THE FERMI@ELETTRA CCD IMAGE ACQUISITION SYSTEM

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Abstract

FERMI@Elettra is a new 4th generation light source based on a linac-driven Free Electron Laser (FEL) which is currently being built in Trieste, Italy. The CCD image acquisition system is a fundamental diagnostic tool for the commissioning of the new accelerator. It is used for the characterization and tuning of the laser, electron and photon beams. The Tango based software architecture, the soft real-time performance and the embedded image processing algorithms are described.

ACQUISITION SYSTEM

CCD

Three Basler CCD cameras (model scA780-54, scA1390-17 and scA1400-17) are currently integrated in the image acquisition system. All of them provide a Gigabit Ethernet connection and a hardware trigger input for the synchronization, and mainly differ for the number of pixels.

A total of 84 CCD cameras are installed:

- 16 are dedicated to the diagnostics of the photo-injector and seed lasers; their purpose is the measurement of the laser beam trajectory along the optical path and the characterization of the laser beam profile;
- 52 are integrated in the fluorescent screen system, which allows the analysis of the electron and photon beams along the linac and the FEL undulators;
- 16 are installed in the photon beam transport system and will be used for the measurement of the parameters of the photon beam provided to the experimental stations.

Up to 18 among the above mentioned CCD cameras have to be concurrently and continuously acquired.

Image servers

In the final configuration five server computers will take care of the acquisition of all the CCD cameras.

Each of them consists of a one-unit 19-inch rack mount server configured with two Xeon QuadCore 3.0GHz processors, 4Gb of DDR3 RAM and up to six Gigabit Ethernet links. One of them is connected to the control system network, three are dedicated to the acquisition of the CCDs and one is used for the real-time communication through the Network Reflective Memory (NRM) [1].

The servers run a GNU/Linux 2.6 kernel patched by the Xenomai real-time extension [2], which provides them with deterministic capabilities. This is used in particular by the Ethernet driver to share time-critical data among the control system computers using the NRM.

IMAGE PROCESSING

For each CCD, a Tango [3] device server is dedicated to the control of the main parameters like exposure and gain, performs the image processing and makes the results available to client applications running in the control room.

Performance and flexibility to adapt to the beam changes are the requirements that the processing software have to fulfil. The performance must guarantee to meet the deadlines because the acquisition and analysis of the image have to be done shot-by-shot. The maximum repetition rate of the linac is 50Hz, which means that a maximum of 20 ms is available to process each image. For this reason, it is convenient to analyze only the portion of image containing the beam profile, conventionally called Region Of Interest (ROI).

The image processing is divided into three steps: automatic ROI detection, calculation of the beam profile moments and data storing with a precise timestamp.

Automatic ROI Detection

Searching the beam spot inside an image could be a complicated task. Sometimes it is easier to find the parts of the image where there is no beam instead, i.e. to define the background.

In order to perform the ROI detection efficiently, the full scale image is under-sampled. The resulting samples size should be at least twice the minimum size of the beam spot in both planes in order to have at least a few points of the beam in the under-sampled image.

If necessary, the image is smoothed by a low pass filter to mitigate the presence of artifacts. A thorough design of the low pass filter parameters can dramatically enhance the magnitude of the beam profile with respect to the noise due to reflections on the vacuum pipe surface (Fig. 1).
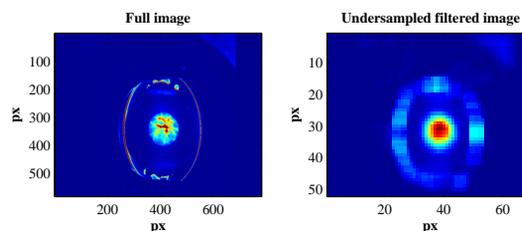

Figure 1: image of the electron beam measured at the exit of the photo-cathod gun, before (left) and after (right) the under-sampling/filtering process.

The background level is estimated through the analysis of the complementary cumulative distribution function of $P(X<=x)$, which represents the probability that a pixel value X is lower then x. This task is performed in three steps:

- subdivide the amplitude range of the image into *N* equally spaced values and store them in the array *vec_lev*[1..*N*];
- For each *vec_lev*[] element, count how many pixel values in the image are higher and store this count in the array *vec_area*[]
- Compare each element of the array *vec_area*[] with the predecessor. If the difference between *vec_area*[*n*] and *vec_area*[*n+1*] for *n*=1..*N*-1 is a above a predefined threshold *T*, then the background level is found (Fig. 2) and corresponds to *vec_lev*[*n+1*].

The experience demonstrates that for most of the beam shapes, with an 8-bit resolution image, a couple of optimal values is N=20, T=0.4.

We can assume that the pixel with maximum value in the under-sampled image corresponds to the centroid of the beam.
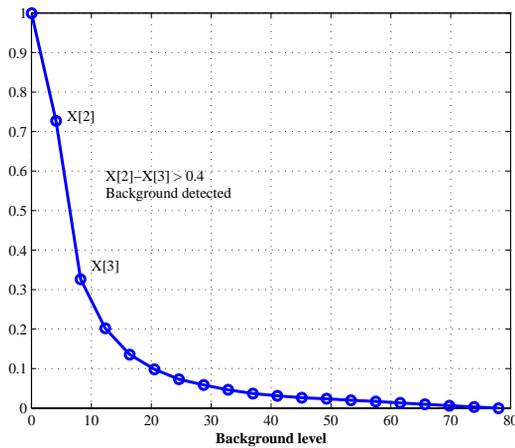

Figure 2: complementary cumulative distribution function calculated from the under-sampled image of Fig. 1

In order to find the ROI, each border of the square that initially contains the centroid is expanded until there is at least one pixel on the border which value is higher than the background level.
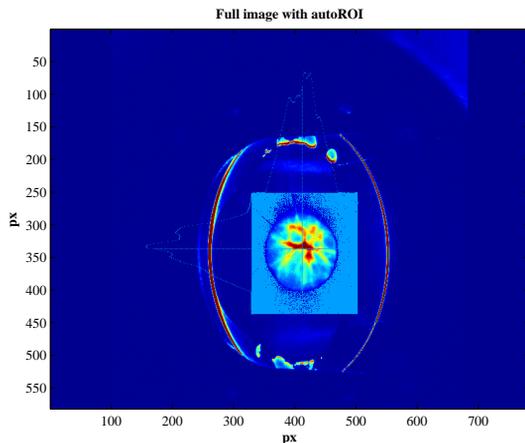

Figure 3: Final result of the image processing. ROI is highlighted directly on the image.

Once the expansion of the ROI around the beam has terminated, the coordinates of the ROI found in the under-sampled image are converted into the original image scales (Fig. 3).

Moments estimation

In order to estimate the moments of the beam profile, besides the "raw" algorithm (average and σ), three possible fitting functions can be used: gaussian, asymmetric gaussian and a seven-parameter function called "Confiteor" [4], of which the gaussian fitting function is a particular case. With the exception of the raw algorithm, the calculation of the fitting function parameters is based on the GNU Scientific Library (GSL) [5] non-linear least-squares algorithm.

A software library for the calculation of the jacobian matrix of derivatives needed in the iterative GSL algorithm has been developed. The fitting iterations stop when the predefined fitting error or a time limit is reached. The first and second moments are then analytically calculated.

The comparison of different algorithms shows that for a beam shape that is far from being gaussian, the gaussian fits could differ a lot from the correct result (Fig. 4).
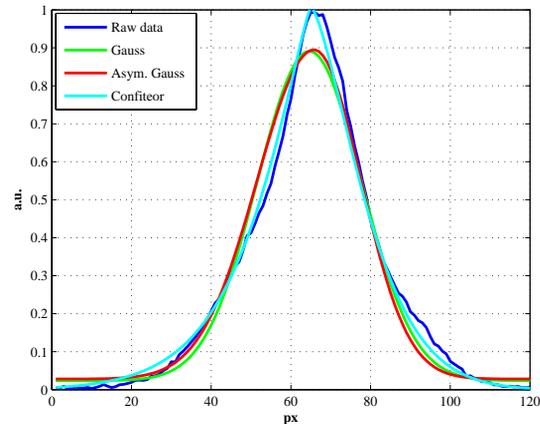

Figure 4: Comparison of the fitting functions applied to a beam which has not a gaussian distribution.

Table 1 shows the horizontal σ calculated by different algorithms and their performance. The results obtained with the raw algorithm and with "Confiteor" are in good agreement; the latter is slower but much more robust in case of "salt and pepper" noise.

Table 1: Comparison between different moment estimation methods (image with full scale size 782x582px, ROI size 120x200px)

Calculation mode	Processing time	σ_x
Raw	2.4 ms	0.309 mm
Gaussian	4.8 ms	0.255 mm
Asymmetric Gaussian	5.2 ms	0.254 mm
Confiteor	9.6 ms	0.326 mm

Data storage

The proprietary binary libraries provided by the CCD cameras vendor can only be used in the Linux user space domain , therefore it is not possible to acquire and store the CCD data in real-time. Despite this limitation, a thorough tuning of the priorities in the Tango device server and the overruling in the assignment of interrupts and processes to the eight CPU cores, allows anyway the acquisition of the beam image shot-by-shot in a reliable way.

The bunch number, a sort of time stamp which identifies each of the accelerated bunches, is distributed in real-time via the NRM along the accelerator. It is used to tag every acquired image and eventually unveil any misalignment (two images with the same bunch number) in the acquisition. The tagged images can be easily correlated with other diagnostics data (e.g. from BPMs, Charge Monitors, …) or with the strength of the accelerator magnets that can also be driven on a shot-by-shot basis.

The beam parameters calculated by the image processing are stored into circular buffers, which support both storing and retrieving operations in kernel and user space. The buffered data can be extracted specifying either the time limits or the bunch numbers. A number of filter methods (mean, median, Kalman, etc.) can be used to extract already de-noised data.

CLIENT APPLICATIONS

Graphical User Interface (GUI)

A GUI developed using Q-Tango [6] supervises the operation of the CCD cameras (Fig. 5). The graphical panel allows to deal with the CCD Tango device server API (attributes and commands) and visualizes the beam image at a selectable refresh rate and with the preferred false colour palette. It is possible to magnify the image, save a snapshot (TIFF) and store the image raw data (CSV).
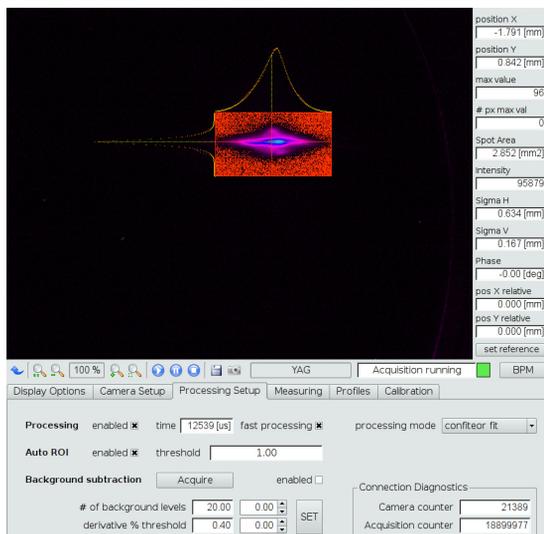

Figure 5: CCD control panel

Moreover, the panel features a smart interface for the CCD calibration process and for measuring distances in the beam image (pixel and mm).

Real-time Machine Physics Applications

The emittance is one of the most relevant parameters that must be optimized in a FEL. It could be measured by changing the focusing characteristics of a quadrupole magnet and measuring the corresponding size of the electron beam using a downstream fluorescent screen. By driving the quadrupole magnet current synchronously to the acquisition of the screen images, it is possible to obtain a good estimation of the emittance in less than 20 shots [7].

Another measurement that takes advantage of the shot-by-shot acquisition is the evaluation of the timing jitter of the electron bunches. The measurement consists in titling each electron bunch by means of a RF deflecting cavity with the proper phase, and intercepting it with a fluorescent screen. The projected image acquired by the CCD represents the longitudinal profile of the bunch and the movement of the centroid in the vertical axis corresponds to the beam timing jitter.

CONCLUSION

The CCD camera acquisition system is one of the most important diagnostics tools for the commissioning of the new accelerator. The capability to acquire beam images and correlate them with the other machine parameters on a shot-by-shot basis has contributed significantly to the success of the commissioning operations.

The auto-tuning of the image processing algorithms, the optimization of the processing code and the introduction of an abstraction layer to allow the integration of other CCD camera vendors, are some of the new developments foreseen for the future.

REFERENCES

[1] M. Lonza et al., "Beam-based feedbacks for the FERMI@Elettra Free Electron Laser", IPAC'10, Kyoto, May 2010.

[2] http://www.xenomai.org

[3] http://www.tango-controls.org

[4] A. Lutman, Private communications, May 2010.

[5] http://www.gnu.org/software/gsl/

[6] G. Strangolino et al., "QTango: a Library for Easy Tango Based GUIs Development", ICALEPCS'09, Kobe, October 2009.

[7] S. Di Mitri et al., "Recent Commisioning Experience on the FERMI@Elettra First Bunch Compressor Area: Investigations of Beam Dynamics, Modeling and Control Software", FEL'10, Malmö, August 2010.