OPERATION OF A SINGLE PASS, BUNCH-BY-BUNCH X-RAY BEAM SIZE MONITOR FOR THE CESR TEST ACCELERATOR RESEARCH PROGRAM*

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Abstract

The CESR Test Accelerator (CESRTA) program targets the study of beam physics issues relevant to linear collider damping rings and other low emittance storage rings. This endeavour requires new instrumentation to study the beam dynamics along trains of ultra low emittance bunches. A key element of the program has been the design, commissioning and operation of an x-ray beam size monitor capable, on a turn by turn basis, of collecting single pass measurements of each individual bunch in a train over many thousands of turns. This new instrument utilizes custom, high bandwidth amplifiers and digitization hardware and firmware to collect signals from a linear InGaAs diode array. The instrument has been optimized to allow measurements with 3×10^9 to 1×10^{11} particles per bunch. This paper reports on the operational capabilities of this instrument, improvements for its performance, and the methods utilized in data analysis. Examples of key measurements which illustrate the instrument's performance are presented. This device demonstrates measurement capabilities applicable to future high energy physics accelerators and light sources.

INTRODUCTION

The X-ray Beam Size Monitor (xBSM) provides experimenters in the CESRTA program with the ability to measure the vertical beam size of individual particle bunches on a turn-by-turn, single pass basis. At present two xBSM instruments have been installed in experimental areas of the Cornell High Energy Synchrotron Source (CHESS). One is used for positrons and the other is used for electrons. Each setup has its own x-ray source, which is a dipole magnet within the Cornell Electron Storage Ring (CESR). The critical energy is 0.6 keV during 2 GeV CESRTA operations. A set of in-vacuum optics focuses the photon flux onto the detector. The geometry of the beam line provides an optical magnification of 2.34 for the positron line and 2.52 for the electron line. A continuous vacuum vessel, containing optics elements and filters which are inserted into the x-ray beam, extends from the x-ray source to the detector. Images are collected via a custom data acquisition system. Figure 1 shows the functional layout of the positron line. The electron line is a near mirror image.

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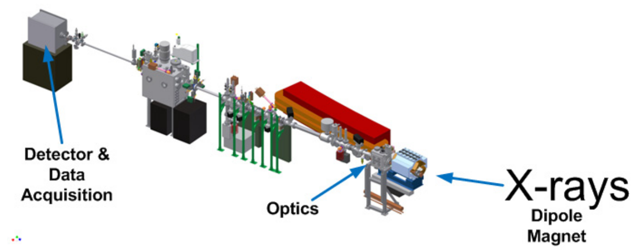

Figure 1: Layout of the xBSM positron line

VACUUM

A multi-stage differential pumping scheme has been implemented to allow "windowless" transmission path from the x-ray source to the detector. The scheme features a series of apertures, turbo pumps and gate valves along the x-ray beam line. This setup allows us to have electronics (printed circuit board, cables, etc) which are not vacuum compatible within the detector box without contaminating CESR. This is critical for the proper operation of the instrument. The vacuum system pressure is automatically controlled and monitored via programmable logic controllers.

DETECTOR

The detector is a vertical linear array of 32 InGaAs diodes with a 50 µm pitch and horizontal width of 400 µm. The InGaAs layer is 3.5 µm thick, and absorbs 73% of photons at 2.5 keV. The time response of the detector is sub-nanosecond.

OPTICS

The xBSM utilizes four different optical elements. For all beam energies, a vertically limiting slit (referred to as a pinhole) is available. For beam energies less than 2.5 GeV, a low energy Fresnel zone plate and a coded aperture are available. At 4 GeV and greater, a high power coded aperture can be inserted into the x-ray beam. The low energy optics are contained on one "chip" which is made from a 2.5 µm silicon substrate with a 0.7 µm layer of gold forming the optical features. The high energy coded aperture is made from a 625 µm silicon substrate with a 10 µm layer of gold. The coded aperture features of the high energy optics are the same but one half the scale of the low energy optics. Figure 2 shows the coded aperture features.

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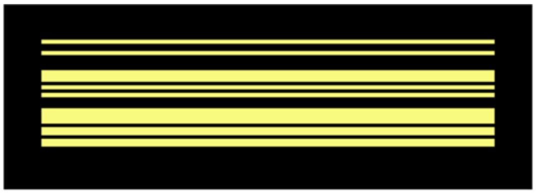

Figure 2: Coded aperture.

The low energy coded aperture provides a series of transmitting and opaque features which range from 10 µm to 40 µm. Analysis of the coded aperture interference pattern yields information about both beam size and photon energy spectrum. Due to the variation in feature size, the coded aperture is sensitive to a range of x-ray energies and very small beam sizes. This, coupled with the relatively high level of transparency, allows the coded aperture to be useful for low energy and low photon count experiments.

Analysis of the Fresnel zone plate has not been fully developed. It has proven to have a very broad background component when used with a wide spectrum x-ray beam, and the introduction of a monochromator limits the number of photons to an unusable level.

The pinhole consists of a vertically limiting set of adjustable tungsten blades which allow for a configurable slit height. This allows the height to be optimized for different particle beam energies.

FILTERS/SLITS

In order to empirically investigate and control the detector response, we have created a movable stage which contains a variety of horizontally limiting slits and filters. These slits and filters are inserted into the x-ray beam between the optics and the detector. The horizontally limiting slits are useful in reducing the amount of flux during high energy and high current operation. Slit sizes from 35 µm to 171 µm have been tested. The filters are used to change the spectral content of the x-ray beam which reaches the detector, and thus derive the energy spectrum based on the response. We have tested 6 µm diamond and 2 µm molybdenum filters and have plans to test a 6 µm aluminium filter.

DATA ACQUISITION

The xBSM instrument has an independent data acquisition channel for each of the 32 detector diodes. Each channel consists of a transimpedance amplifier, a variable gain amplifier (-4 dB to 20 dB), a 12 bit 300 MSPS analog to digital converter, a field programmable gate array (FPGA), a local 1 Msample SRAM buffer and a programmable sample clock delay. Figure 3 shows a single channel.

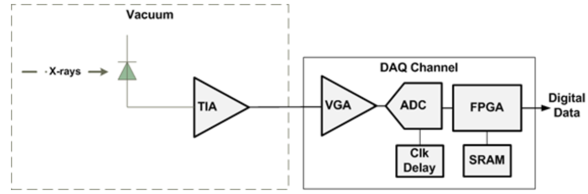

Figure 3: Data acquisition channel

Each of these data acquisition channels is synchronized to the storage ring via a 24 MHz instrumentation clock. This clock is derived from the CESR master oscillator and contains encoded triggers and turns markers. A local timing board receives this 24 MHz clock and utilizes a voltage controlled oscillator, phase detection circuit and programmable delays to generate the sample clocks for all 32 channels. These individual sample clocks have adjustable delays in 10 ps increments to allow for fine phase adjustments.

This timing control capability is used to peak sample the signal generated when x-rays are absorbed by the diode detector. Figure 4 shows the signals generated by two 4 ns spaced bunches and their corresponding sample points.

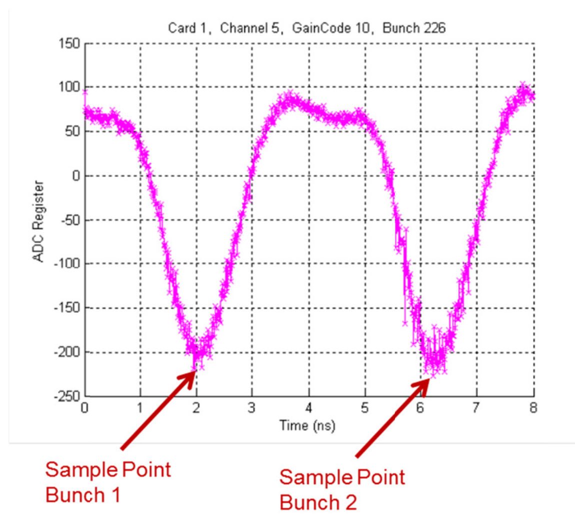

Figure 4: Peak sampling of 4 nS spaced bunches.

A single channel samples each of these bunches when clocked at 250 MHz with the sampling clock edges aligned with the peak of the signal. Note that the image shown is a composite made by shifting the sample point in 10 ps increments. All 32 channels are synchronized with the CESR turn marker and gated with a bunch pattern which matches the CESR fill pattern. The peak value detected on all 32 channels is collected and used to form a detector image.

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SOFTWARE

A Matlab based graphical user interface is used to control the data acquisition and motorized features of the instrument. All data is written to disk and is available to both real time and offline analysis programs. The control program has limited analysis functionality that provides fitting and display of a sample of the turn by turn beam size measurements in real time and allows for the possibility of real time particle beam tuning.

Offline analysis is performed using the xBSMRootFitter. This locally developed, C++ based analysis software uses the CERN ROOT package to book, store, fit and display histograms. It leverages MINUIT for fitting and FFTW for frequency analysis. It provides a variety of plots and analysis. xBSMRootFitter provides systematic compensations such as pedestal subtraction, channel by channel calibrations, gain range scaling, bunch to bunch crosstalk compensation and bad channel suppression.

PINHOLE IMAGE ANALYSIS

The pinhole is a simple optical device which has a single slit and an opaque masking material. In order to generate a model for the image we apply the derived x-ray spectrum to a numerical calculation of Fraunhofer diffraction. The broad energy spectrum smooths out the outer diffraction features and allows us to approximate the image as a sum of two gaussians plus a flat background. Figure 5 shows the model (line with points) and the two gaussian function (solid red line).

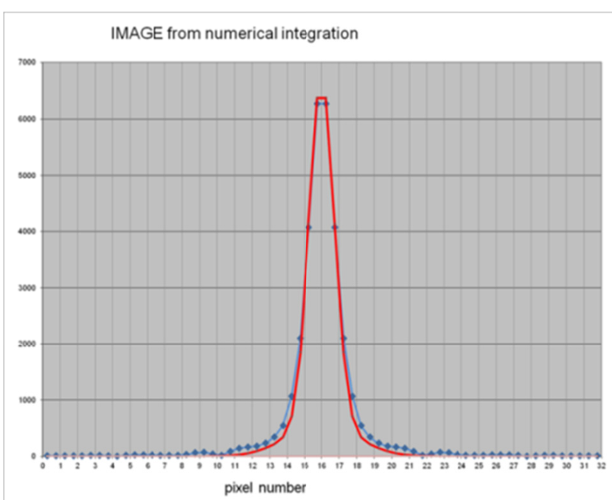

Figure 5: Pinhole model and function.

This function is used to fit the detector image data and calculate a beam size and image offset on the detector. Figure 6 shows a single bunch, single turn detector image with a fit applied.

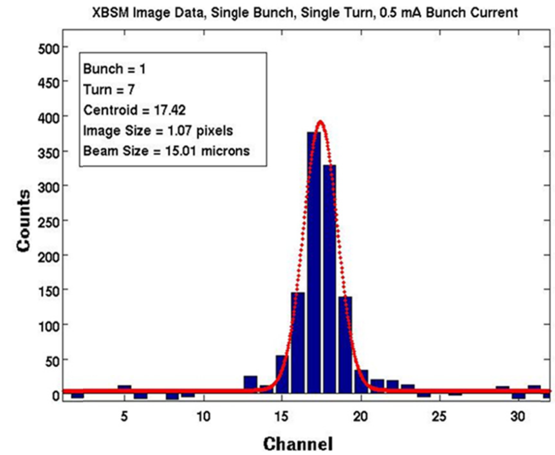

Figure 6: Pinhole detector image with fit.

CODED APERTURE IMAGE ANALYSIS

The coded aperture is a multi-slit optical device which generates a diffraction pattern at the detector. This diffraction pattern is calculable using the derived x-ray spectrum and the detailed geometry and materials of the coded aperture. We parameterize the diffraction pattern as the sum of 12 gaussians. Figure 7 shows the model smoothed to a source size of 7 µm (line with dots), the 12 gaussians (various colors, solid lines), and the resulting function (single solid red line).

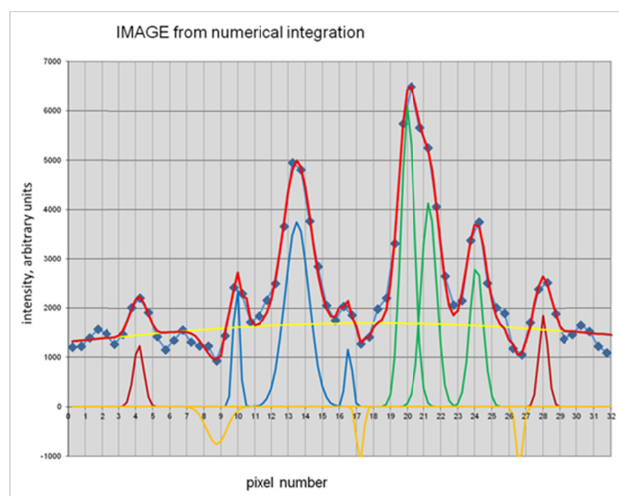

Figure 7: Code aperture model and function.

This function is used to fit the detector image data and calculate a beam size and image offset on the detector. Figure 8 shows a single bunch, single turn, detector image with a fit applied which corresponds to a source size of 9.85 µm.

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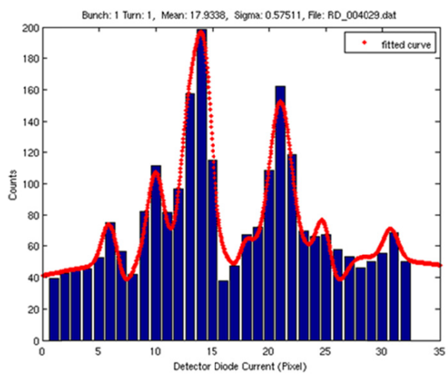

Fig 8: Coded aperture detector image with fit.

SIZE AND OFFSET MEASUREMENTS

The xBSM is capable of bunch by bunch, turn by turn, single shot measurements of beam size and offset of the image on the detector. Figures 9 through 12 are representative measurements of a single bunch of positrons in CESR. The size of a single bunch is plotted over 1024 turns along with the frequency spectrum of the size variations.

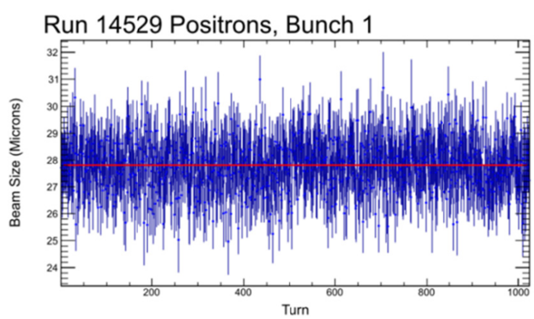

Figure 9: Single bunch size over 1024 turns.

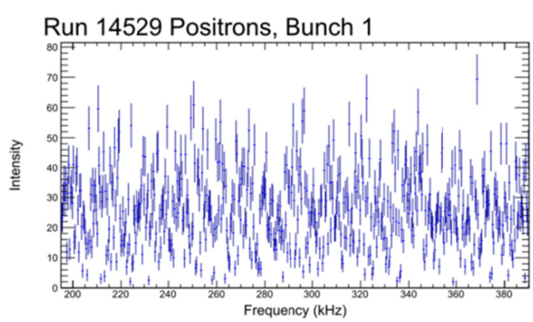

Figure 10: Frequency spectrum of bunch size of a single bunch.

The offset of the image on the detector can also be plotted, giving the experimenter beam motion information. The peak in the spectrum of offsets in Figure 12 appears at the vertical betatron tune.

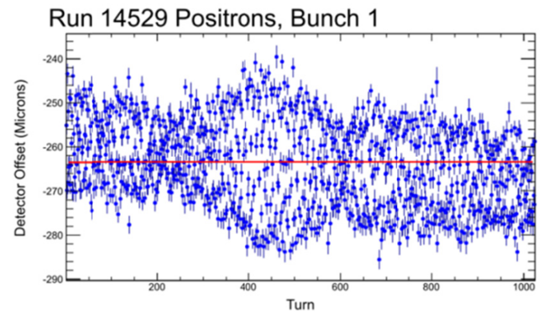

Figure 11: Image Offset Over 1024 turns.

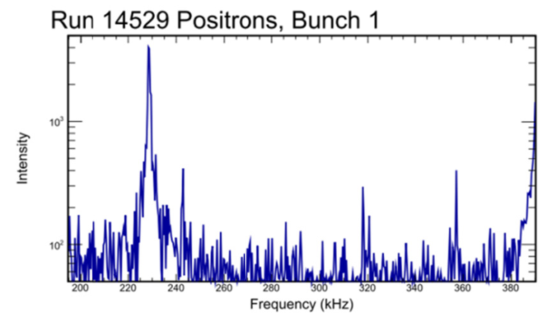

Figure 12: Spectrum of image offset over 1024 turns

PHYSICS MEASUREMENTS

The xBSM is in regular use during CESRTA experimental runs. The following are two examples of experiments which have collected and analysed xBSM data. The physics phenomena which are evident in these plots are outside the scope of this paper. Work is on-going to decouple systematic instrumentation effects from beam physics.

Intra beam scattering (IBS) is a phenomenon of current dependent beam size in small beams. The xBSM is used to measure the beam size and detector offset of individual bunches versus beam current over many turns. Figure 13 represents an IBS experiment using a single bunch of positrons undergoing decay from 10^{11} particles to 10^{9} particles. Data sets were collected under identical conditions using the pinhole and coded aperture.

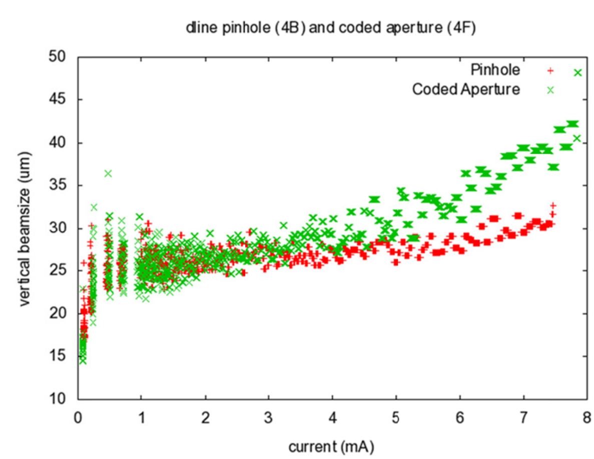

Figure 13: Positron IBS experiment beam sizes versus current.

During the IBS experiments, the image offset is also analysed. Figure 14 is an image offset spectrum plot for a similar current decay as above. A current dependent tune shift can be observed moving from approximately 210 kHz to 235 kHz.

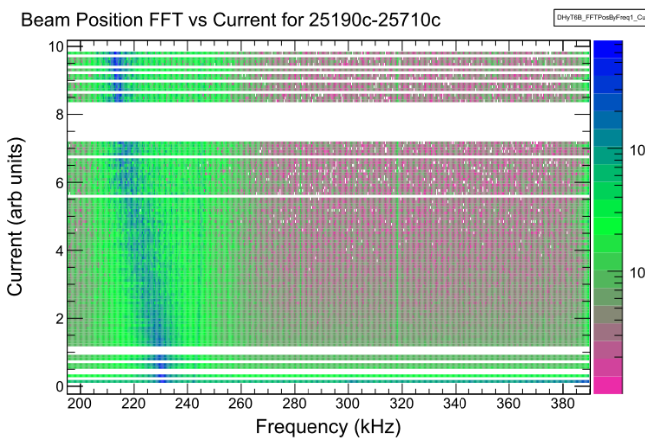

Figure 14: IBS image offset spectrum.

Experiments in the beam dynamics program study electron induced multi-bunch phenomenon in CESR. The xBSM is used to measure the beam size and detector offset for individual bunches along trains of bunches over many turns. The spacing between bunches can be varied in 4 nS increments while the bunch current is held constant at approximately 1 mA. Figure 15 shows a comparison of different bunch spacing and the effect of the electron cloud on the bunch size along the train.

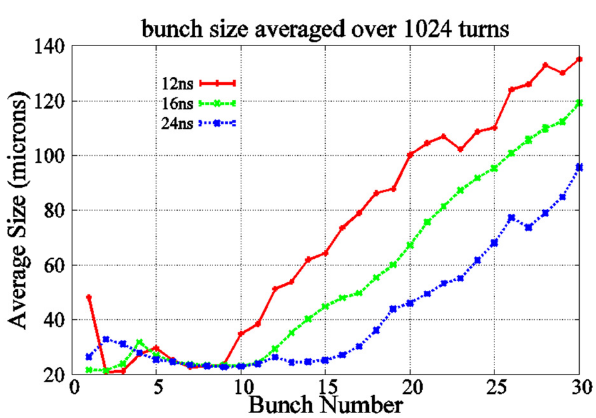

Figure 15: Beam size along a train of bunches.

FUTURE MEASUREMENTS

One future extension of the xBSM concept involves measuring the instabilities and head-tail oscillations of a single bunch. Figure 16 demonstrates a possible bunch oscillation and four slices of the bunch size.

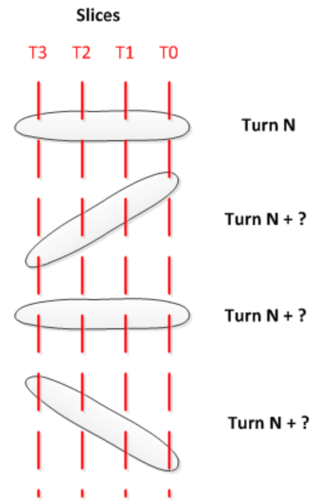

Figure 16: Bunch slicing.

This measurement will utilize high speed diode detectors with rise and fall times on the order of 35 ps. This response time coupled with a four channel phased digitizer will allow for four longitudinal "slices" of the bunch to be measured.

SUMMARY

The xBSM is routinely used in the CESRTA experimental program for precision measurement of beams with vertical size as small as 9 µm. There is an on-going effort to understand systematic effects and to optimize the analysis of images. The device has proven essential to the CESRTA program to understand intrabeam scattering and the emittance diluting effect of the electron cloud.

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