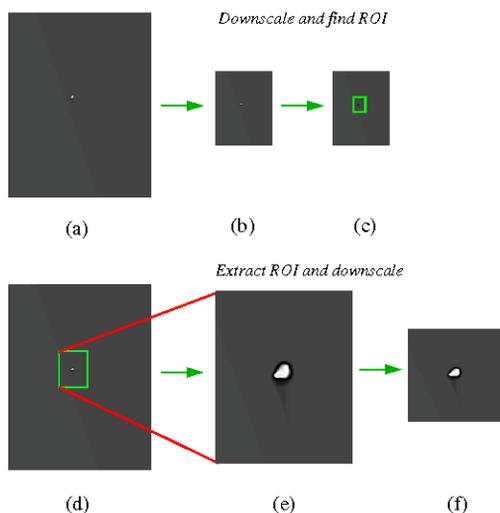


Figure 3: Overview of the downscaling process.

In order to improve the accuracy of the results, we use a two-step scheme as illustrated in Fig. 3. First the original

image (a) is downscaled to a predefined size (b). From the downscaled image, the beam size and position can be determined to define a region of interest (c). The ROI is then applied to the original image (d) and the corresponding portion of the image is extracted (e). If necessary, downscaling is applied once again to the extracted image (f), and the result of that is finally used for the analysis. Fig. 4 shows how this procedure influences the calculation time and the error of the result in contrast to Fig. 2.

Experiences

With reasonable settings for the downscaling sizes used for ROI and analysis, we can reduce the overall computing time for an analysis by about a factor of 20 without losing accuracy. In practice, 300-400 pixels side length are used for the ROI downscaling which is large enough for very small beam sizes. The second downscaling usually becomes relevant only for slice analysis.

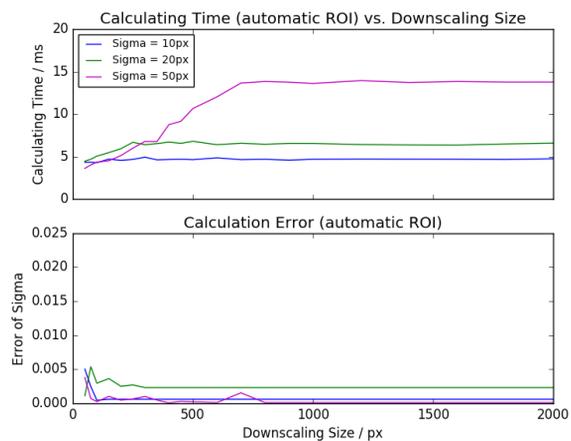


Figure 4: Calculation time and error versus downscaling size when a ROI is applied.

Disturbances

On images of 4-segment CCD cameras, background disturbances as shown in Fig. 5 often occur. These are due to radiation which influences the readout process inside the camera electronics. Since the observed artifacts show up as spikes in the axis projections, which can make it difficult to calculate the beam size and position correctly.

For performance reasons, we do not apply preliminary noise reduction to the whole image. Instead, a peak detection algorithm can be applied on the projections before the ROI calculation. It can additionally be supplemented by Gaussian smoothing. The latter can also work as kind of an image stabilizer that keeps the ROI more stable if multiple pictures are taken. Alternatively, we also use an area average instead of linear interpolation algorithm [9] for downsizing. This has a noise reduction effect, although at the price of higher CPU consumption. The final analysis is performed within the region of interest where such disturbances are not significant any more since most of the background noise has been cut away.

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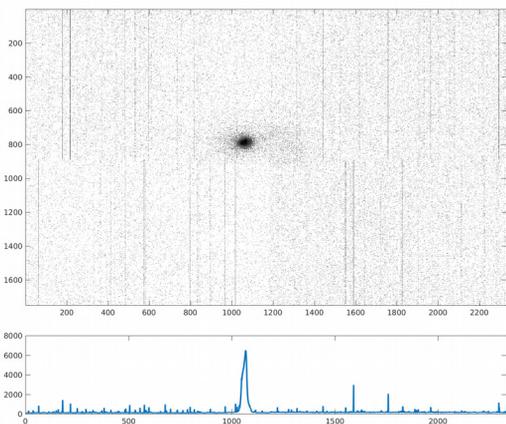


Figure 5: Artifacts due to radiation effects in the camera.

SLICE ANALYSIS

As a basis for slice emittance measurements, the camera images need to be divided into horizontal or vertical slices. Each slice is analyzed separately (Fig 6).

The base point for the slicing is the center of the beam which can be determined by different methods. The size of the slices can either be relative, based on the beam dimensions (sigma) or given in pixels.

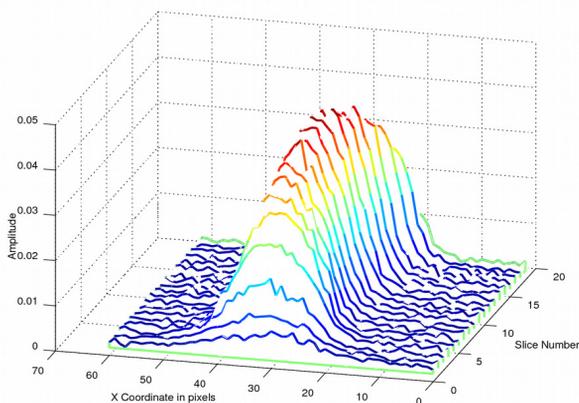


Figure 6: Principle of slicing.

Table 1 shows in which way different settings have an influence on the calculation times. Along the slice axis, the downscaling must not be too small so that the slice borders are still precise enough. The optimal setting here depends on the bunch length and the number of slices.

The example shows that a ROI together with moderate downscaling already speed up the analysis by a factor of 8. Further first-level and second-level downscaling also reduce the processing time, but hardly affect the slice analysis which takes the most CPU time. The computing time for slice analysis strongly depends on the number of slices. Nevertheless a slice analysis with a reasonable number of slices is possible at 10 Hz.

It is essential that slices can be identified by indices and that slices from the different screens in the diagnostics section have a common reference point and can be related to each other. The profiles of the individual slices are made available, which could become useful for phase space tomography in the future [12].

Table 1: Processing Times for Slice Analysis.

50 Slices						
Settings						
ROI active	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE
ROI Downscaling	None	500	500	200	200	200
Analysis Downscaling	None	1000	500	500	200	200
Processing Times / ms						
Analysis	9.81	3.04	1.72	1.59	1.00	
Conversion+Downscaling+Projections	72.50	5.44	3.10	2.91	1.24	
ROI	0.00	4.08	3.96	0.79	0.79	
Slicing + Slice Analysis	140.34	20.40	19.65	19.74	19.05	
Total	222.65	32.97	28.43	25.03	22.05	
20 Slices						
Settings						
ROI active	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE
ROI Downscaling	None	500	500	200	200	200
Analysis Downscaling	None	1000	500	500	200	200
Processing Times / ms						
Analysis	9.74	3.09	1.71	1.63	0.97	
Conversion+Downscaling+Projections	66.78	5.43	3.21	3.96	1.21	
ROI	0.00	3.90	3.95	0.81	0.82	
Slicing + Slice Analysis	60.23	7.40	6.89	6.77	7.99	
Total	137.48	19.82	15.76	13.17	10.99	

Configuration

The operation of the image analysis server can be controlled by a large set of parameters in order to adjust it to different situations and measurements. A graphical configuration tool (Fig. 7) is therefore most helpful in order to configure the servers properly and immediately see the results. For each camera, distinct parameter sets can be stored and recalled.

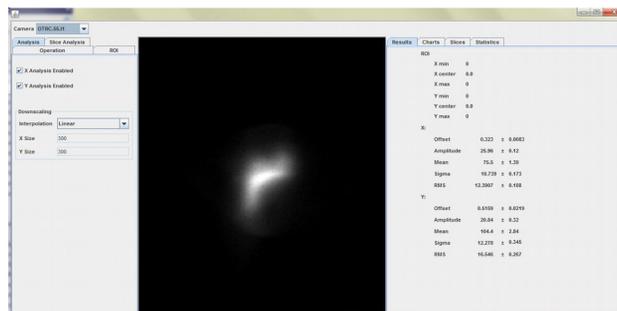


Figure 7: A screenshot of the image analysis configurator.

Offline Analysis

For performance reasons, the image analysis server does not store raw image data. Additional offline tools are supplied to collect and analyze images separately. This has proved useful to check parameter settings and verify measurements as well as to debug and test the algorithms. Measurement results can be stored in JSON format so that they can easily be read by many programming languages like MATLAB, Python, or C++ for further analysis, comparison, and processing.

STATISTICS

Beside continuous image analysis at 10 Hz, the image analysis server is also required to process series of images and produce a total result of averages and errors. Error estimations have special importance for emittance measurements. Therefore it can operate in a sampling

mode where a given number of images are analyzed, and a final result is delivered. This is done for both simple analyses and slice analyses as well. Filtering allows to throw out invalid shots if desired.

In the case of slice analyses, coordinates of different ROIs and downscaling factors need to be normalized to a common base and interpolated, and slices of multiple images have to be matched. Fig. 8 shows a typical result of a slice emittance measurement.

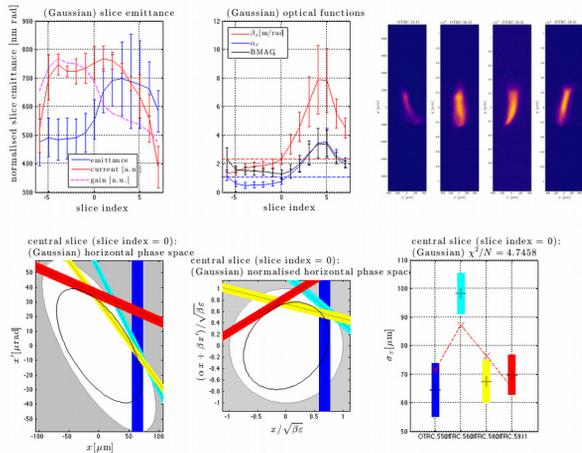


Figure 8: Result of a slice emittance measurement.

CONCLUSION

At the European XFEL, optimized image analysis servers have been developed and implemented. They are well established for emittance and slice emittance measurement. These servers calculate beam profiles or perform slice analyses at a rate of 10 Hz. A two-staged size reduction scheme is used to accelerate the processing. Experience has shown that that analysis works precisely

and reliably, and that each image analysis server is able to process up to four image streams in parallel at a 10 Hz rate on μ TCA hardware.

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