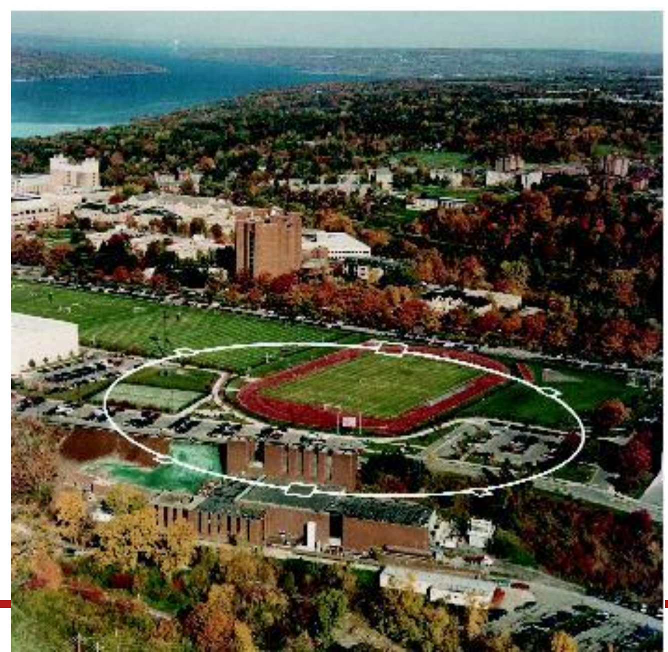
Operation of a Single Pass, Bunch-by-bunch x-ray Beam Size Monitor for the CESR Test Accelerator Research Program

October 3, 2012



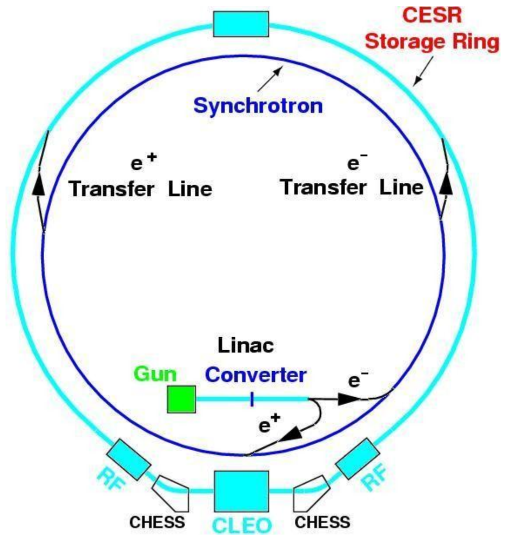
Goals

Goals For This Presentation:

1. Provide an overview of the efforts required to design, commission and operate an x-ray beam size monitor in support of a scientific program

2. Highlight the instrument capabilities, limitations and characteristics

3. Provide examples of present and future measurements

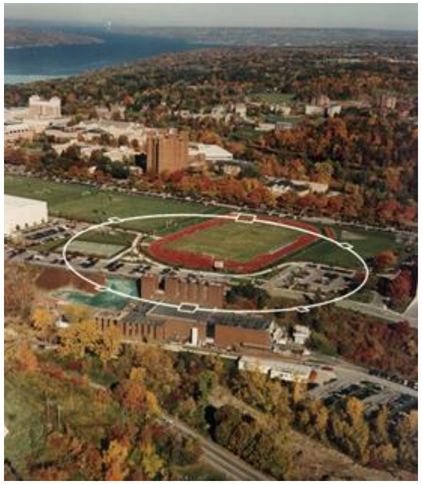


Cornell Electron Storage Ring (CESR)

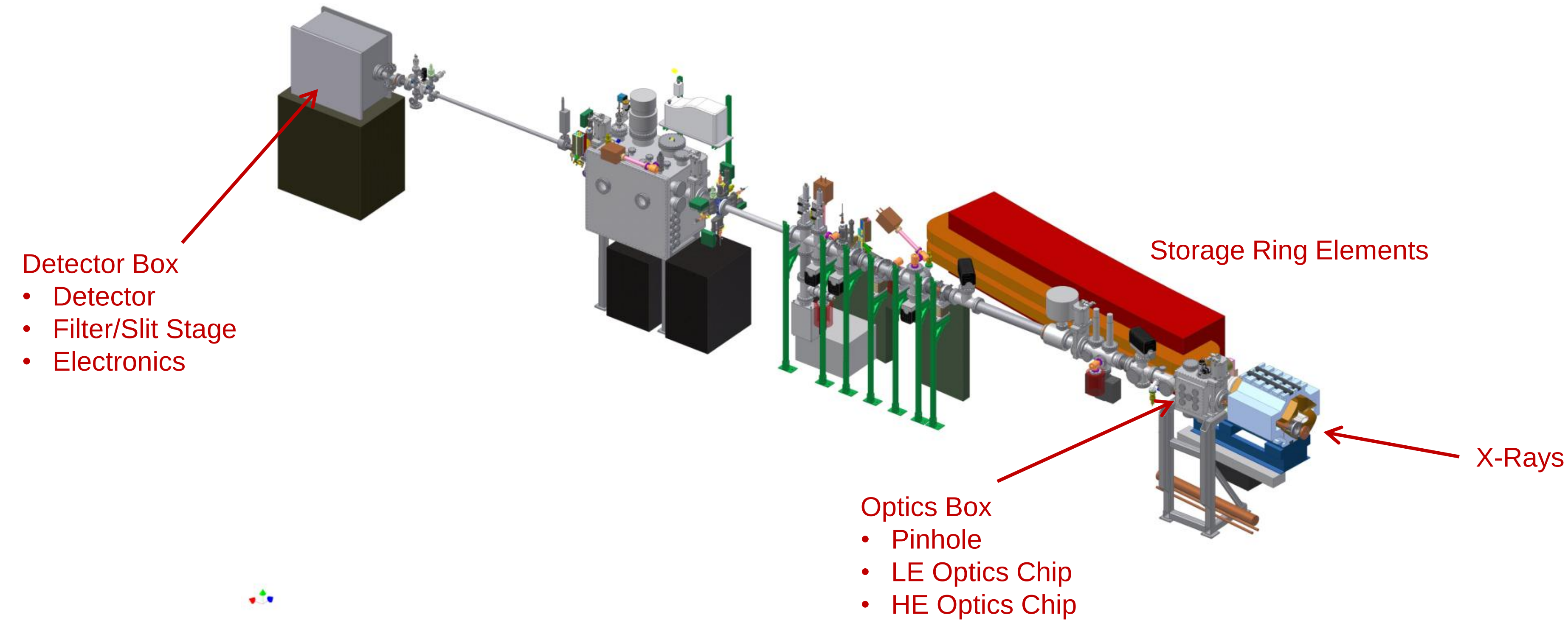
- Dual beam (positron/electron) storage ring with a 768 m circumference
- Configurable beam energies from 1.8 GeV to 6 GeV
- Beam currents up to 400 mA for counter-rotating beams
- Bunch spacings down to 4 nS in increments of 2 nS

Cornell High Energy Synchrotron Source (CHESS):

- High intensity x-ray source
- 7 instrumented x-ray beam lines with 11 user experimental stations
- The positron instrument is installed in D-Line and the electron instrument is installed in C-Line



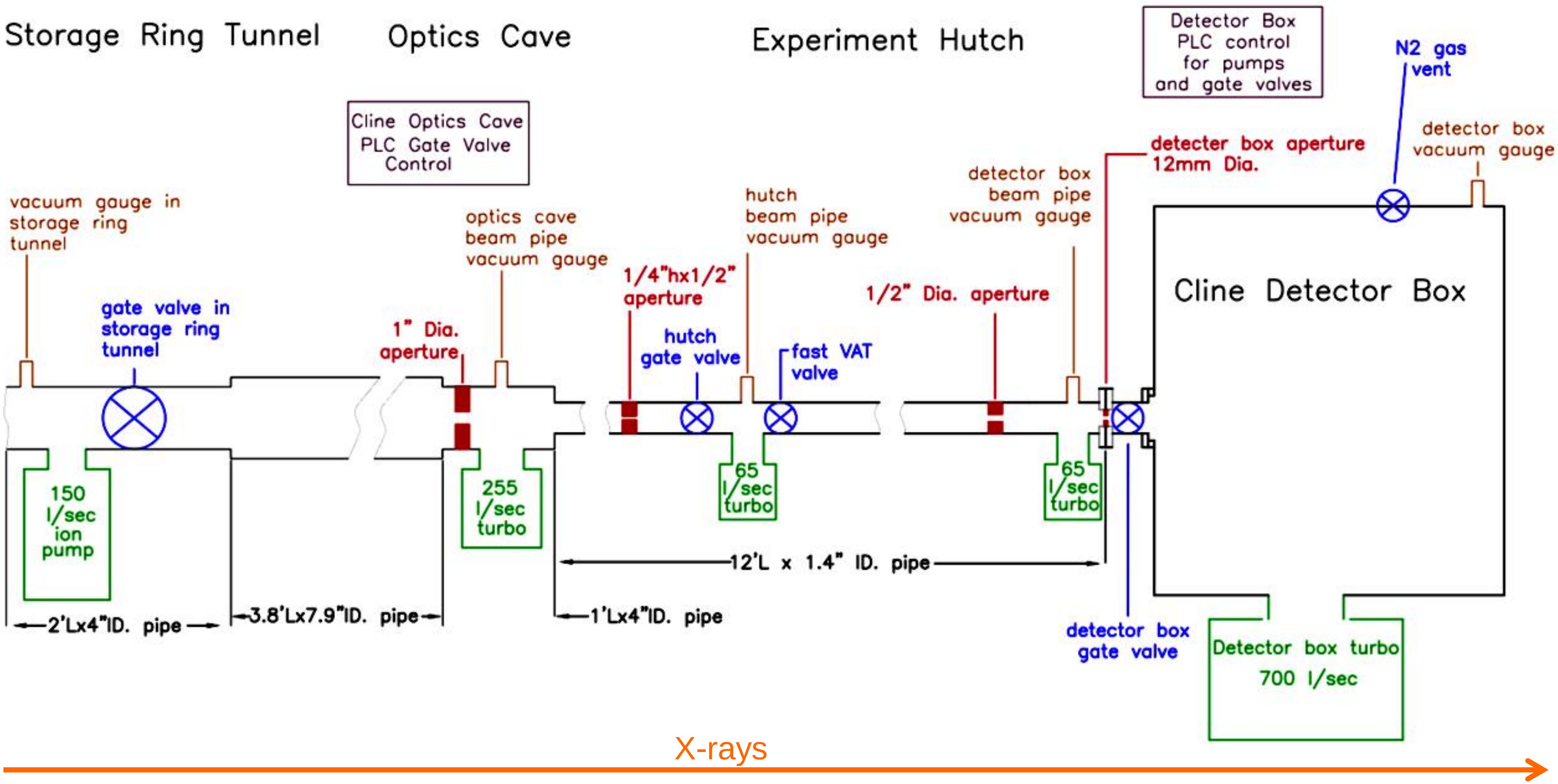
Overview



The basic setup consists of the following:

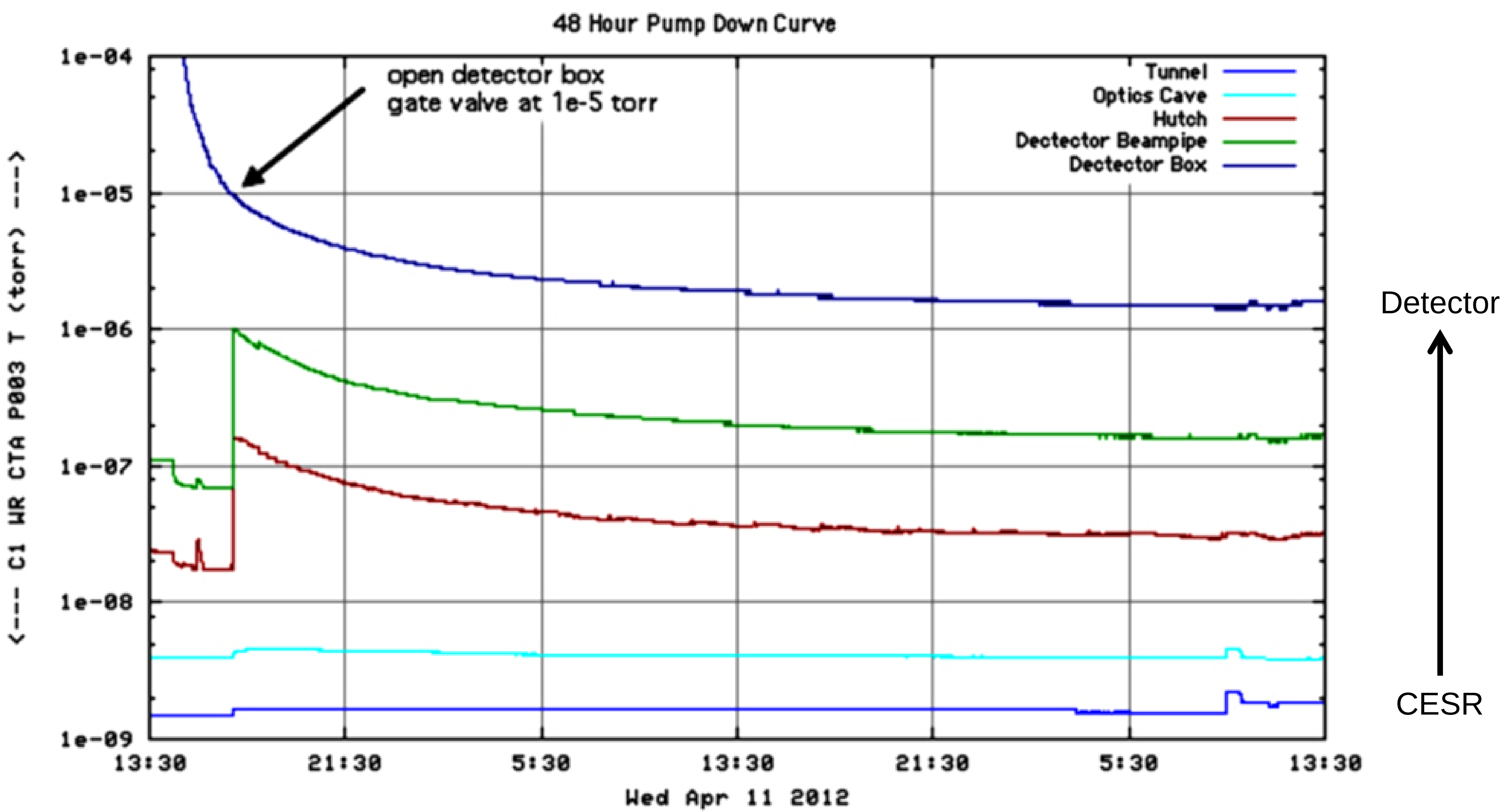
- X-ray source dipole magnet which is part of CESR
- Continuous vacuum vessel which extends from the source to the detector
- Optics box contains moveable stages with several optics elements which can be inserted into the x-ray beam
- Detector box contains movable stages which hold filters and the beam size detector and associated amplifiers
- Control and analysis software running remotely

Vacuum Overview



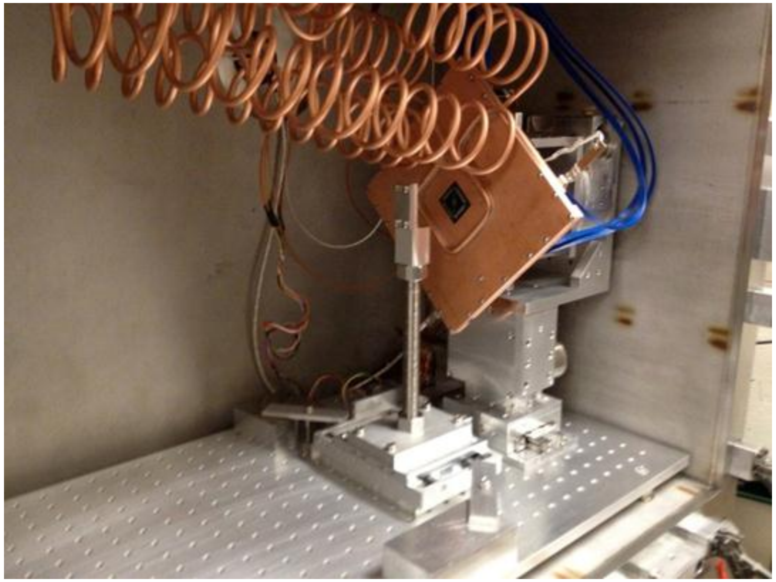
- Continuous vacuum vessel from x-ray source to detector
- Multi stage differential pumping with gate valve protection controlled via programmable logic controllers
- Allows for non UHV compatible electronics to be installed in the detector box WITHOUT contaminating the storage ring vacuum
- Provides a “windowless” x-ray transmission path from source to detector

Vacuum Pressures Along Beam Line

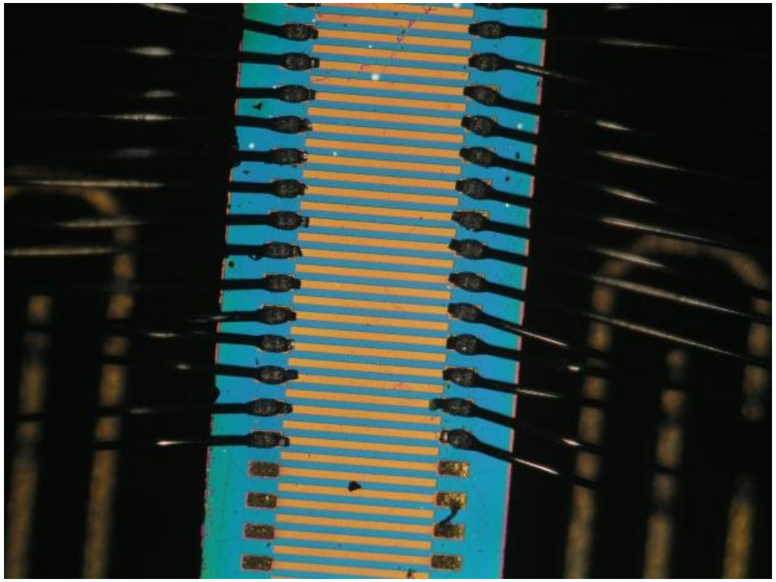


Vacuum Pressure Along Beam Line

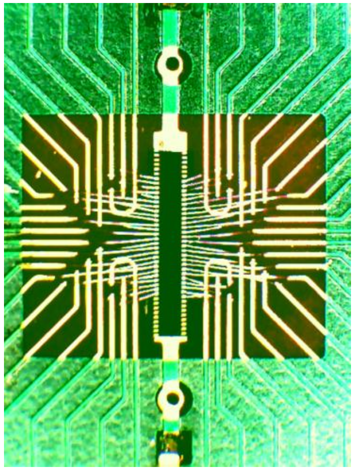
Detector



Installed Detector



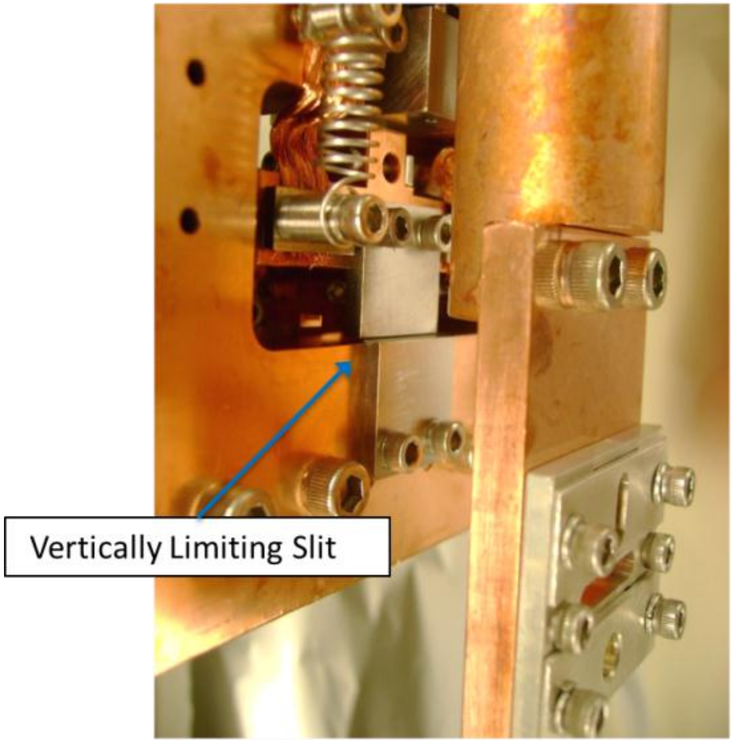
Detector Diode Segments

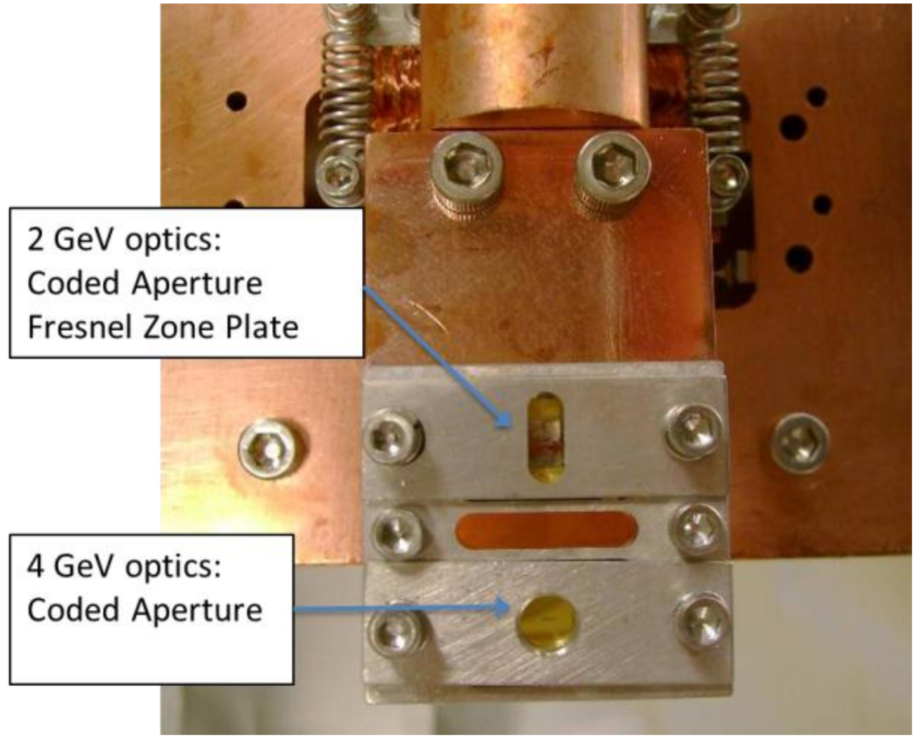


Mounted Detector

- The standard detector is a vertical array of 32 InGaAs diodes with a 50µm pitch and horizontal width of 400µm.
- The diode array is mounted to a printed circuit board and the diode connections made with wire bonds
- The InGaAs layer is 3.5 µm thick, which absorbs 73% of photons at 2.5keV; there is a 160nm Si_3N_4 passivation layer.
- The time response of the detector is sub-nanosecond
- The detector is mounted on a rotatable stage, studies thus far have focused on vertical beam size measurements in the vertical orientation

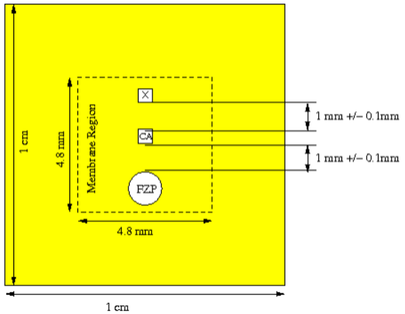
Optics Stages





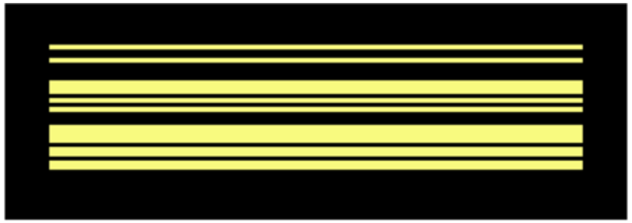
- For all beam energies an adjustable vertically limiting slit (pinhole) is available (typ height = 45 μm)
- For less than 2.5 GeV, a low energy Fresnel zone plate and a coded aperture are available
- At or above 4 GeV a high power coded aperture is available on a high energy chip
- These elements reside in the storage ring vacuum and can be selected and aligned remotely to meet the requirements of various measurements

Optics Elements



Low Energy Optics Chip Layout

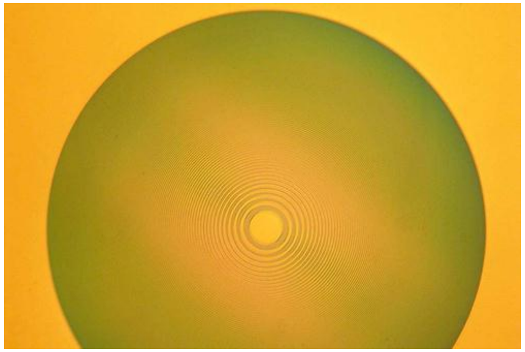
- There are three features, a box, a coded aperture and a Fresnel zone plate



Coded Aperture

- Creates a diffraction pattern at the detector
- 2.5 µm Si substrate with a 0.7 µm thick layer of electroplated gold
- 310µm x 1200µm, 8 transmitting elements (10µm to 40 µm)
- Usable with non-monochromatic x-ray beams and small beam sizes
- Useful for low photon count, low energy measurements

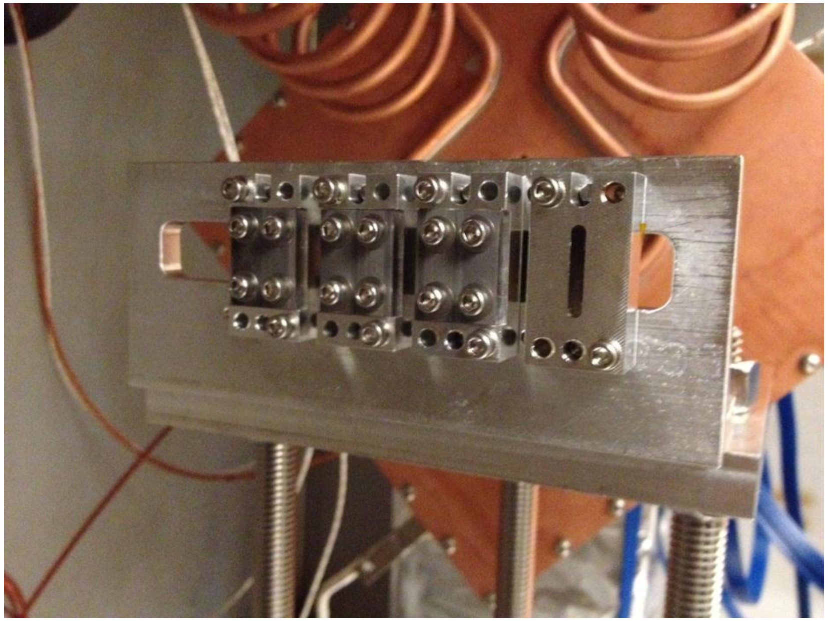
- High power device features are half the scale
- 625 µm substrate with a 10 µm thick layer of electroplated gold

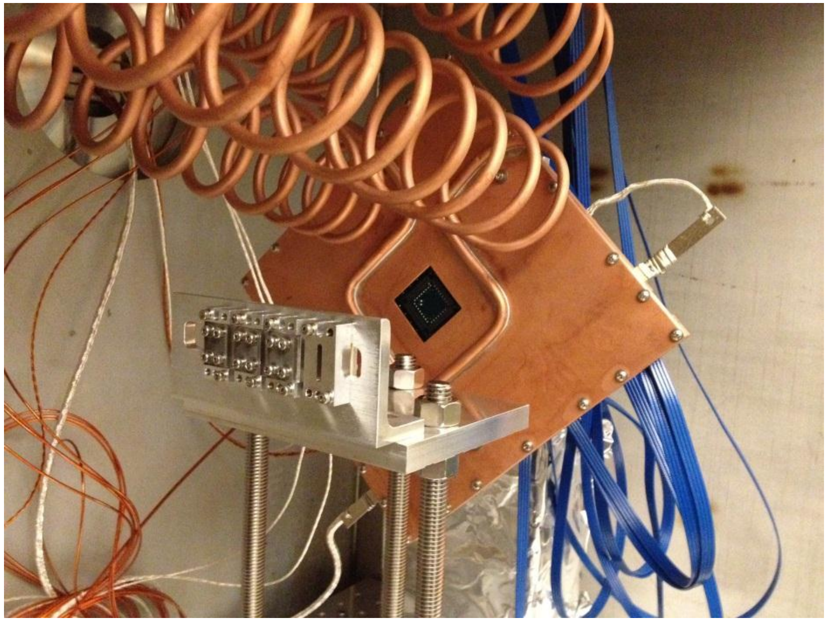


Fresnel Zone Plate

- True focusing device
- The Fresnel zone plate has been problematic due to low photon counts when using the required monochromator
- The Fresnel zone plate pattern has 120 transmitting rings in a diameter of 1200µm.

Filters/Slits





Filter/Slit Stage

- Stage with multiple elements which can be inserted into the x-ray beam between the optical elements and the detector
- Horizontally limiting tungsten slits (35 µm – 171 µm) used for high energy and or high current operation
- Filters used to change the spectral content of the x-ray beam and thus control the detector response
  - 4 µm diamond filter
  - 2 µm molybdenum filter
  - 6 µm aluminum filter (soon)
- Used to derive the x-ray spectrum used in analysis

Data Acquisition

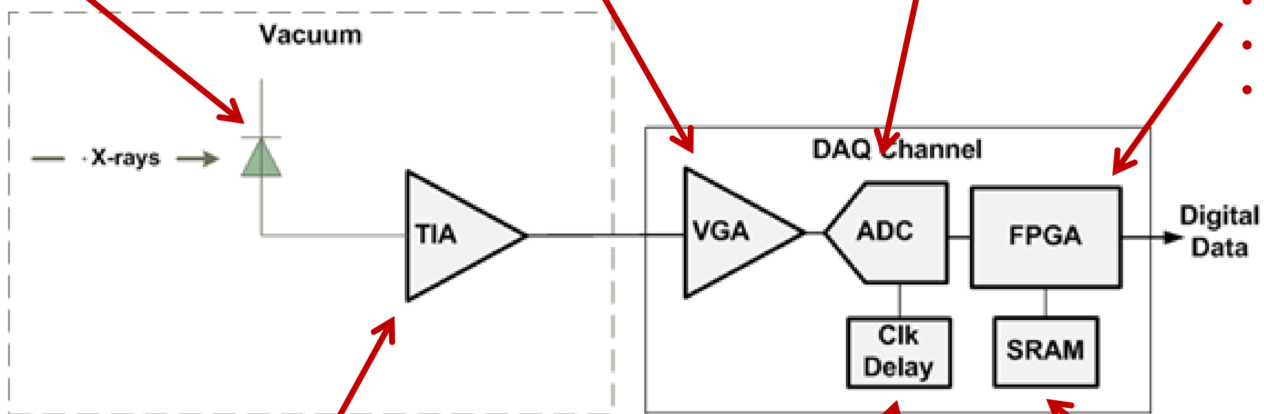
- The xbsm data acquisition system is capable of collecting beam size measurements on a single pass, bunch by bunch, turn by turn basis
- There is an independent data acquisition channel for each of the 32 detector diodes

Diode Segment

Variable Gain Amplifier
- Digitally controlled
- -4 dB to 20 dB

Analog To Digital Converter
- 12 bit
- 300 MSPS

FPGA
- Local control
- Register interface
- Memory interface

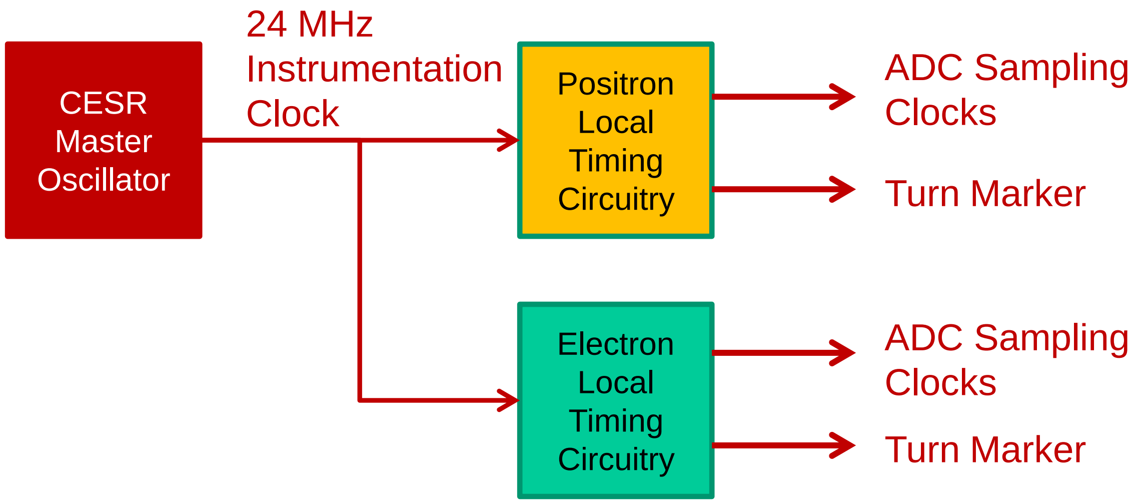


Transimpedance Amplifier

Clock Delay
- Digitally controlled
- 10 pS increments

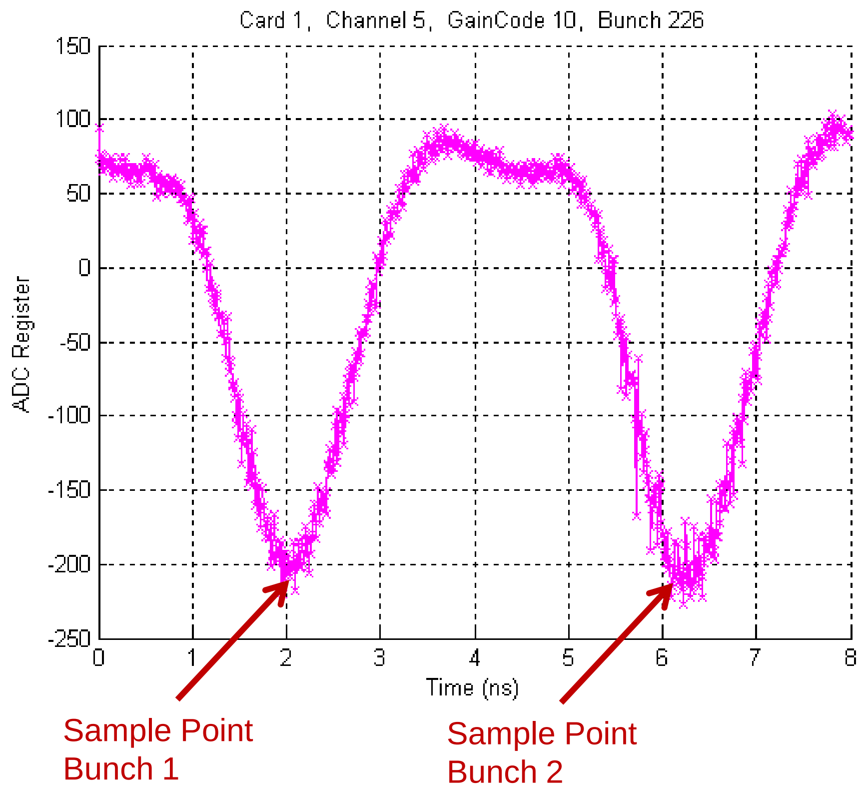
SRAM Memory
- 1 M sample storage

Synchronization



Local Timing Circuitry:
- Receives 24 MHz instrumentation clock
  - Embedded turn marker
  - Hardware triggers for instrument synchronization (xBSM, BPM)
- Generates 32 programmable sampling clocks
  - 250 MHz, 125 MHz, etc (based on bunch spacing)
  - Configurable clock delay for alignment and sampling
- Adjustable turn marker for synchronization

Peak Sampling

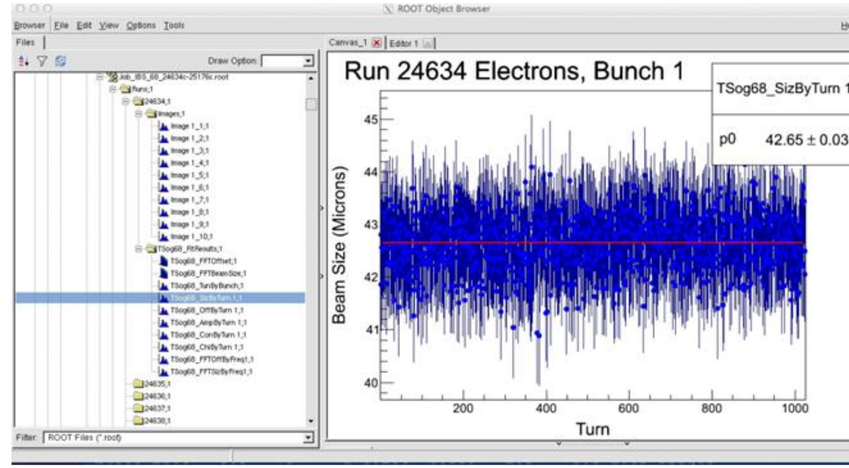


- We use the timing controls and bunch pattern gating to align the sampling points with the beam
- This alignment allows for bunch by bunch sampling of the amplitude peak of the diode response signal
- All 32 channels are aligned and sampled synchronously resulting in the capture of a detector image

NOTE: This image is a composite made by shifting the sample point in 10 pS increments with some tolerance

Software

Matlab Control GUI



xBSM Root Fitter Single Bunch Size Summary

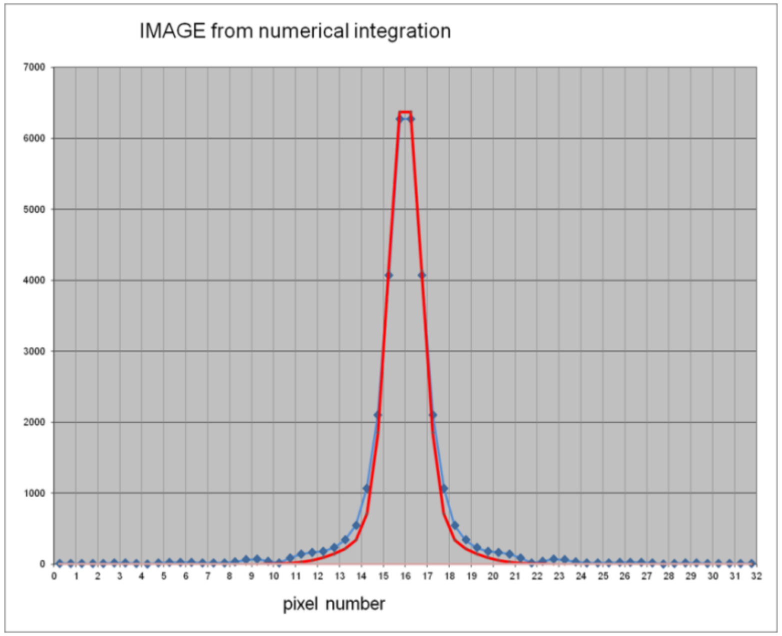
Data acquisition and instrument control software written in Matlab

- Graphical user interface panels for timing, acquisition and instrument motor control
- Provides basic analysis and display of a sample of the turn by turn measurements
- Allows for the possibility of real time particle beam tuning
- Analysis of large data sets is slow

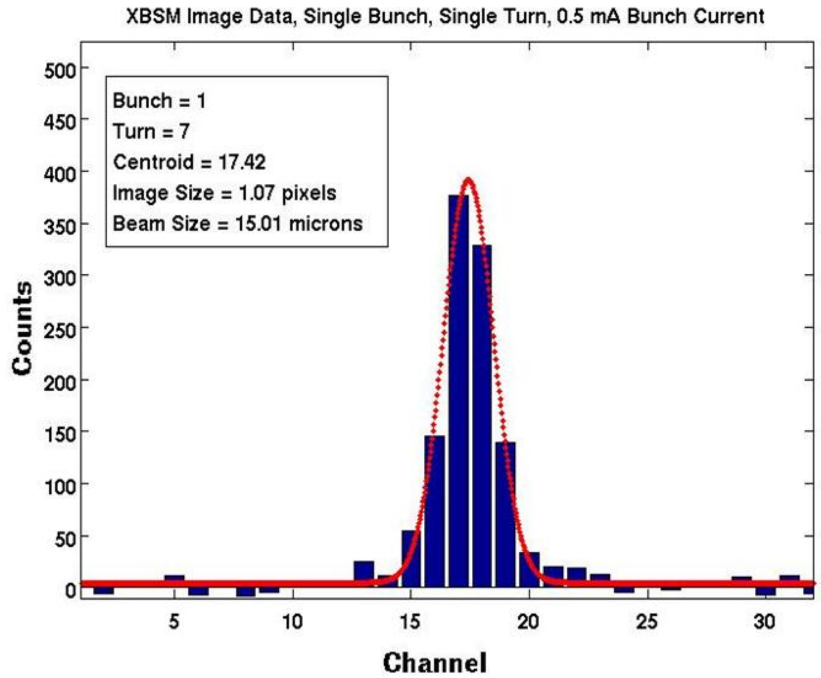
Offline analysis is done via locally developed XbsmRootFitter

- C++ based, utilizing the CERN ROOT package to book, store, fit and display histograms
  - ROOT uses MINUIT for fitting and FFTW frequency analysis
- Very flexible package which allows for a variety of plots
- Routines for systematic compensations
  - Pedestal subtraction, channel calibrations, gain-range scaling, bunch to bunch crosstalk compensation

Pinhole Analysis



Model and Function

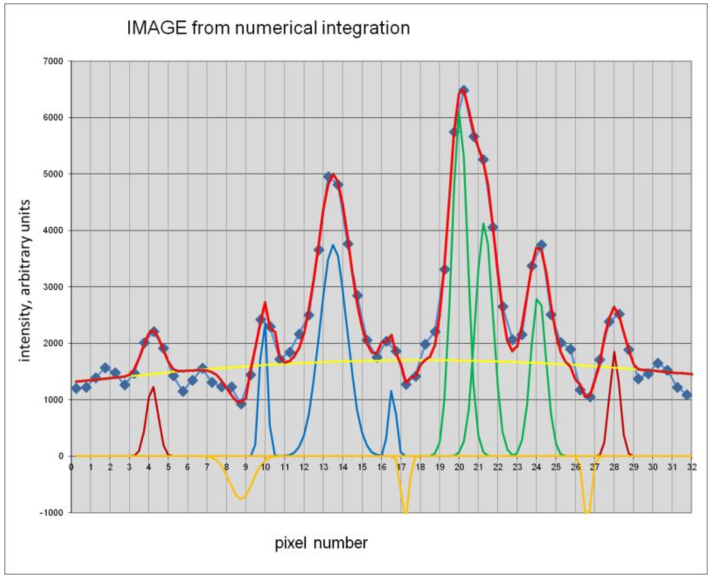


Detector Data With Fitting Function

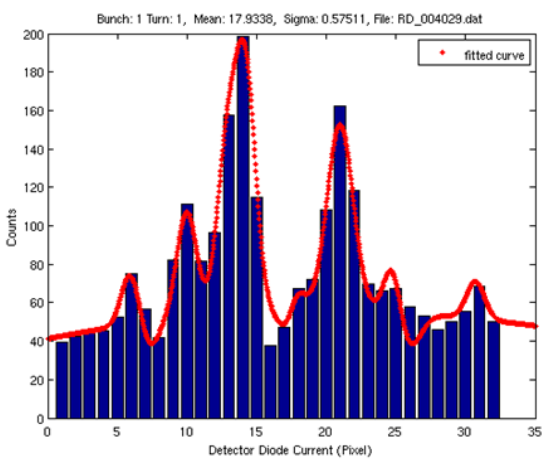
- The pinhole is a simple optical element with a single slit and an opaque masking material which produces a diffraction pattern at the detector
- In order to generate a model for the image, we apply the derived x-ray spectrum to a numerical calculation of Fraunhofer diffraction
- The outer diffraction features are smeared due to the energy spread.
- This allows us to approximate the pinhole image as a sum of two gaussians (broad and narrow) plus a background
- The resulting fitting function is used to fit the detector image data and calculate a beam size and image offset

Coded Aperture Analysis

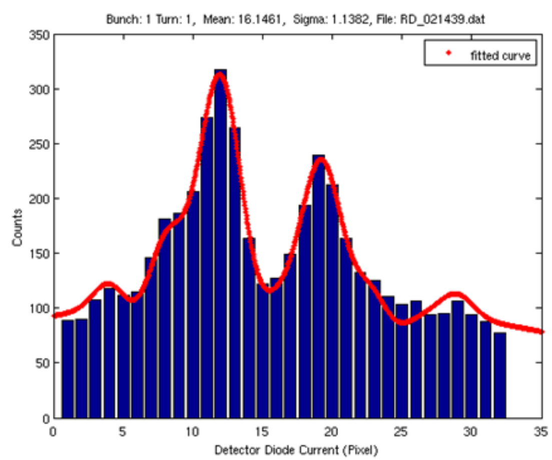
- The coded aperture is a multiple slit optical device which generates a diffraction pattern at the detector
- The diffraction pattern is calculable using the derived x-ray spectrum and the detailed geometry and materials of the coded aperture
- This pattern can be calculated for a range of beam profiles and positions and used to generate a searchable matrix of templates (see J Flanagan, proc. DIPAC11)
- Alternatively, we have parameterized the diffraction pattern as a sum of 12 gaussians with no un-modeled background
- This is convenient for analytical chi squared fitting
- The resulting fitting function is used to fit the detector image data and calculate a beam size and image offset



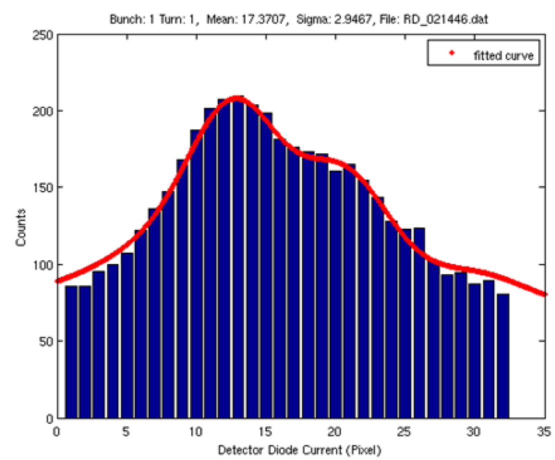
Model and Function



9 µm beam size



21 µm beam size

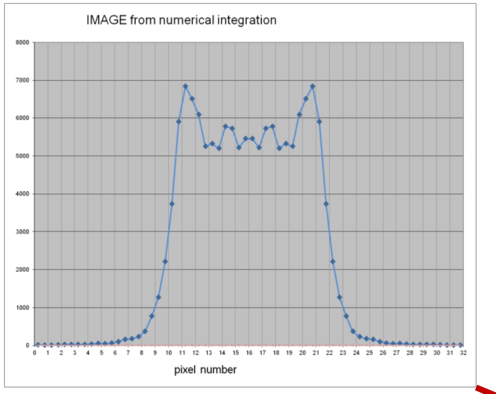


58 µm beam size

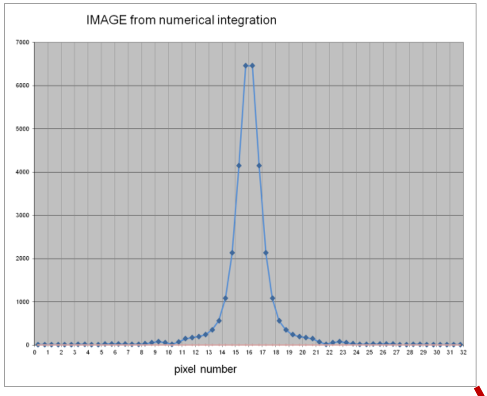
Detector Data With Fitting Function

Pinhole Optimization

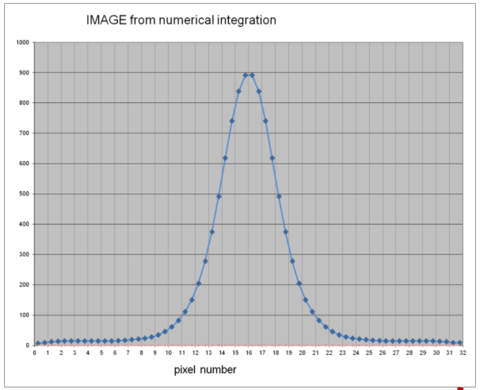
- The pinhole image is sensitive to average x-ray energy and the height of the opening
- Modeled image response to variations in pinhole height



Height = 200 µm



Height = 45 µm



Height = 15 µm

- CESRTA requires operation at several different beam energies
- The pinhole height is controllable remotely
- The height is optimized for each operating beam energy

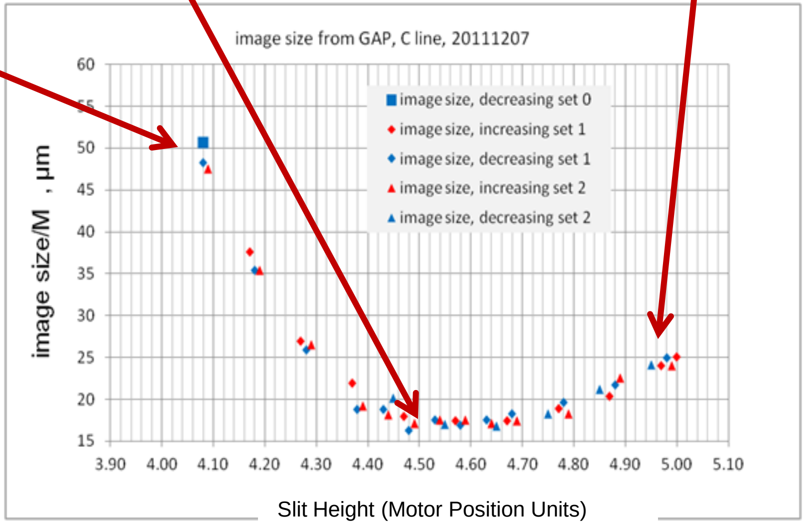
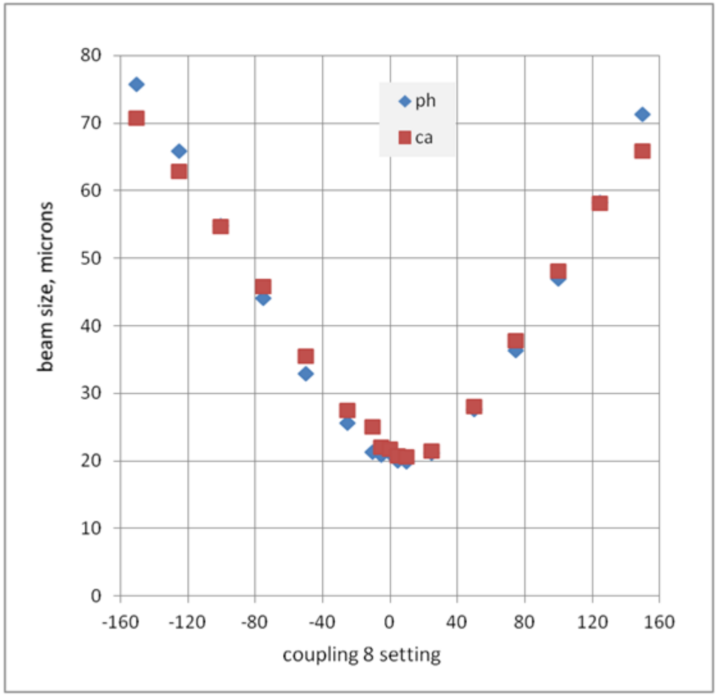
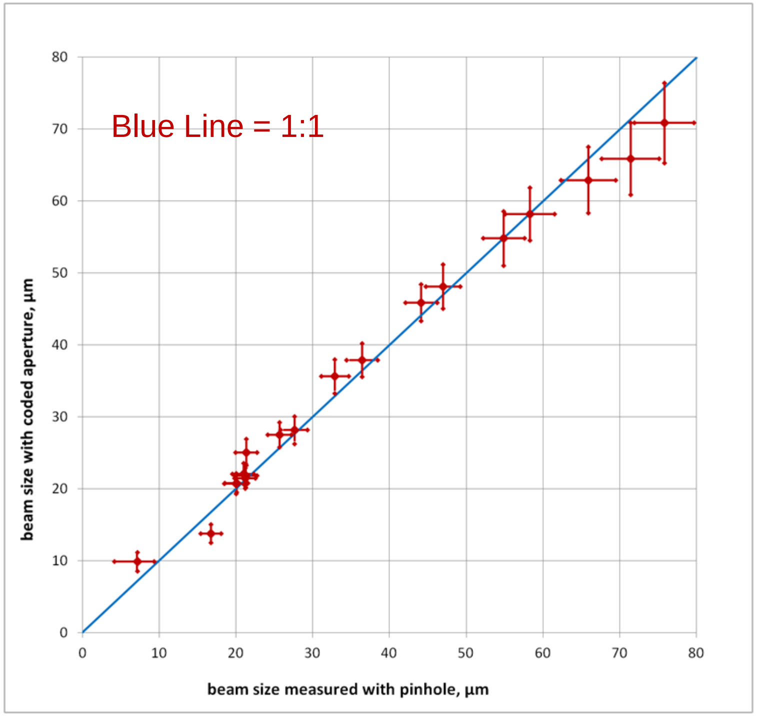


Image Size Vs Pinhole Height Scan

PH and CA Comparison



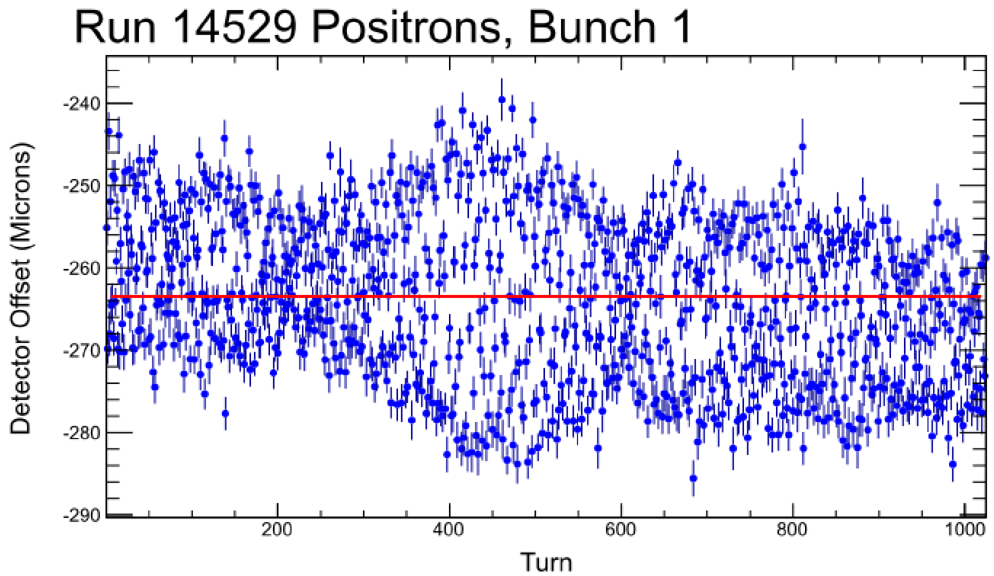
Controlled Beam Size Scan



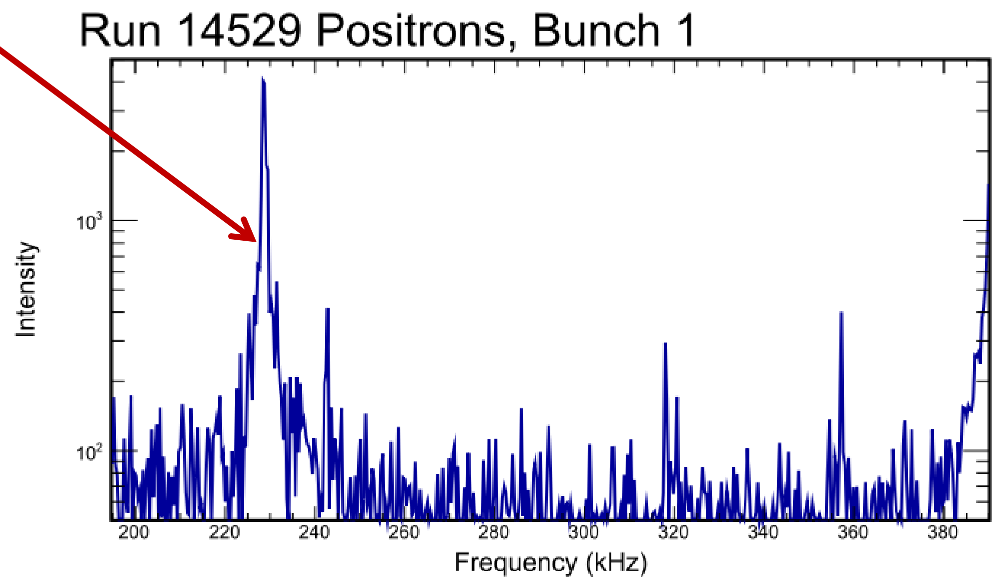
Coded Aperture Size Vs PH Size

- Cross check pinhole results versus coded aperture results for identical conditions
- Artificially increase and decrease the beam size by introducing a closed dispersion bump in a wiggler
- Plot coded aperture results versus pinhole results
  - Points represent turn averaged data
  - Brackets represent the RMS spread of the single bunch single turn measurements
- We also used a specially tuned beam to capture two very small beam size measurements and added them to the plot to extend the range of comparison

Basic Measurements

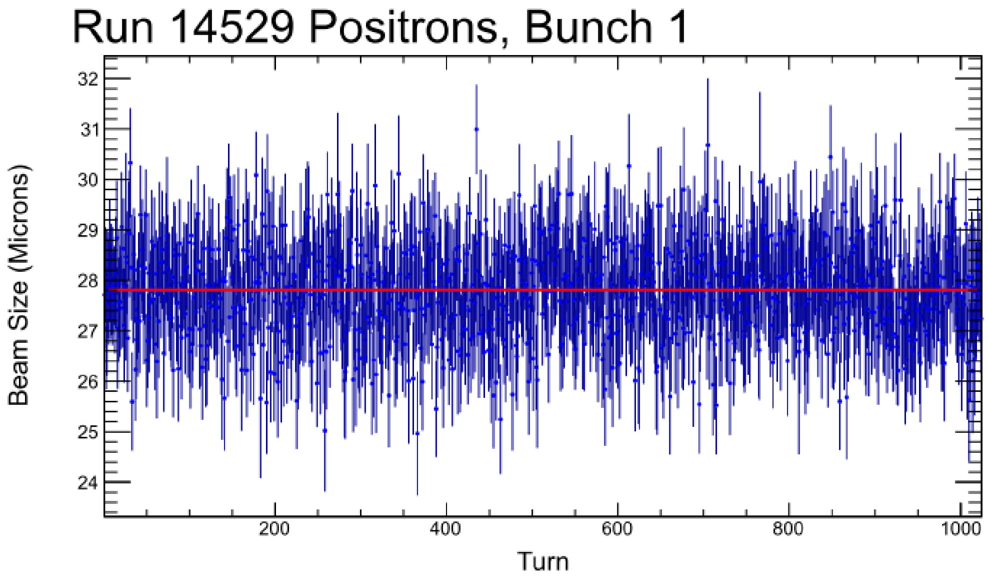


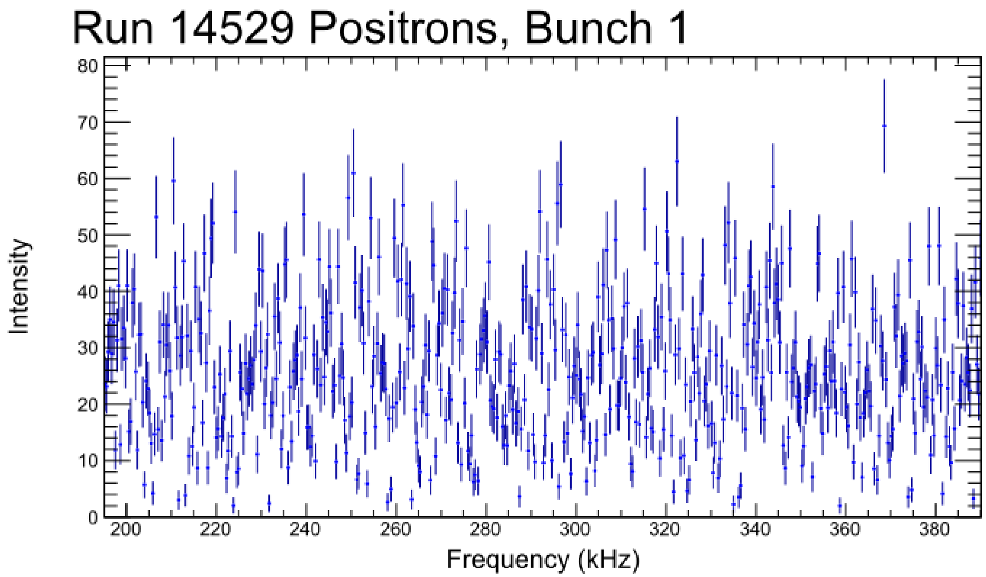
Vertical Tune



Beam Position At Detector

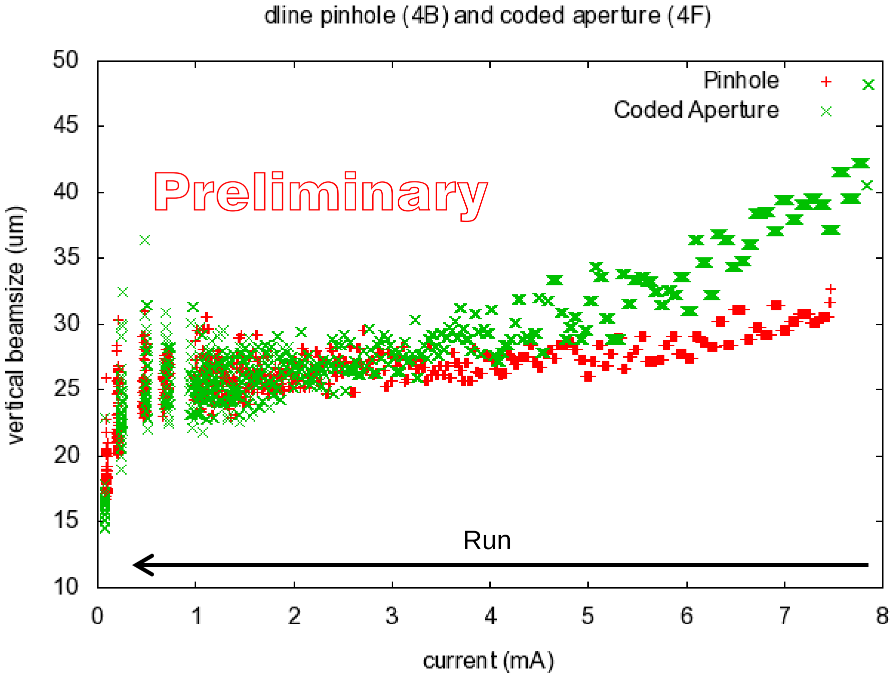
Basic Measurements



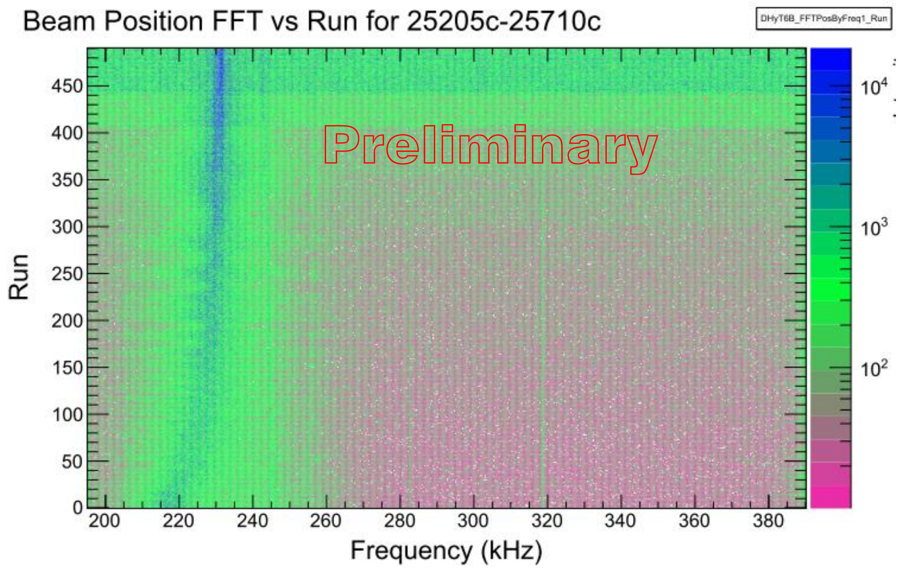


Beam Size

Intra Beam Scattering



Beam Size Versus Current



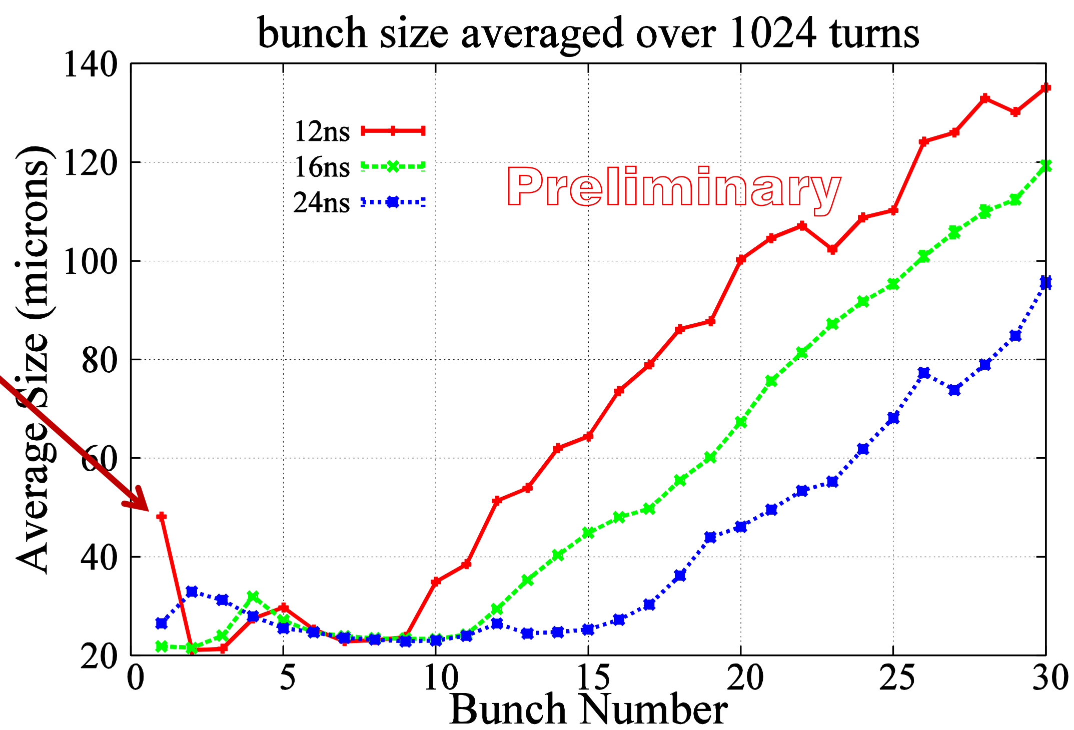
FFT Of Position Data

- Intra Beam Scattering is a phenomenon of current dependent beam size seen in very small beams
- A typical experiment consists of filling the storage ring with single bunch charged to 10^{11} particles and allowing the bunch to decay down to 10^9 particles while recording the turn by turn change in vertical beam size
- The xBSM is used to collect beam size versus current of individual bunches over many turns
- Turn by turn measurements allow for frequency analysis of beam dynamics

Disclaimer: The physics phenomena which are evident on this slide are outside the scope of this presentation

- This program studies electron cloud induced multi-bunch phenomenon
- A typical experiment involves loading the storage ring with a multi bunch train (20, 30 or 45 bunches) with a spacing of 4 nS to 28 nS (4 nS increments) between bunches and bunch currents of approximately 1 mA
- The beam size for each bunch is measured on a turn by turn basis for up to 4096 turns

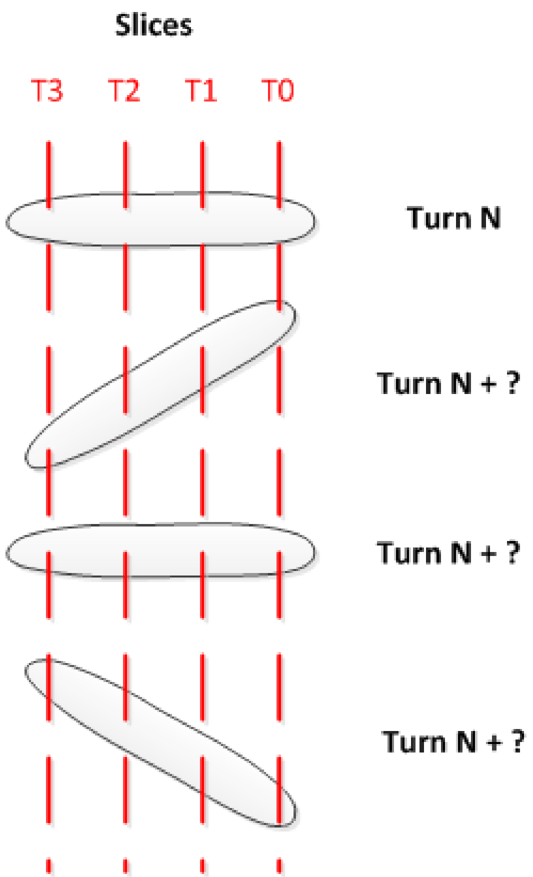
This Is Real



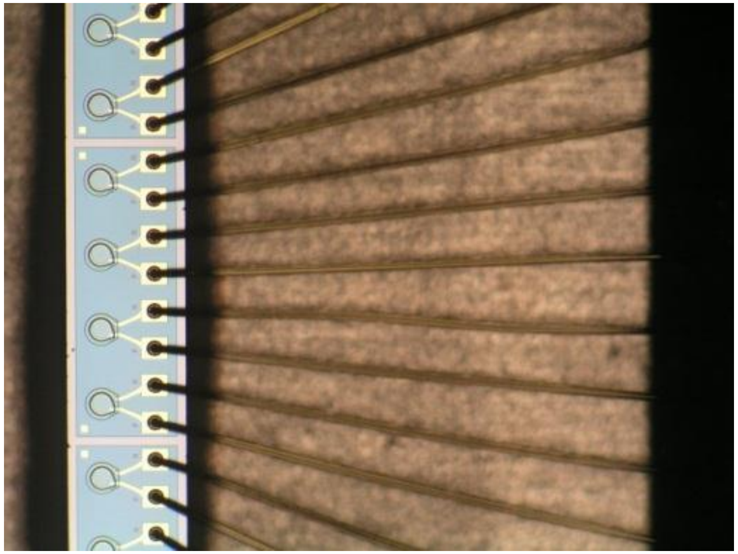
Positron Bunch Size (Pinhole Optic) Along 30 Bunch Train

Disclaimer: The physics phenomena which are evident on this slide are outside the scope of this presentation

Future Measurements



Multiple Longitudinal Slices Per Turn



1x12 Telecom Diode Array

Bunch Slicing:

- Acquire a size profile for a single bunch on a single turn
- A measurement requires multiple longitudinal slices of a single bunch
- Testing high speed diodes (tr/tf ~35 pS) with parallel sampling

Summary

Summary:

- The xbsm is routinely used in the CESRTA program for precision measurement of beams with a vertical size as small as 9 µm
- There is an ongoing effort to understand systematic effects and to optimize the analysis of images
- Now that we have achieved basic functionality of the instrument, we need to undertake a more detailed characterization of the operational characteristics (resolution, accuracy, repeatability, etc)
- The device has proven to be essential to the CESRTA low emittance tuning program and to understand intrabeam scattering and the emittance dilution effect of the electron cloud

xBSM Team

Name	Organization	Responsibility
Mike Billing	LEPP	Experimenter
Chris Conolly	CHESS	Operations
Eric Edwards	CHESS	Vacuum Controls
Michael Ehrlichman	LEPP	Experimenter
John Flanagan	KEK	Analysis
Brian Heltsley	LEPP	Analysis
Aaron Lyndaker	CHESS	Hardware
Mark Palmer	LEPP/FNAL	Project Manager
Dan Peterson	LEPP	Analysis
Nate Rider	LEPP	Project Coordinator
Dave Rubin	LEPP	Principal Investigator
Robert Seeley	CHESS	Vacuum
James Shanks	LEPP	Experimenter
Kiran Sonnad	LEPP	Experimenter
Chris Whiting	CHESS	Vacuum

Primary Team Members

LEPP = Laboratory For Elementary Particle Physics
CHESS = Cornell High Energy Synchrotron Source
KEK = High Energy Accelerator Research Organization

Thank You

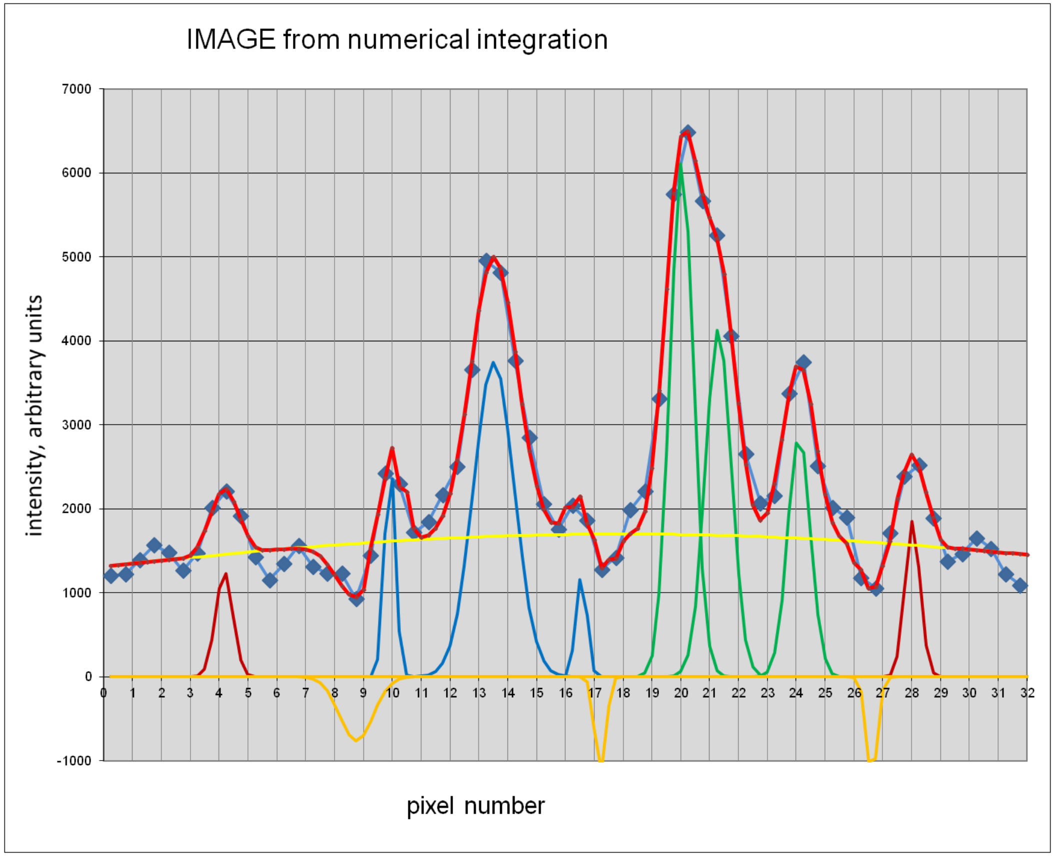
Additional Slides

Abstract

Abstract:

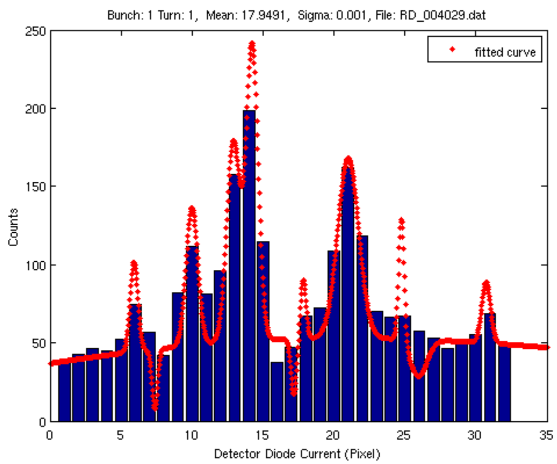
The CESR Test Accelerator (CesrTA) program targets the study of beam physics issues relevant to linear collider damping rings and other low emittance storage rings. This endeavor requires new instrumentation to study the beam dynamics along trains of ultra low emittance bunches. A key element of the 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.

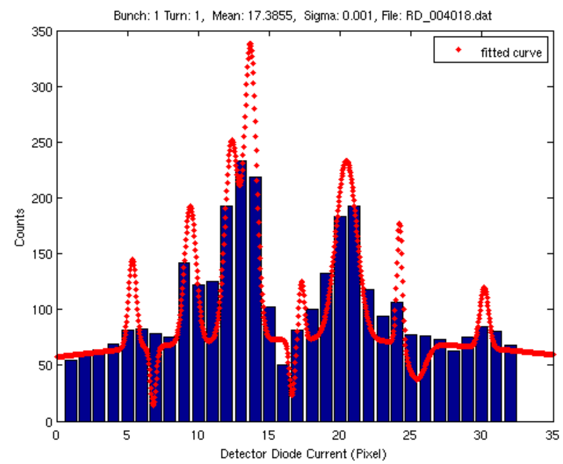
Coded Aperture Analysis

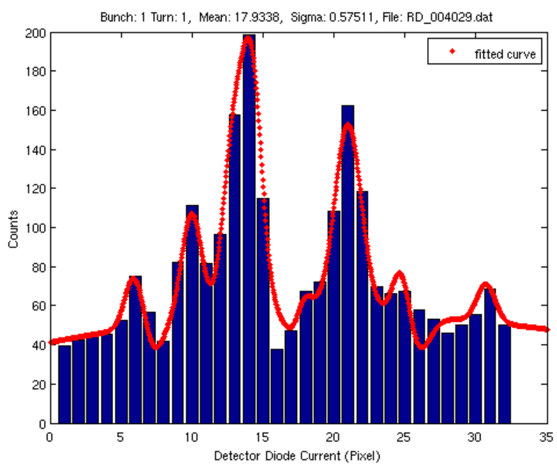


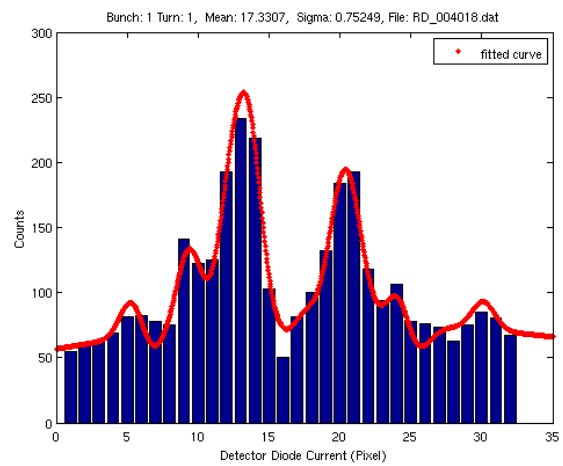
The calculation of the diffraction results in the blue points. (Calculated values have been smoothed with an RMS of 17.68 microns at the image or 7.0 microns at the source.) The calculated image is fit to the sum of 12 Gaussians, shown in various colors in the figure. The resulting sum of Gaussians (also smoothed) shown in the red curve closely matches the calculated diffraction pattern.

Coded Aperture Analysis



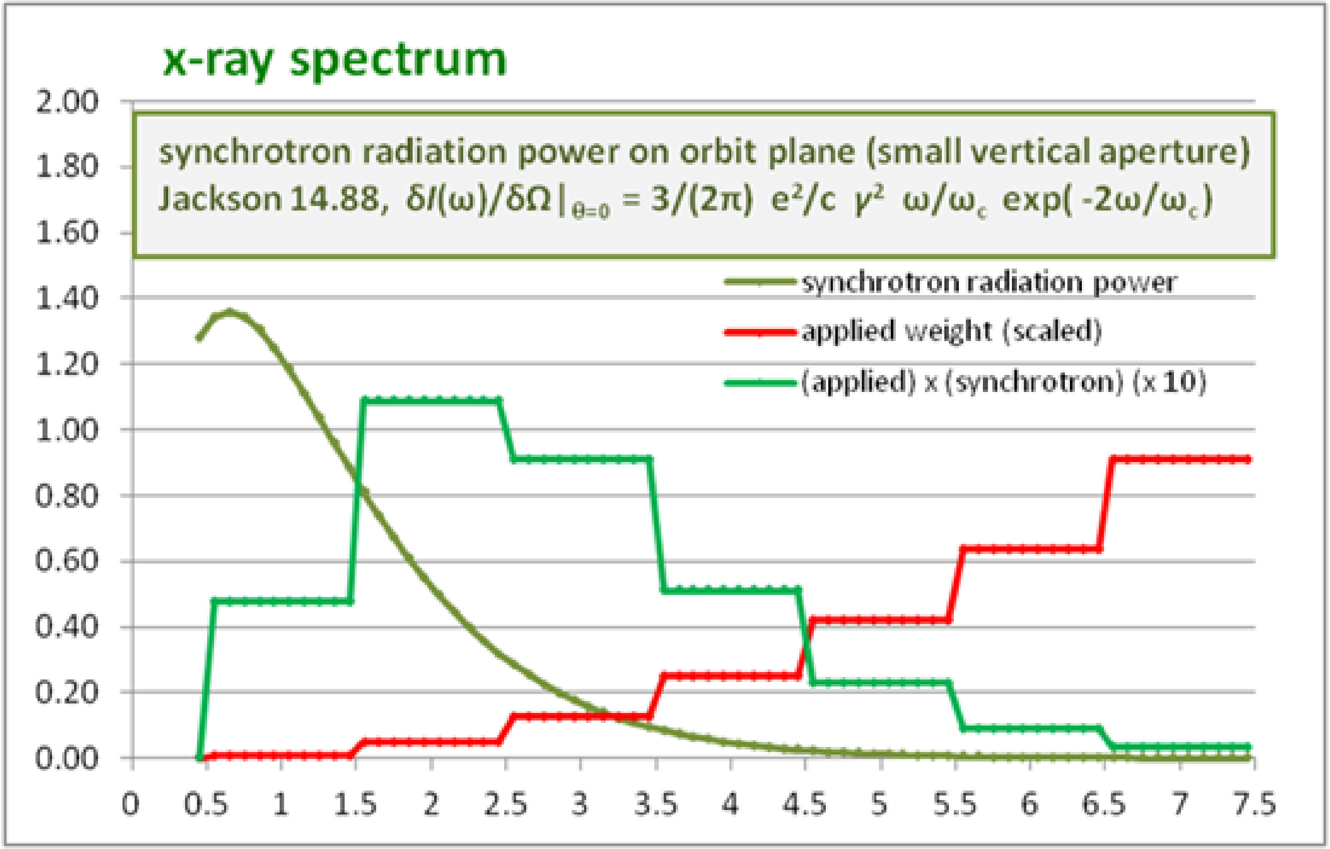






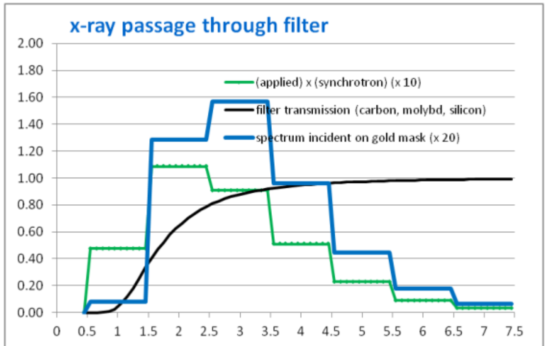
The model provides a function describing the image for zero beam size, shown superimposed on an image. To fit the image, this function is convoluted with a single Gaussian representing the beam size, magnified on the detector.
Examples are shown for beam sizes of 9.85 and 13.77 microns.

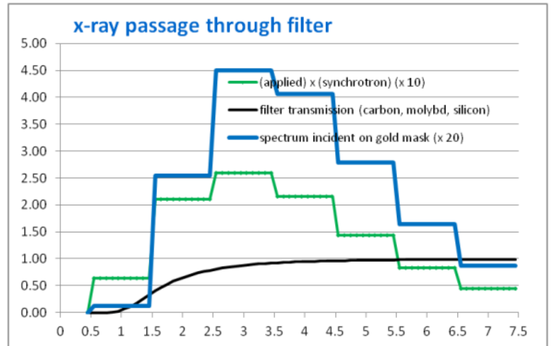
Derived Spectrum



Derived x-ray spectrum

Spectrum Development





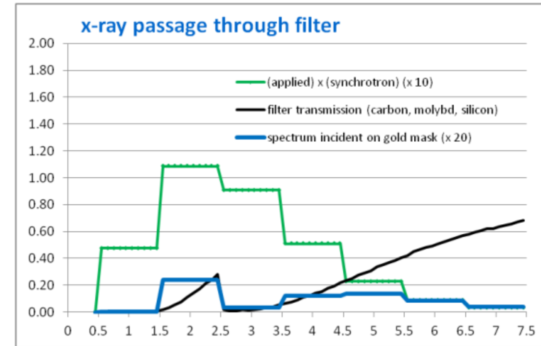


Table values represent pinhole image relative integrated area for various filter and particle beam energy conditions
(constant pinhole slit width)
(particle beam current normalized)

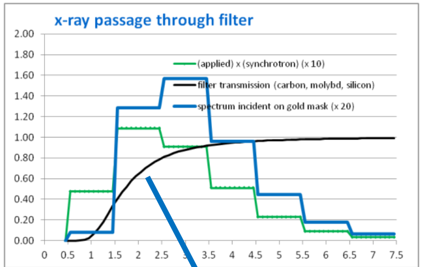
Jackson formula, with applied transmission: $(E_{x\text{-}ray})^{2.31}$

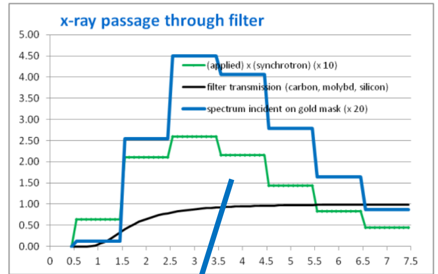
data in black, {model} in red

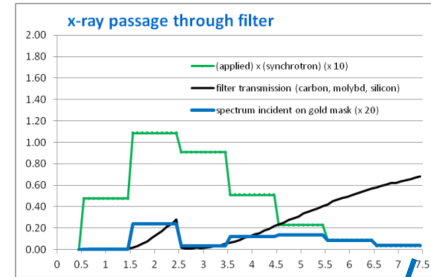
	no filter		4 µm diamond filter		2 µm molybdenum filter	
1.800 GeV	**0.304**	**{ 0.284 }**	**0.079**	**{ 0.076 }**	**-----**	**{ 0.0081}**
2.085 GeV	**1**	**{ 1 }**	**0.520**	**{ 0.521 }***	**0.050**	**{ 0.066 }**
2.300 GeV	**---**	**{ 2.356 }**	**1.917**	**{ 1.595 }**	**0.299**	**{ 0.273 }**

* this is a tuned value

We find we can fit this data, reasonably well for the conditions we have examined, with the Jackson formula modulated by an empirical description of the unknown other filters and detector response.
We will collect more complete data in the future (missing points, aluminum filter).







pinhole image relative integrated area

(constant pinhole slit width)

(particle beam current normalized)

average x-ray energy in blue

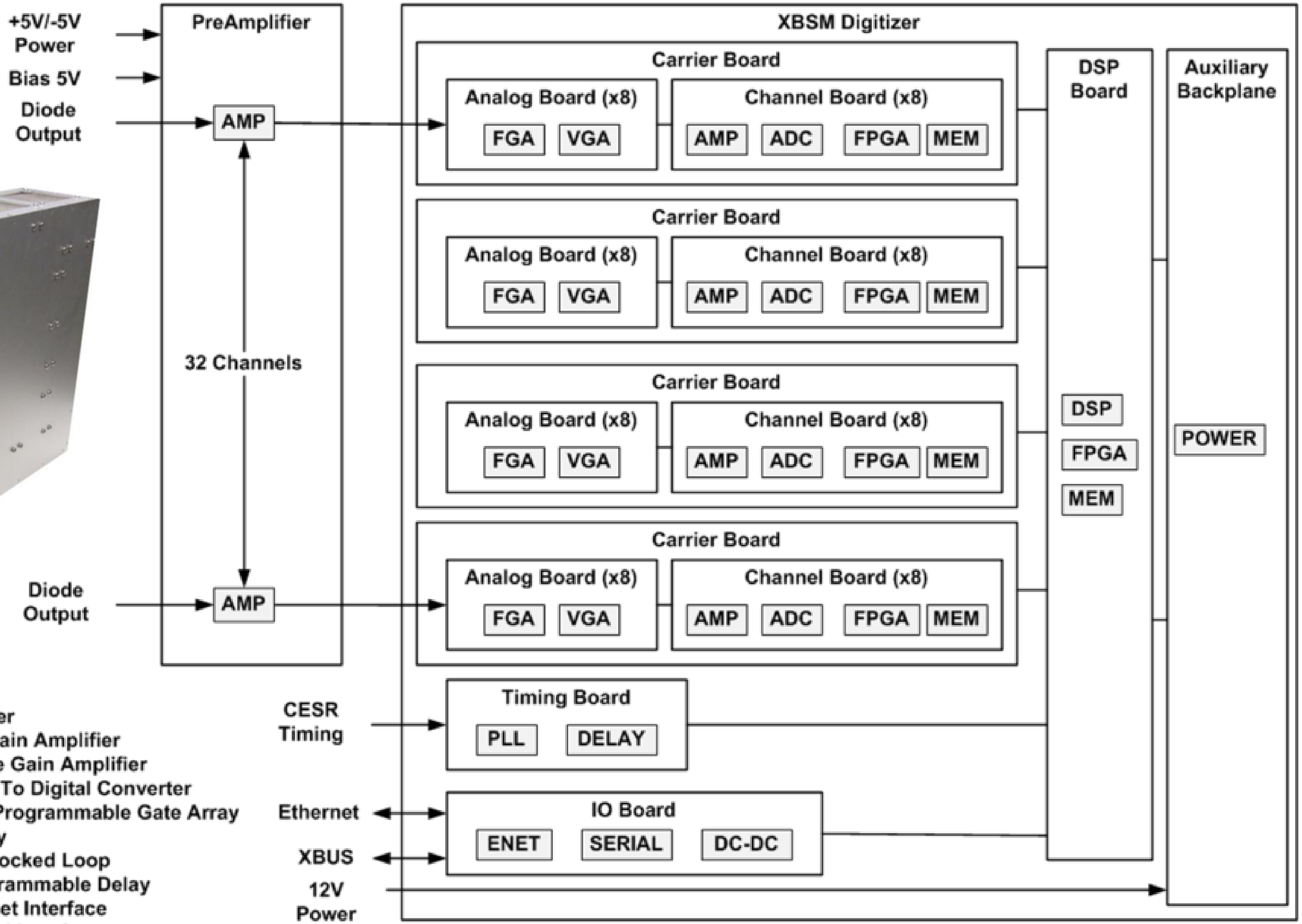
{model} in red Jackson formula, with applied transmission: $(E_{x\text{-ray}})^{2.31}$

data in black

particle energy	no filter	4 µm diamond filter	6 µm aluminum filter	2 µm molybdenum filter
1.800 GeV	1.96 keV **0.304** { 0.284 }	2.42 keV **0.079** { 0.076 }	2.23 keV --- { 0.036 }	2.70 keV --- { 0.0081}
2.085 GeV	3.09 keV **1** { 1 }	3.50 keV **0.520** { 0.521 }*	3.86 keV --- { 0.210 }	4.47 keV **0.050** { 0.066 }
2.300 GeV	3.95 keV --- { 2.356 }	4.23 keV **1.917** { 1.595 }	4.69 keV --- { 0.736 }	5.27 keV **0.299** { 0.273 }

* this is a tuned value

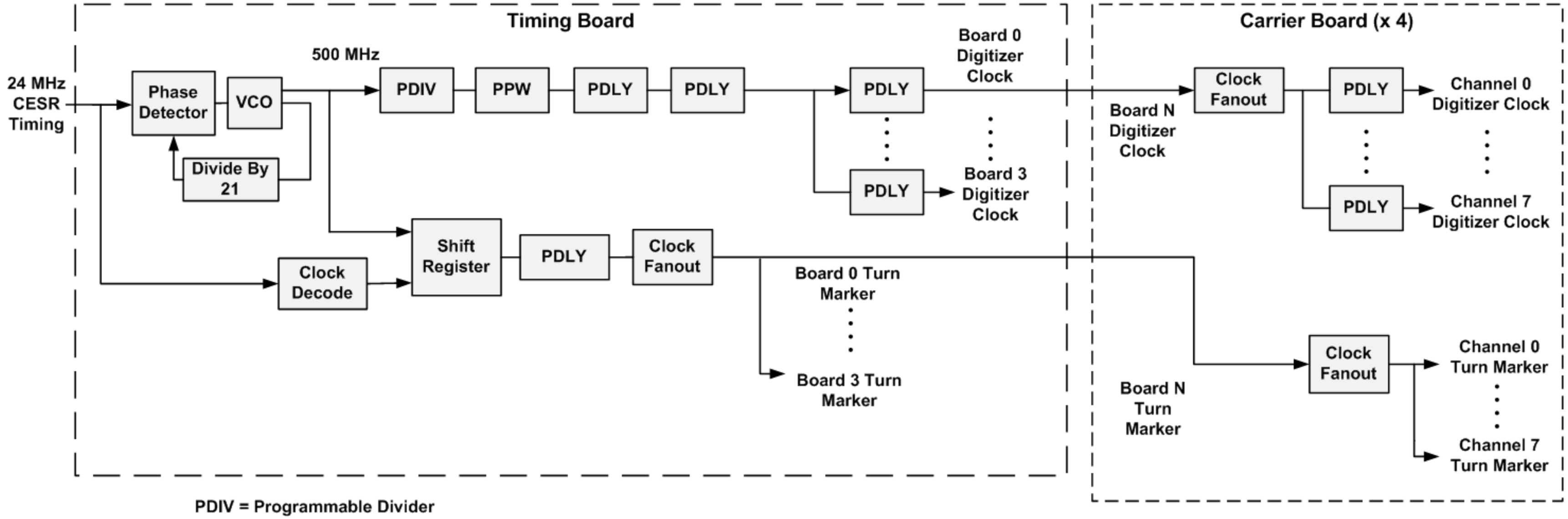
Data Acquisition



AMP = Amplifier
FGA = Fixed Gain Amplifier
VGA = Variable Gain Amplifier
ADC = Analog To Digital Converter
FPGA = Field Programmable Gate Array
MEM = Memory
PLL = Phase Locked Loop
DELAY = Programmable Delay
ENET = Ethernet Interface
SERIAL = Serial Interface
DC-DC = Dc To DC Converters
DSP = Digital Signal Processor
POWER = Power Distribution

Data Acquisition Functional Diagram

Data Acquisition



PDIV = Programmable Divider
PPW = Programmable Pulse Width
PDLY = Programmable Delay

Local Timing Circuitry