IMAGE PROFILE DIAGNOSTICS SOLUTION FOR THE TAIWAN PHOTON SOURCE

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Abstract

TPS (Taiwan Photo Source) is a third generation 3 GeV synchrotron light facility, featuring ultra-high photon brightness with extremely low emittance which will be a state-of-the-art synchrotron radiation facility and is being in construction at National Synchrotron Radiation Research Center (NSRRC) campus. Beam image profile and its analysis play an important role in beam diagnostics of a particle accelerator system. However, due to the CCD image collection devices are distributed around the linac, booster, and storage ring, a distributed EPICS system based image profile diagnostics solution was proposed, which are based on GigE Vision camera with PoE support. This solution provides an easy way for cabling, and delivery adequate performance. Implementation plan for the TPS and results of prototype test at existed facility to examine functionality of hardware and software will be summarized in this report.

INTRODUCTION

The TPS is a state-of-the-art synchrotron radiation facility featuring ultra-high photon brightness with extremely low emittance [1]. Civil construction was started from February 2010. The building will be finished in 2012. Machine commissioning is scheduled in late 2013. User service will start from 2014. The TPS accelerator complex consists of a 150 MeV S-band linac, linac to booster transfer line (LTB), 0.15–3 GeV booster synchrotron, booster to storage ring transfer line (BTS), and 3 GeV storage ring. The storage ring has 24 DBA lattices cells with 6-fold symmetry configuration. The latest generation diagnostic systems will equip to help TPS achieve its design goals.

To optimize the machine operation and diagnostic applications, the beam profile and its analysis play an important role in the beam diagnostics of a particle-accelerator system. The use of a destructive (fluorescent screen, YAG:Ce, $Y_3Al_5O_{12}$ [2]) or non-destructive (Microchannel plate, MCP [3]) screen monitor, or a synchrotron radiation monitor [4] to measure the beam profile is a simple mechanism that has been widely used in synchrotron facilities. The beam-profile image conveys extensive information about beam parameters, including the beam centre, sigma, tilt angle etc. As is customary, the beam profile as a two-dimensional (2D) image is recorded with cameras. The fluorescent screens that convert the flux density of the beam into a measurable signal as a function of position, and a charge-coupled device (CCD) camera for image acquisition, are used in applications of this kind. Thanks to inexpensive CCD cameras and the availability of computer technology, the obtaining, storage and analysis of 2D images has become easier and quicker. The images of the beam as recorded with cameras are most conveniently represented as light intensity with 2D circular or elliptical Gaussian distributions.

In this report, a distributed EPICS system based image profile diagnostics solution was proposed, which are based on Gigabit PoE (Power over Ethernet) embedded vision system with PoE camera. This solution provides an effective way to simplify wiring, and increased performance, load independence and reliability, which can be used at various places such as screen monitor, synchrotron radiation monitor, ICCD, and streak camera, as a standalone image acquisition and processing system.

OVERVIEW OF INFRASTRUCTURE

The infrastructure is developed by using a Gigabit PoE embedded vision system installed the EPICS IOC and integrated with Matlab program to build up a data acquisition and processing system. For the beam diagnostic application, this system is responsible for the beam profile acquisition from fluorescent screen, gated ICCD or streak camera, and used to analysis to find the beam characteristic data. The infrastructure employed can be divided into hardware and software components as described in the following subsections.

Vision System and Camera

In the image profile diagnostics solution, a Gigabit PoE embedded vision system (ADLINK, EOS-1200 [5]), as shown in Fig. 1, was used instead of traditional computer and switch. This device is a rugged and compact embedded vision system equipped with the 2nd generation CPU (i7) and four independent PoE ports. It also supports a rich I/O capability, including four serial ports (RS232/422/485), two USB 3.0 ports, 32 PNP/NPN isolated digital I/Os, which make it ideal to integrate, and deploy with other subsystem for system development.

Figure 1: Gigabit PoE embedded vision system.

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Two type of GigE Vision PoE cameras are available which consist of square pixel size of 7.4 μm × 7.4 μm and 3.75 μm × 3.75 μm for low-precision measurement of screen monitor at linac, LTB, BTS, booster, and high-precision measurement of synchrotron radiation monitor at storage ring. The cameras have software and external trigger input port which can be used to capture image by software control or receive trigger signal from event based timing system [6] for periodic data acquisition. Due to we are interested in the intensity of the beam profile, the monochromatic mode of this camera was used in this application. The GigE Vision camera is connected with Gigabit PoE embedded vision PC by Ethernet interface to build up local area network. The CCD power can be controlled via the PoE manager function for device resetting.

Software

The Gigabit PoE embedded vision system, running a Linux operating system based on EPICS, is designed as an IOC (Input / Output Controller) for data capture, analysis, and other devices control. For one of the applications (screen monitor), the block diagram of software (IOC, Matlab, and GUI) and hardware configuration is shown in Fig. 2. There are three EPICS IOCs build-in which responsible for CCD image capture and parameter control, analysis results storage, and motion stage control, respectively. One analysis program constructed by Matlab running on host can get raw image array from IOC1 and analysis the key parameters (sigma, center position, tilt) then write into IOC2. All the variables are the EPICS PVs which can remote set/get whole parameters via channel access (CA). A graphical user interface was developed to control/monitor the system.

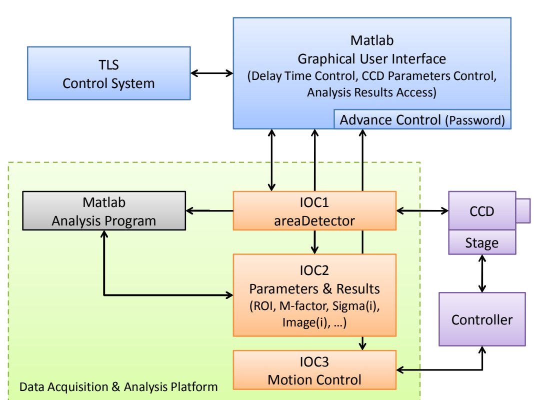

Figure 2: The block diagram of software and hardware configuration.

Users Interface

The user interfaces are constructed by Matlab GUI. The layout of the Matlab display GUI for screen monitor is shown in Fig. 3. Through the Channel Access (CA, LabCA) [7], the Matlab program can read/write the database records. The GUI can run in multiple clients simultaneously and read the analysis results from EPICS IOC and display them in the window. The GUI contains six parts: menu, toolbar, control panel, fitting results, projected profile, and raw image. The menu and toolbar provide save data, colormap change, ROI specify, simulation, reset and close program, and zoom in/out functions. In the control panel it contains active the program, 3D viewing, multi-exposure, and background subtract functions. The fitting results area contains sigma and centroid data in the units of pixel and mm, and beam tilt angle. Two directions, horizontal and vertical, of beam projected profile of raw data and fitting curve are predrilled in two axes. The camera raw image with the colorbar is integrated into the display GUI. The function of export the raw image data and analysis results can be done. It also can create a simulated beam image for the purpose of evaluating the fitting correctness. In this study, the compiled Matlab programs help us to develop standalone application without running it in Matlab prompt which is to minimize the requirement of licence and save budget.

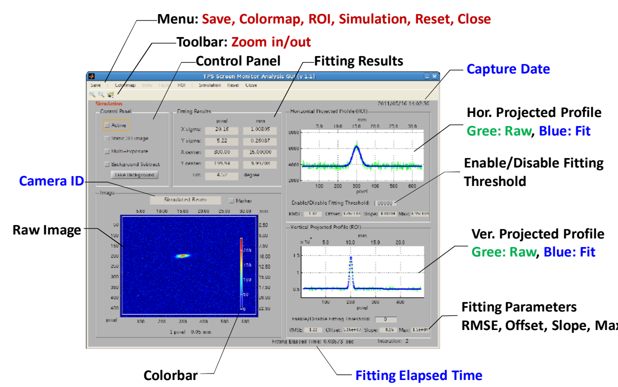

Figure 3: Layout of the Matlab display GUI.

Analysis Methods

For the analysis of projected 2D circular or elliptical Gaussian distribution beam profiles. This Gaussian curve fit by least-squares minimize, called “lsqcurvefit” method is one of the optimization toolbox in Matlab which can solve nonlinear curve-fitting problems in the least-squares sense that minimized the sum of squared differences between the measured and predicted data. “lsqcurvefit” is an iterative method which returns results that minimizes the residuals when the tolerances supplied are satisfied. That is, given input data *xdata*, and the observed output *ydata*, find coefficients *x* that “best-fit” the equation *F(x,xdata):*

$$\min_{x} \frac{1}{2} \sum_{i} \left(F(x, xdata_i) - ydata_i \right)^2 \tag{1}$$

, where *xdata* and *ydata* are vectors and *F(x,xdata)* is a vector valued function. This method can be used to deal with high signal-to-noise levels image, but it takes a long computing time due to it is an iterative algorithm. Fortunately, the maximum number of function evaluations (MaxFunEvals, default 500) and iterations

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(MaxIter, default 400) allowed, and termination tolerance (TolX, default 1e-6) can be configured to satisfy operational requirements. The algorithm was developed and tested in Matlab environment. The beam profile images model can be built by a general two-dimensional elliptical Gaussian function, as expressed by

$$f(x,y) = A\mathrm{e}^{-\left(a(x-x_0)^2+2b(x-x_0)(y-y_0)+c(y-y_0)^2\right)} \quad (2)$$

, here the coefficient A is the amplitude, x_0, y_0 are the center of x, y and a, b, c are defined as following:

$$\begin{aligned} a &= \frac{\cos^2\theta}{2s_x^2} + \frac{\sin^2\theta}{2s_y^2} \\ b &= -\frac{\sin 2\theta}{4s_x^2} + \frac{\sin 2\theta}{4s_y^2} \\ c &= \frac{\sin^2\theta}{2s_x^2} + \frac{\cos^2\theta}{2s_y^2} \end{aligned} \quad (3)$$

, where theta (θ) is the rotate angle and s_x, s_y are the sigma of x and y.

Timing Evaluation of Analysis Program

A timing evaluation of the analysis program was made. Two key processes can affect the time required for each image frame processing procedure: reading/writing data from PV via EPICS channel access, and fitting the projected profiles. The reading or writing of data from PVs, including some conditions and raw image data array, takes less than 20 ms with camera exposure time. The data processing, including twice fitting (horizontal and vertical) and recognition of the tilt angle, takes less than 50 ms. The program thus requires less than 70 ms per cycle, which implies a maximum rate around 14 Hz of processing. This performance is adequate for the TPS 3-Hz and TLS (Taiwan Light Source) 10-Hz facilities.

IMAGE DIGNISTIOCS PLANS

Screen Monitor

There are 21 screen monitors are designed in the TPS located at linac (5), LTB (5), booster ring (6), and BTS (5). Fluorescent screens will be installed at injection and extraction section and at the other lattice cells to facilitate booster commissioning, troubleshooting and psychology needing – to see is to believe. The screen material will be YAG:Ce, which has excellent resolution of the beam image and exhibits high sensitivity and high radiation hardness. The linac, LTB, booster and BTS are configured almost identically with same cameras and the infrastructure is shown in Fig. 4. The 10/24 ports PoE switches are used to connect the cameras then uplink to the vision system EPICS IOC. The IOC is constructed based on Linux OS with areaDetector EPICS module [8] and compiled Matlab analysis program. The camera timing trigger clock is locked with TPS injection system, which is produced from a timing IOC via copper cable.

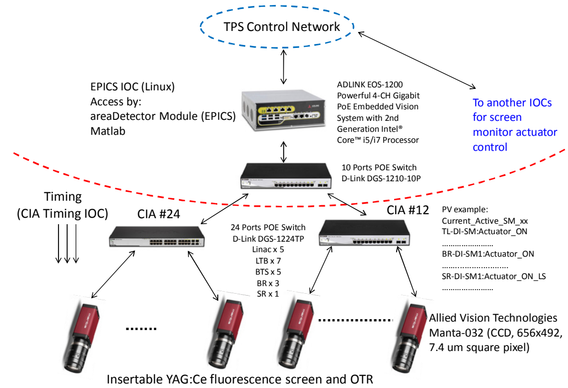

Figure 4: TPS screen monitor configuration plan.

Synchrotron Radiation Monitor

Synchrotron radiation from a dipole will be used to observe the beam profile at TPS. The synchrotron radiation monitors are designed in LTB, BTS, booster, and storage ring. In the LTB and BTS, a simple visible light optics at bending magnet captured by external trigger GigE Vision CCD camera is planned for useful routine operation. In the booster synchrotron, near UV optics and synchronized with the machine cycle is planned. The photon diagnostics for the TPS storage ring will utilize visible light and X-ray of the synchrotron radiation generated in a bending magnet. In the storage ring, due to the small beam size and emittance (~1 nm-rad), an X-ray pinhole camera with crystal screen and GigE Vision CCD camera is planned, and possible for the feedback signal for beam size feedback. Two X-ray pinhole cameras imaging of the electron beam from bending magnets is the baseline design for the TPS emittance measurement. As they offer the required resolution and the dynamic range to measure the electron beam size accurately at all stored beam currents from below 1 mA to 500 mA range. Optimization of the X-ray pinhole system will give possibility to measure very small beam sizes in a few microns typically. Its main function will include measurement of the electron beam energy spread and vertical beam size. A near UV light profile measurement for low light application and visible light synchrotron light interferometer for precision beam size measurement are also planned in TPS storage ring.

Streak Camera and Gated ICCD

Synchrotron radiation from a dipole has the capability to monitor bunch length with a streak camera and beam dynamic profile with a gated ICCD, which will be also provided in TPS. Visible light beamline station will be built to measure various beam parameters by streak camera, ICCD camera and interferometer. Streak camera operates at 250 MHz synchroscan mode is preferred to observe beam behavior of the consecutive bunches. Integrating the streak camera and ICCD system with EPICS IOC on Gigabit PoE embedded vision system are preferred. Due to these two kinds of diagnostics devices need timing trigger signal for doing correct actuation. Another cPCI timing platform is needed. The event

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receiver (EVR) card plugged in cPCI platform which can provide the precisely timing trigger signal received from EVG (event generator system, it is available in TPS) for streak camera and ICCD applications.

PROTOTYPE TEST

Prototype of the proposed system was development and pre-test in TPS linac screen monitor and TLS booster synchrotron. The results will be presented in following subsections.

TPS Linear Accelerator

The TPS 150 MeV linac system was contracted to the RI Research Instruments GmbH (former ACCEL Instruments GmbH) [9]. The hardware of beam instrumentation comprises five YAG:Ce screen monitors were provided by the vendor and each screen is mounted at 45° to the beam direction and driven with a pneumatic driver. The fluorescent light is emitted in the horizontal direction. The optics consist a refraction mirror to bend the light 90° to the 75-mm lens and a GigE Vision CCD camera. The five screen monitor beam profiles are shown in Fig. 5.

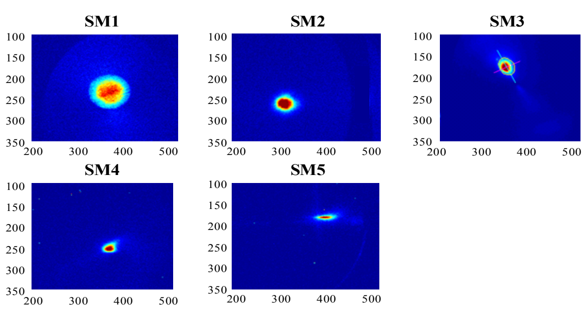
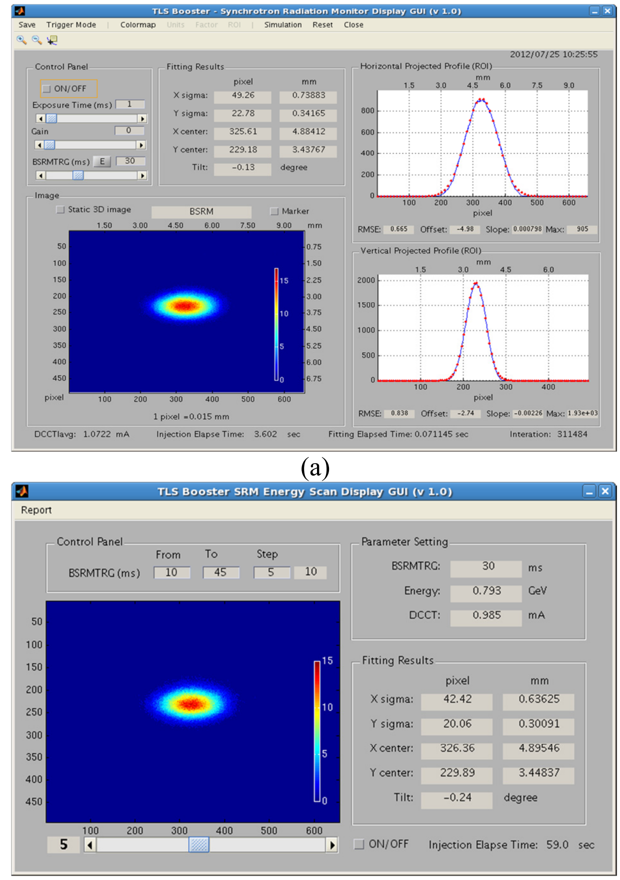


Figure 5: Beam profiles of the TPS linac screen monitor.

TLS Booster Synchrotron

For the TLS booster synchrotron, the layout of the synchrotron radiation monitor consists of molybdenum mirror, vacuum window, lens, band-pass filter (BPF, 550 nm, spectral width 10 nm), a GigE Vision CCD camera, a two axes motion stage and an EPICS IOC. The photons of synchrotron radiation emitted by the electron bunches passing through a dipole in the booster ring are reflected from a molybdenum mirror and passed through a convex lens (f = 500 mm) onto a CCD image sensor. The simple optics offers image reduction 2:1. The user interfaces are shown in Fig. 6. The fixed energy mode, as shown in Fig. 6(a), the beam profile was recorded right at the CCD exposure time and trigger delay set to 1 msec and 30 msec (corresponding to the energy is around 0.8 GeV). The scan energy mode, as shown in Fig. 6(b), can automatically adjust the trigger delay and record the data sequentially. Raw image and fitted parameters are published as EPICS PVs, it can access by application clients for further usage.



(a)

(b)

Figure 6: TLS booster synchrotron radiation monitor user interface. (a) Fixed energy mode; (b) Scan energy mode.

The synchrotron radiation monitor of the booster synchrotron can serve to diagnose the ramping process of the booster. In the TLS booster, the electrons are produced from an electron gun and accelerated to 50 MeV with a linear accelerator. Before the beam is extracted to the storage ring, the energy of the electron beam in the booster is increased from 50 MeV to 1.5 GeV within a 50-ms ramping process. The beam size decreases when the energy increases. The CCD trigger timing must be adjustable within the ramping cycle. The duration of CCD exposure should be as small as possible. The beam size during the ramping process is a function of time.

The summarized beam profiles and key parameters during acceleration in TLS booster are shown in Fig. 7, and the measured beam size variation, beam center position and beam tile angle were listed inside. The measured variation of beam size and position of the beam center with energy ramping point are shown in Fig. 8 and Fig. 9. It is clearly shown that the beam size will become smaller when energy increased. There is a significant position shift in horizontal at the ramping time around 45 msec due to the bumper fired. The tile angle of the beam profile is almost the same during whole ramping process.

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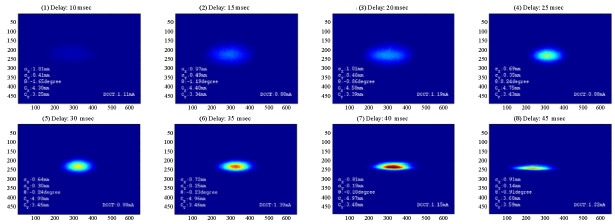

Figure 7: TLS booster synchrotron radiation profiles based on 1 msec CCD exposure time at different energy ramping point (Energy scan mode).

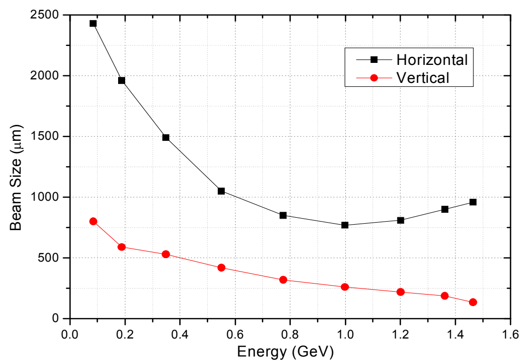

Figure 8: Measured variation of beam size with energy ramping point.

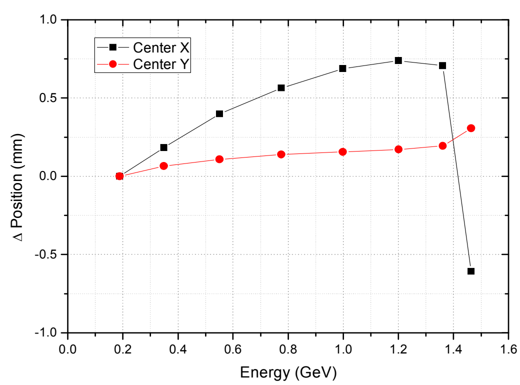

Figure 9: Measured variation of the position of the beam centre with energy ramping point.

The stability of the ramping process of the booster synchrotron plays an important role as injector for a synchrotron light source. The TLS booster synchrotron is designed to accelerate electrons from linac 50 MeV injection to full operational energy 1.5 GeV with stored beam current about a few mA. This repetition rate is 10 Hz. Continuous observation of the difference of beam profile variation during ramping energy can be used as indicator related to the operation stability of the booster synchrotron. With the CCD trigger delay fixed at 10, 20, 30 and 40 ms, the ramping beam profiles (eight times) are recorded. These results of the beam profile show that the beam size slightly altered at the same ramping energy point during the eight captures, especially in the low energy region. The possible reason of this variation may be the signal-to-noise ratio lower at the lower energy region. Experiments confirmed that by appropriately adjusting the gain value of CCD, which can effectively reduce the variation. An average beam size of horizontal and vertical and its deviation at varied energy points is shown in Table 1. The design of the current imaging system of the TLS booster synchrotron radiation monitor allows measurement of all required parameters (beam size, centroid and orientation tilt angle) with sufficient resolution for current beam tests.

Table 1: Eight Captures Average Beam Size of the Horizontal and Vertical and its Standard Deviation at Varied Energy Points

Trigger (ms) Energy (MeV)	10 188	20 550	30 999	40 1362
σ_x (mm)	1.96±0.16	1.09±0.12	0.77±0.03	0.91±0.01
σ_y (mm)	0.61±0.03	0.48±0.04	0.26±0.02	0.18±0.01

*CCD parameters: exposure time = 1 msec, gain = 0.

SUMMARY

The design and implementation of the beam image diagnostics system for the TPS are in proceed. A distributed EPICS IOC system based image profile diagnostics solution was proposed, which are based on GigE Vision CCD camera with PoE support. Compiled Matlab programs are running in this platform as a data processing engine, this approach is efficient method to develop image analysis application. The prototype will be implemented and tested for all screen monitors of the TPS and synchrotron radiation monitor of the TLS booster synchrotron. The testing results shown the system can satisfy the requirement of TPS.

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