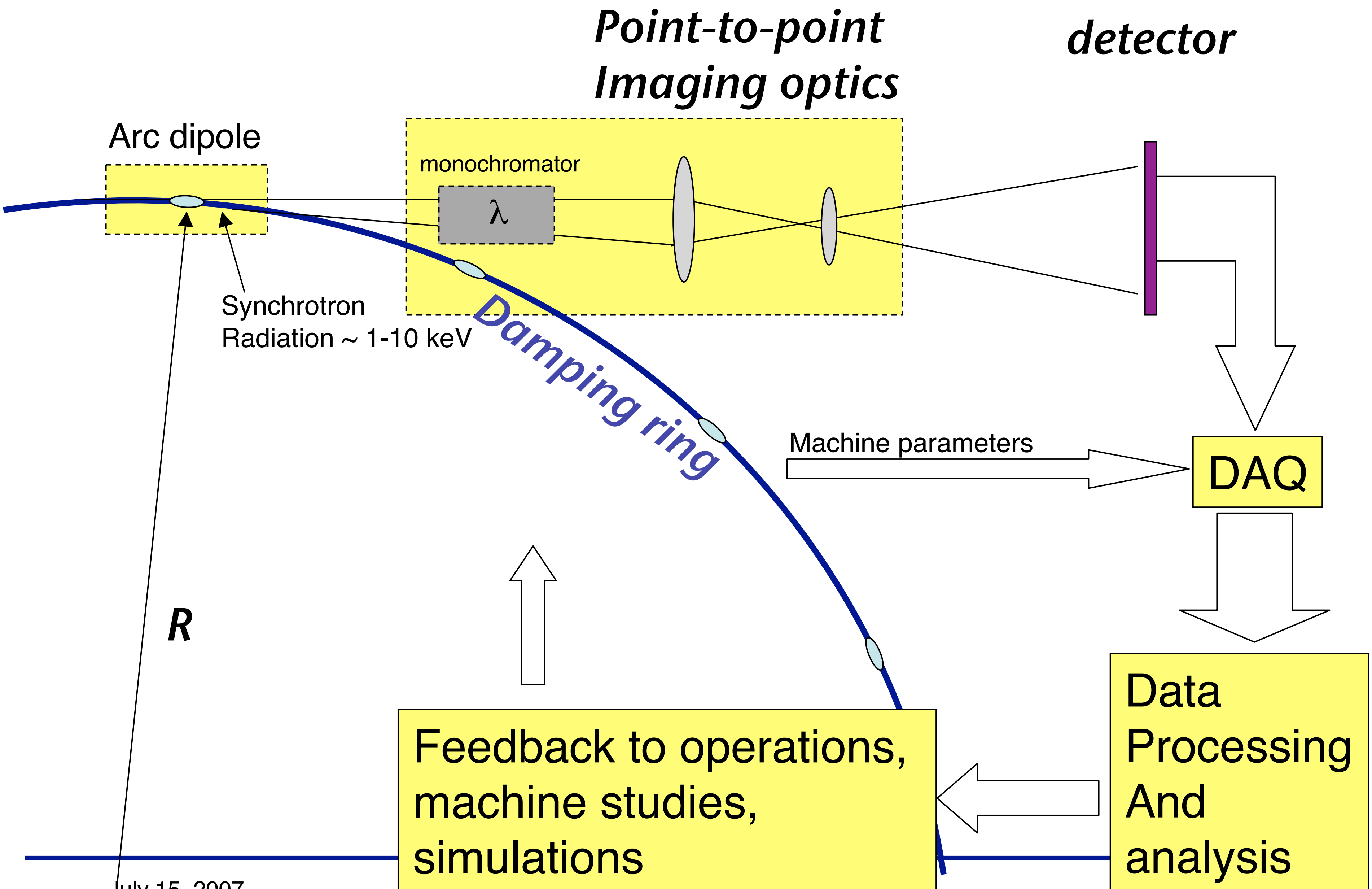
X-Ray Beam Size Monitor for CESRTA

Bunch-by-bunch measurements of beam profile for fast emittance determination

- Image individual bunches spaced by 4ns.
- Transverse resolution << 10~15μm beam size
- Non-destructive measurement.
- Flexible operation.
- Start simple, allow various upgrade paths.

Concept



Point-to-point
Imaging optics
detector
Arc dipole
monochromator
λ
Synchrotron
Radiation ~ 1-10 keV
Damping ring
Machine parameters
DAQ
R
Feedback to operations,
machine studies,
simulations
Data
Processing
And
analysis

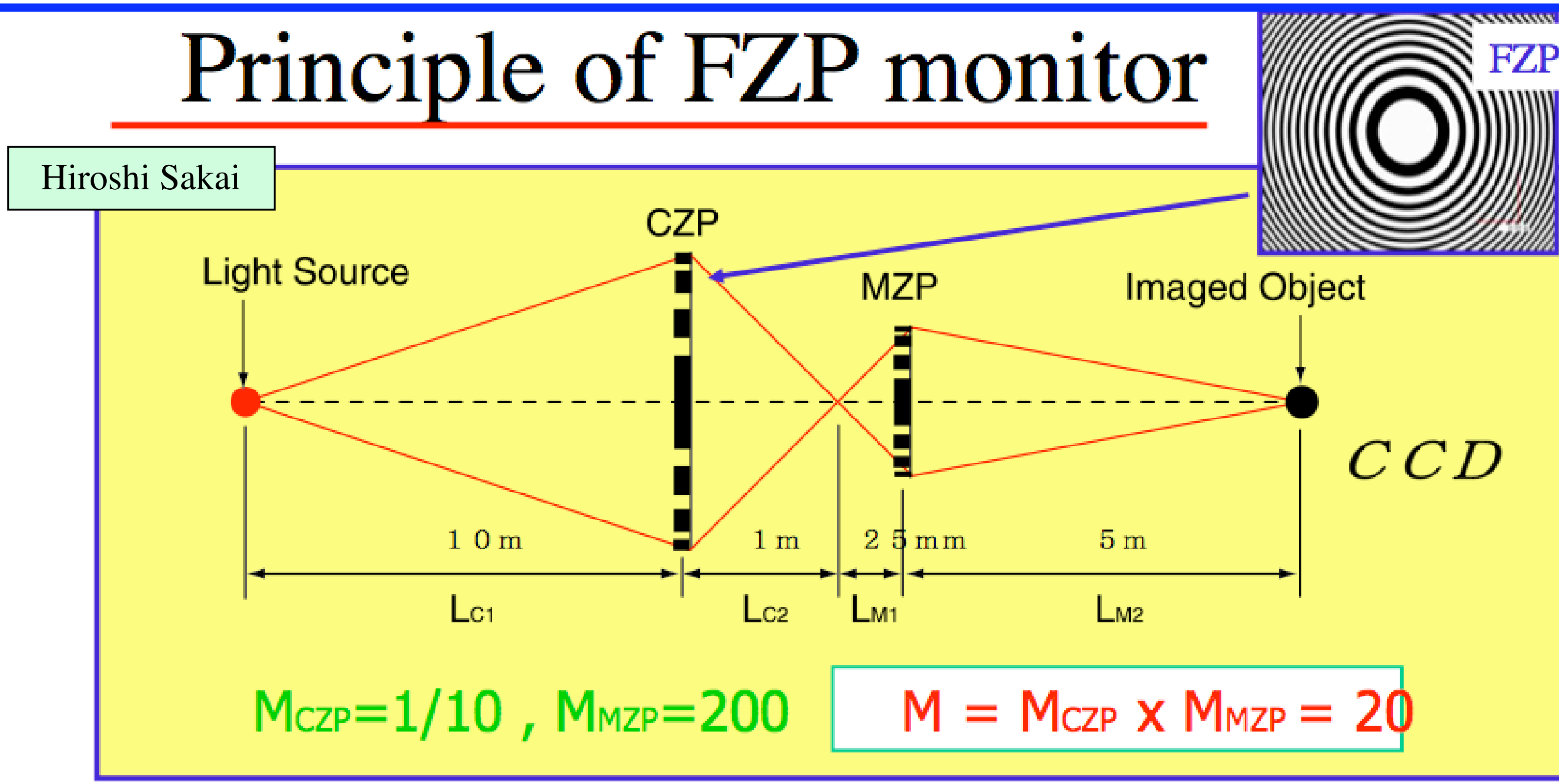
ILC damping ring requirements/motivation

Like CESRTA itself, this beam size monitor is motivated by ILC needs.

Beamsize monitoring in the ILC Damping Rings requires bunch-by-bunch capability because long trains are “folded” in the DR.

This means neighboring bunches can be at quite different stages of their damping history. Single bunch isolation is essential; averaging over hot and cold bunches yields a meaningless result.

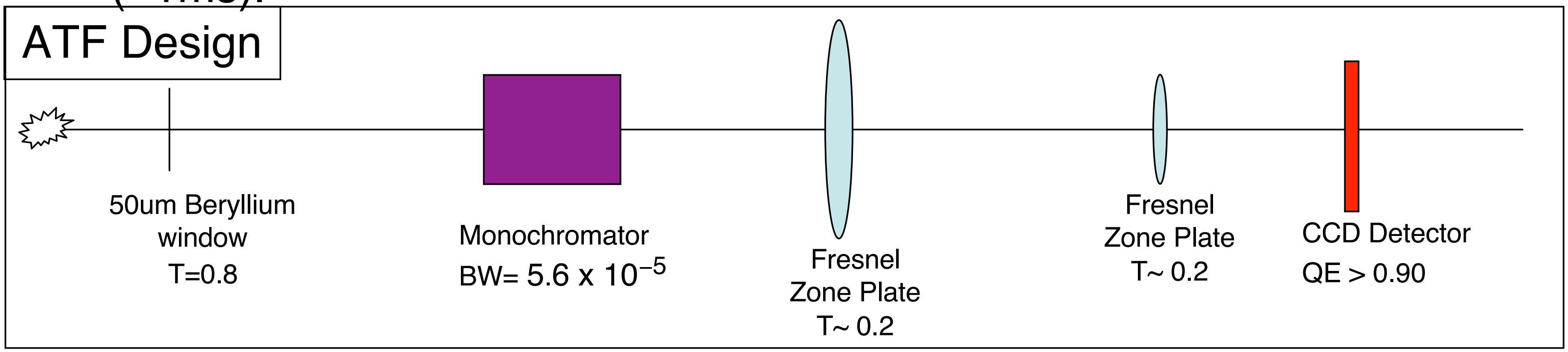
Example: x-ray BSM at KEK-ATF



- 3.24 keV xrays from ATF bend dipole (monochromator: $\Delta E/E \sim 6\times10^{-5}$)
- Vertical beam size $\lesssim 10\mu m$
- Spatial resolution at source = 0.7 μm;
- Time resolution ~ 1ms

Design Considerations for CESRTA (Part 1)

KEK-ATF design is optimized for resolution (< 1 μm) and not for speed (~1ms).



For CESRTA Goals, optimization is different from ATF:

1. vertical beam size is σ_y~10-15μm → $\lesssim$5 μm resolution suffices.
2. bunch-by-bunch requirement → need adequate photon transmission for a single pass measurement. Precision is determined by photon statistics, not optical resolution.

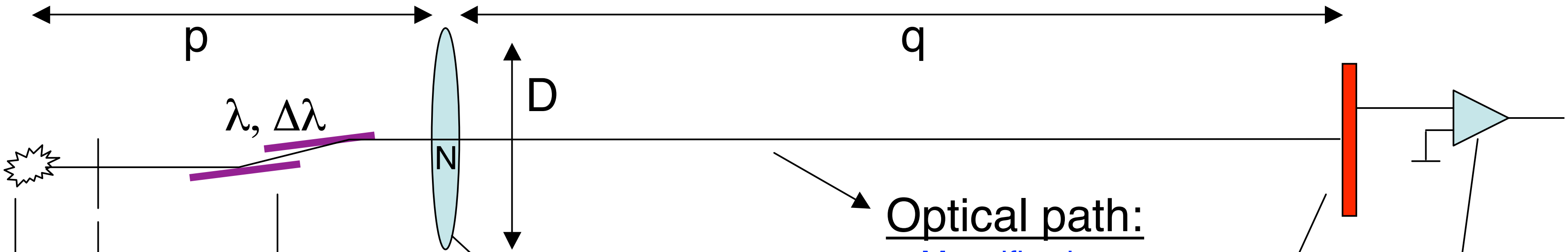
The design shown above, imported into CESRTA, yields ~10 photons per bunch → Needs modification!

Design Considerations for CESRTA (Part 2)

Strategy: Increase photon transmission, give up some resolution.

- Delete second lens. Improves transmission x5.
- Use multilayer mirrors: x100 larger bandwidth than silicon crystal
- Move objective lens closer to source. Diameter can be reduced, which decreases the number of rings needed, matches bw of mirrors.
- Overall spatial resolution degrades, but photon transmission increases.
- *Photon yield in CESRTA ~ $10^{2\sim3}$*
- For simplicity, reduce to one-dimensional measurement (σ_y)

Features that affect performance



Optical path:
Magnification
Backgrounds

Zone Plate:
Diffraction - finite D
Chromatic aberration
Transparency

Detector:
Pixel size
Absorption
Carrier mobility

Monochromator:
Surface quality - flatness
λ, λ
Bandwidth Δλ/λ
Reflectivity

Readout:
Equivalent noise charge
Bandwidth

Vacuum window:
Absorption
Uniformity

Source:
Diffraction from source of known angular divergence
Bunch current, critical energy, etc

Color coding:
Photon yield
Resolution
Distortions
Speed

Interrelationships and Optimization

- $D^2 = 4N\lambda f$ — Fresnel Criterion
- $\sigma = \frac{\lambda\gamma}{2}\sqrt{\frac{3\lambda_c}{\lambda}}$ — Diffraction limited resolution (SR fan)
- $\frac{D}{p} \geq \frac{1}{\gamma}$ — Objective lens encompasses all of SR fan
- $\frac{1}{N} = \frac{\Delta\lambda}{\lambda}$ — Match bandwidth of monochromator
- $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$ — Image-object-focal length relation
- $M = \frac{q}{p}$ — Magnification of one-lens system
- $M = \Delta x/\sigma_y$ — Set magnification for optimal sampling in pixel detector

7 Equations in 9 unknowns. optimize over remaining variables: source-lens distance (p), and x-ray wavelength (λ).

Parameters for CESRTA xray Beam Size Monitor

Beam and Radiation Parameters

Parameter	Value	Units
Beam energy	2.0	GeV
Bunch current	1.0	mA
Bunch Charge	1.6×10^{10}	
Vertical size (σ_y)	$10 \sim 15$	μm
Lorentz γ	3914	
Dipole bend radius	31.654	m
Critical energy	0.564	keV
Critical wavelength	2.2	nm
Photon energy	2.0	keV

Optical System Parameters

Parameter		Value	Units
Source to lens distance		4.0	m
Lens to detector distance		12.0	m
Height of synch rad fan at lens		0.63	mm
Image magnification factor, M		3.0	
Detector Pixel Size		25	μm
Lens diameter		1.02	mm
Number of Fresnel zones		140	
Focal length		3.0	m
Transparency		0.18	
Multilayer mirror bandwidth		0.010	
Multilayer reflectivity		0.36	
Overall transmission factor		0.023	
Energy transmitted, per bunch		1.04	MeV
Ionization charge in detector		39.9	fC
Resolution:	detector pixellation	2.4	μm
	diffraction at source	1.3	μm
	chromatic aberration	0.5	μm
	Fresnel zone plate PSF	0.3	μm
Total resolution		2.8	μm
Number of photons on detector		521	

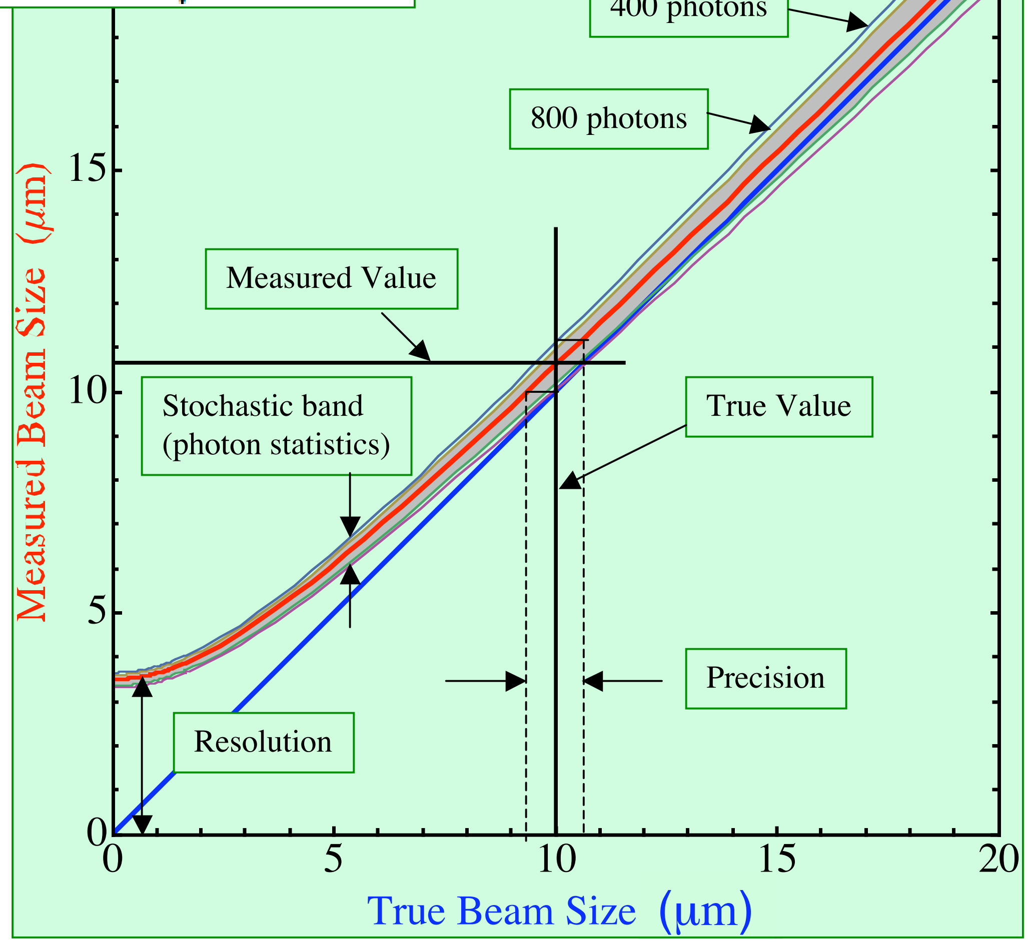
Sidebar: Resolution, Precision, and Photon Statistics

- Optical transfer function is characterized by a resolution (point spread function). This is a *fixed property* of the optical system.
  For CESRTA design, it is 2-3μm. (Figure at right assumes 3.5 μm)

- Photon statistics (and electronic noise, if applicable) fluctuate from snapshot to snapshot.

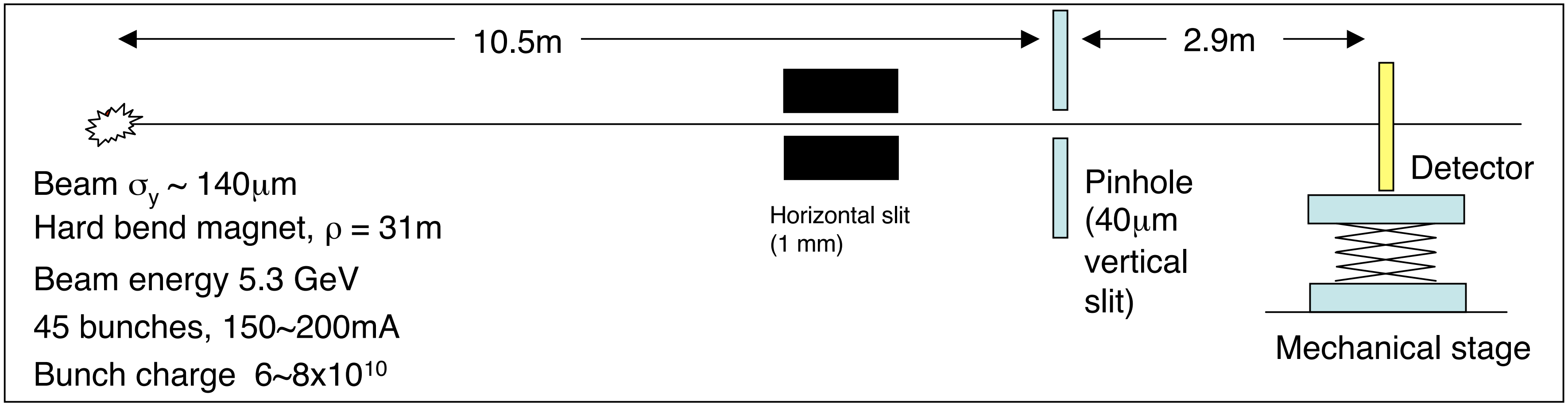
- The *measurement precision* of this system is determined by the stochastic element, not the fixed correction*.

$$\sigma_{obs} = \sqrt{\sigma_y^2 + \sigma_{res}^2}$$



* Residual uncertainty in the optical resolution will appear as a systematic error

Prototype study, in CHESS, 2006 (Slide 1)



Single GaAs photodiode (46μm dia)

Optics: pinhole. (40μm vertical slit)

White beam (no monochromator)

Data acquisition: *72MHz (14ns interval); 12 bit ADC.*

Mechanically scanned vertically and horizontally through the beam -- "synthetic aperture camera"

Single bunch, single pass data - no averaging over turns.

Prototype study, in CHESS, 2006 (Slide 2)

Single bunch, single pass snapshots

Result of vertical beam scan

(single pixel)

Measured:

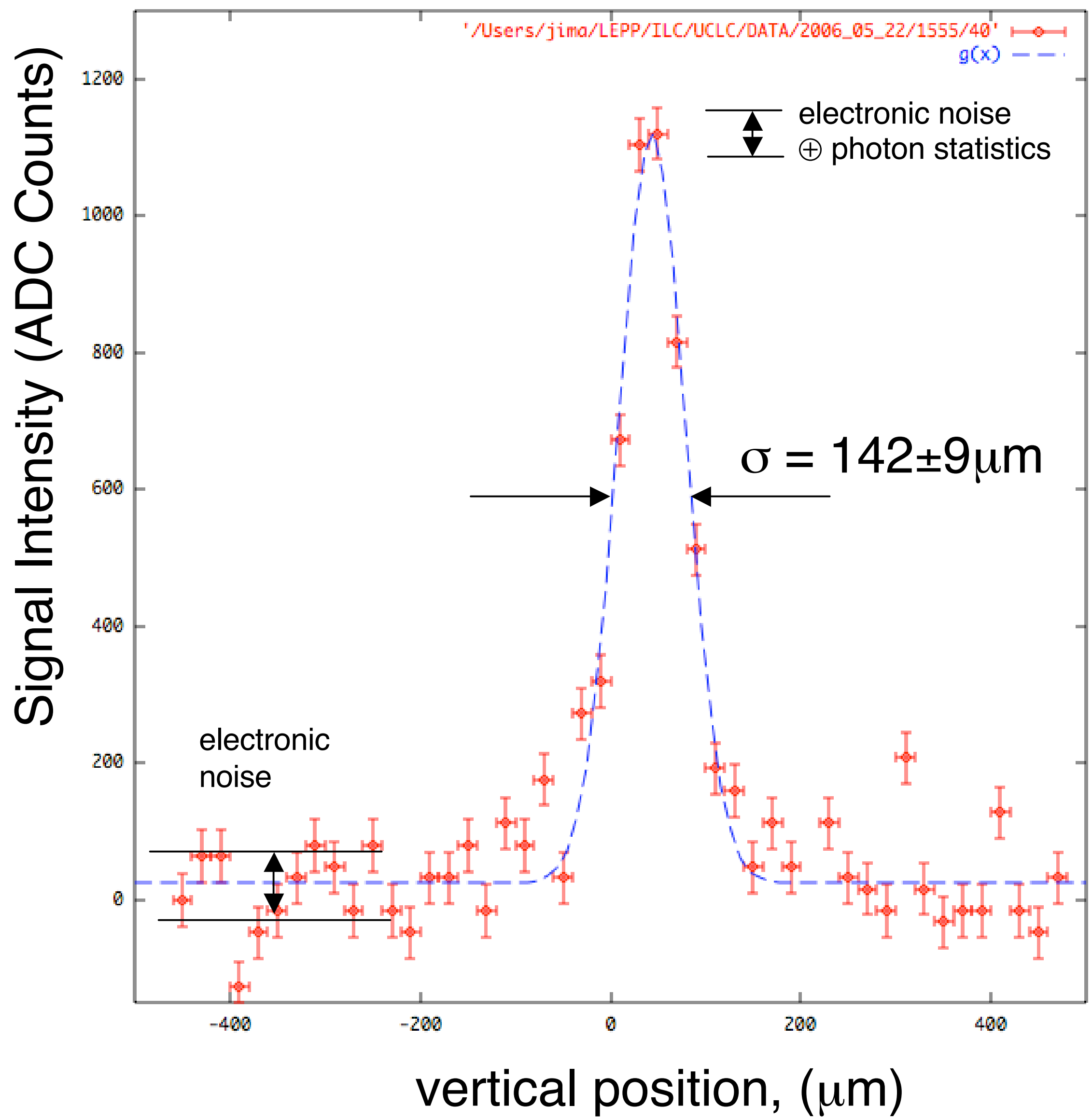
- $S/N_e = 27$
- photons per bunch is ~400
- Signal risetime << 300ps
- Observed beam size 142±9μm (expect ~150)

Calculated:

- Energy abs'd/bunch 6.0 MeV
- Ionization per bunch 230 fC
- Averge photon energy: 13keV

Radiation damage post-study:
700GRad over 4 days, diode current dropped x2.

(Comment: electronic noise was _not_ optimized!)



Prototype study, in CHESS, 2006 (Slide 3)

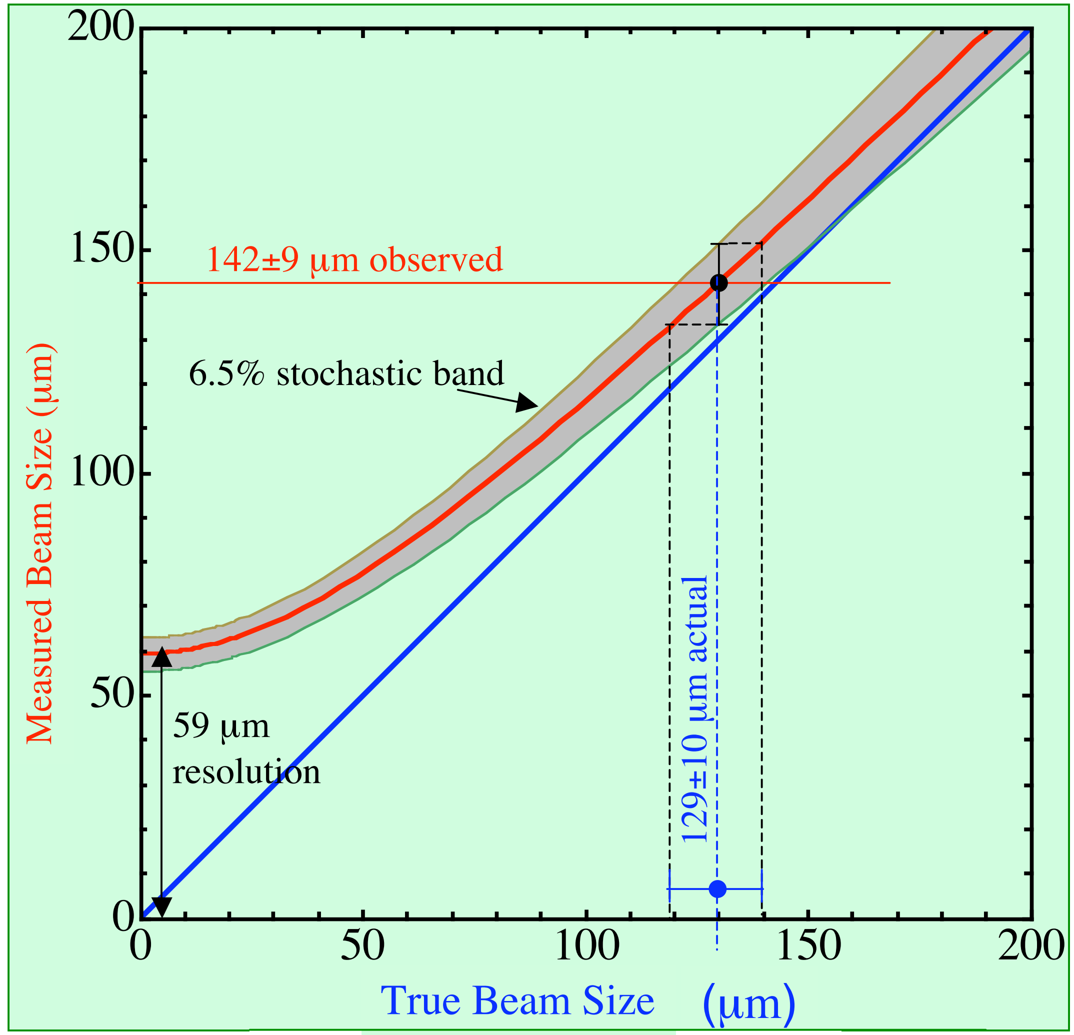
Beam size (σ_y) measurement.

Finite optical resolution:

Fixed offset in σ_y measurement → fixed correction.
59μm here.

Finite photon statistics:

Stochastic error from one measurement to the next.
6.5% here*



*includes electronic noise

X-ray beam size monitor for CESRTA

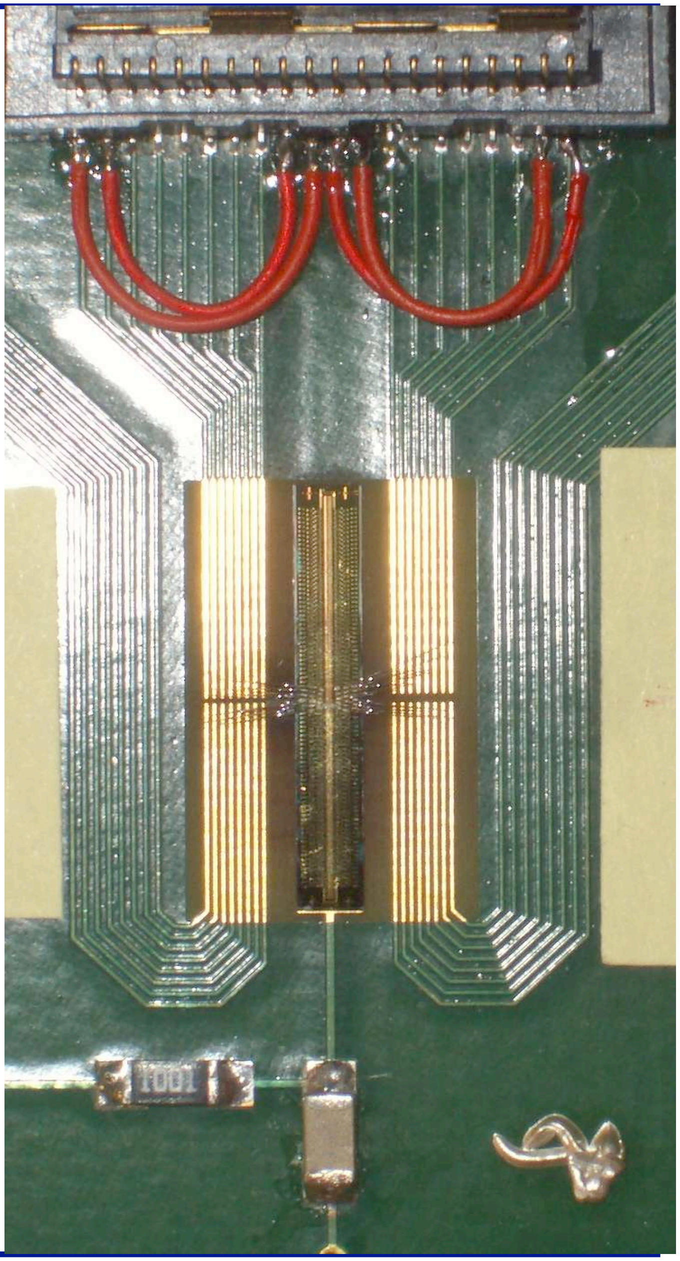
1. Sensors
2. Data acquisition
3. Xray optics
   a) Monochromator
   b) Fresnel Zone Plates

Sensors

- GaAs/InGaAs 1-dim photodiode array
  - 512 diodes, 25μm x 500μm
  - Hamamatsu G9494-512D
  - Off-the-shelf

- Why GaAs?
  - High carrier mobility (8400 cm^2/Vs) & drift velocity (200 μm/ns)
  - High Z, high density
    - short abs length
    - ~ 1μm at 2.5keV

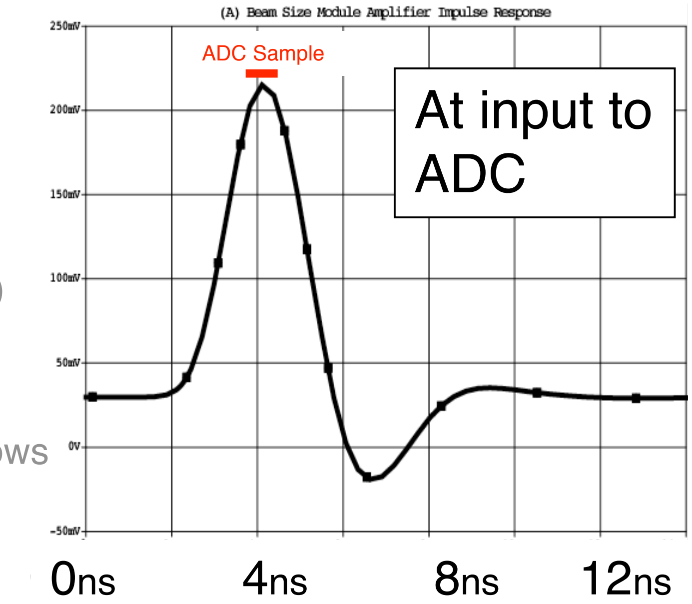
  (The items above, from "High carrier mobility" to "~ 1μm at 2.5keV", are grouped by a brace labelled:) Fast: << 1ns
  - Room temperature ops.
  - Good radiation hardness
  - Commodity parts available;
    - IR receivers for 10Gbps optical ethernet

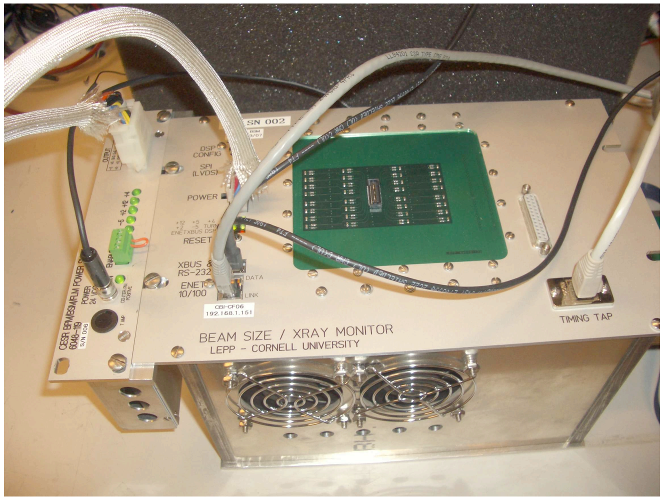


Data Acquisition

Existing system:

- 32 channel parallel digitization, every 14 ns
  - Preamp: OPA842,
    - gain=2, 150MHz bw, 20μV rms noise at input
  - ADC: AD9236
    - 12 bit, 500 MHz, 80MSPS, SNR=70dB (~3300)
- DSP provides power & flexibility
  - On board storage and processing
  - Deep memory holds10K turns of 45 bunch data - allows easy, optional integration over multiple turns
    - Low beam current circumstances
    - Study of beam tails, halo, etc
  - Bunches can be timed in to 10ps
- In use in several CESR diagnostic systems
  - BPMs (high gain input, dual ADCs)
  - Fast Lumi Monitors
  - Optical Beam Size Monitor (high gain input)
  - xRay Beam Size Monitor



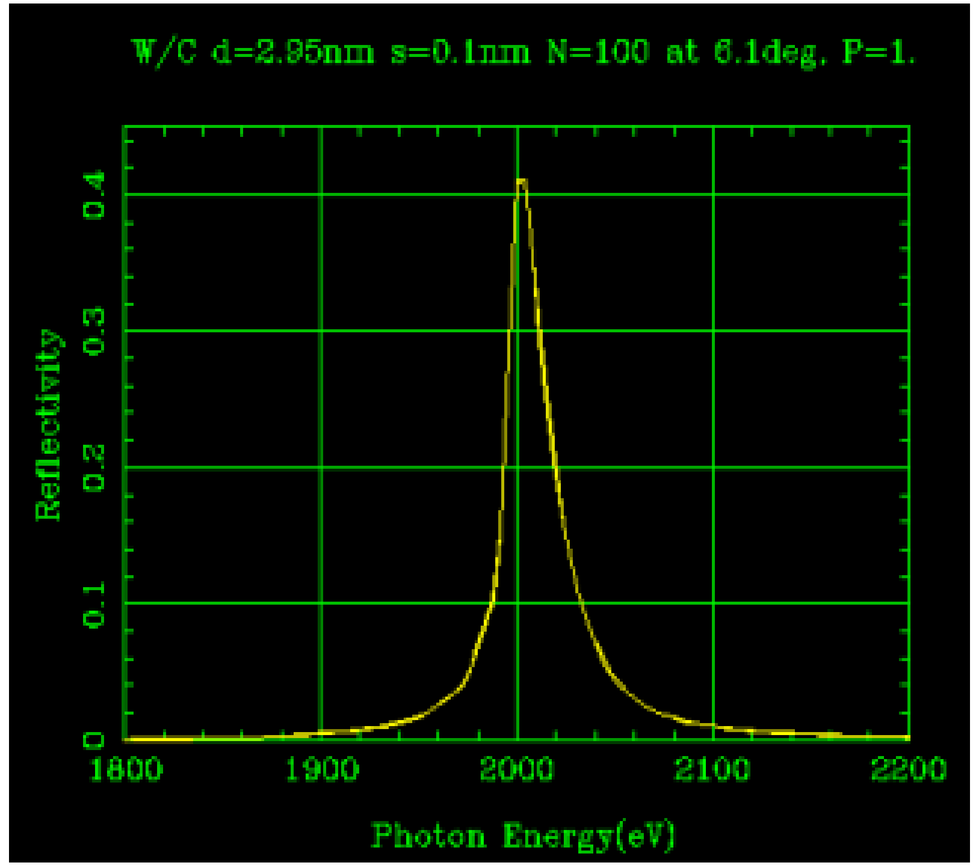


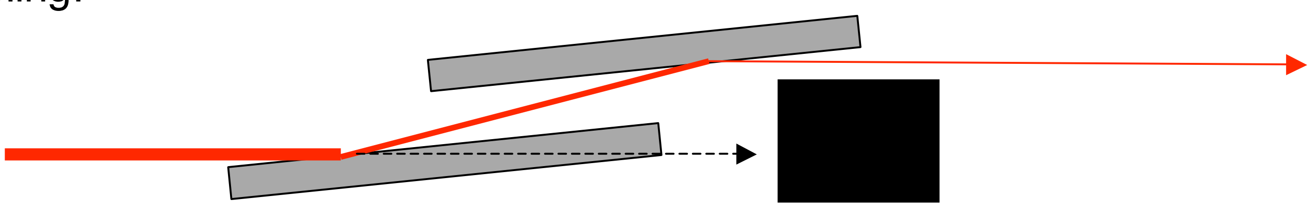
Upgrades required for CESRTA (4ns bunch spacing)

- Higher bandwidth, lower noise front end. Prototype exists…
- Faster digitization: multiple paths, as for BPM system. Details under discussion

Monochromator

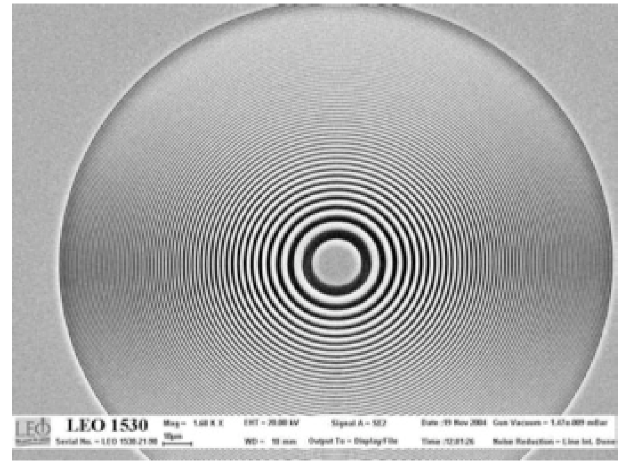
- Tungsten-Carbon multilayer mirror pair
  - 100 layers, 2.95nm period, SiO2 substrate
  - Appropriate bandwidth: ~1%
  - Reflectivity ~ 40%
  - Bragg angle ~ 6^{o} --> limited footprint
  - Expertise in laboratory (CHESS)
    - Design/procurement
    - Mounting, alignment, & controls
    - Cooling!



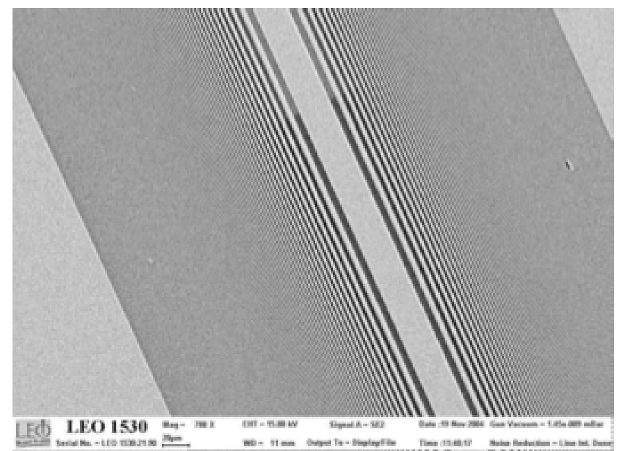


Fresnel Zone Plates

- Provide point-to-point imaging
- Require approx monochromatic beam
  - $\lambda/\Delta\lambda \sim$ # rings
  - Simple FZP (# rings ~ 10^2) well matched to multilayer mirror BW.
  - These requirements are very modest:
    - Photon-hungry application → need large BW, → small number of rings
- Commercially available (xRadia,…)
- PSF determined by width of last ring
  - FZP, monochromator, magnification, detector pixel size must all be related: optimization



2-dim focussing



1-dim focussing

Zone Plate Studies at CHESS, June 2007

Alex Kasimirov

test at A2

optics: mirror, Mls: W/B_4C T=0.2 , $\Delta E/E \approx 0.5\%$
E=14.727 keV

DOE type	Focal length, F [cm] at 4 keV	Aperture of DOE, A [µm]	Outermost zone width, dr_n [µm]	Number of zones
33 (circular)	25	A=194	0.4	122

L_s=38.6 m; F=0.92 m; L_f=0.94 m

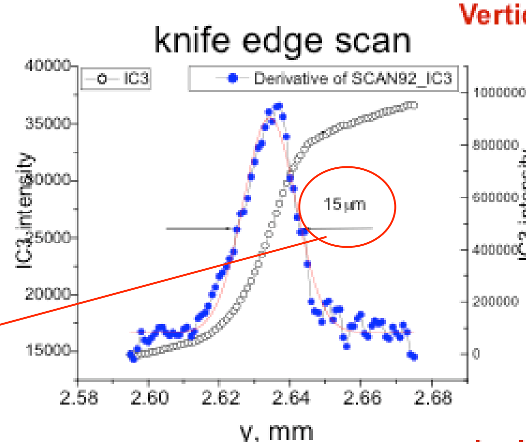
Demagnification=L_f/ L_s=0.024

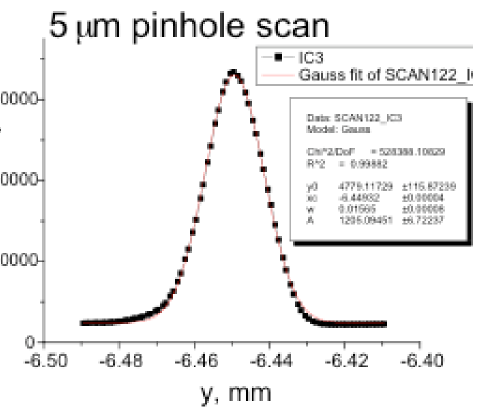
source: vertical $2\sigma_y$=320 µm
horizontal $2\sigma_x$=2880 µm

we should expect: $w_y \approx 8$ µm
$w_x \approx 70$ µm

Referred to detector plane

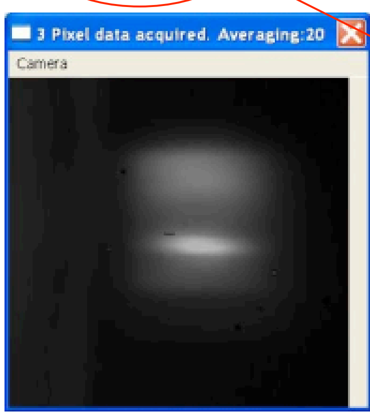
Vertical:

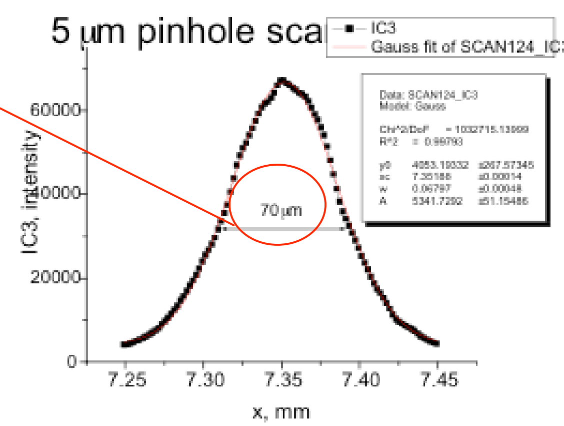




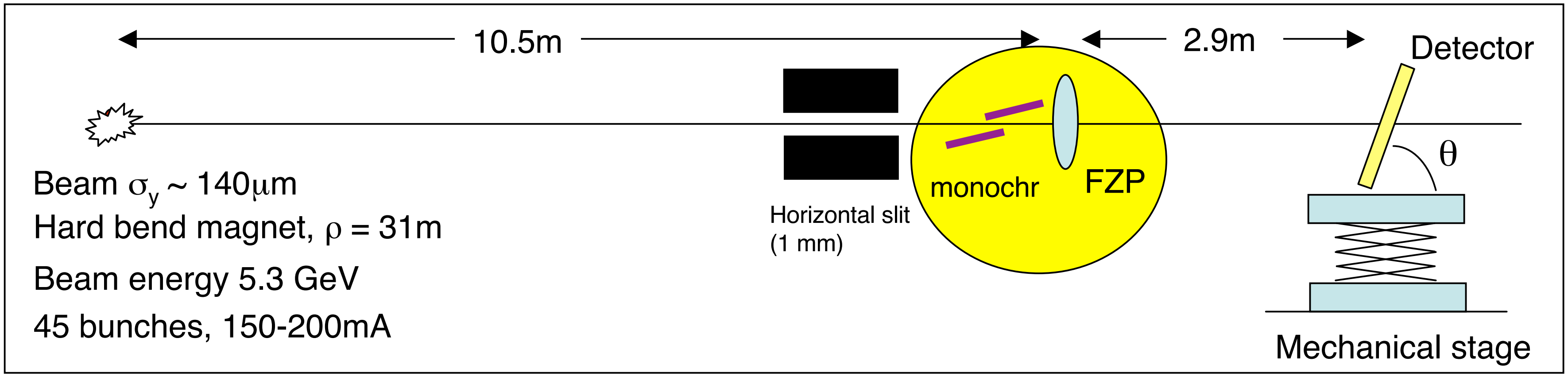
horizontal:

source image:





Next Prototype study, in CHESS, October 2007



- Test prototypes of all key components of CESRTA design
  - *multilayer mirrors*, cooling, mechanics, alignment, orientation
  - *Fresnel Zone Plate* .. x3 *de*magnification (okay - large beam)
  - full size 1-dim detector, 32^{++} channels simultaneous readout
  - test adjustable effective pixel height ($\Delta x \sin\theta$)
  - single pass, single bunch snapshot imaging, as before
  - improved high BW, low noise readout
  - study radiation damage in more detail than previous run
- Not tested:
  - 4 ns bunch conditions, 2 GeV beam

Manpower & resources

Physicists

- LEPP: J.A., Mark Palmer, Jake Lee
- CHESS: Ernie Fontes, Alex Kazimirov, Peter Revesz
- Alfred University: Robert Holtzapple

Engineers

- John Dobbins, Charlie Strohman, Eugene Tanke

Laboratory shops and technical staff

CHESS scientists provide expertise in xray optics

LEPP scientists provide expertise in detector technology & electronics

Scale to needs: upgrade paths for xBSM

- The design shown here is minimal. Can be ready on Day One.
- With experience, and depending on needs, improvements could be undertaken:
    - Additional readout channels --> expand dynamic range, simplify operations
    - Two-dimensional photodiode array for full x-y imaging

Broader Impacts

Students who have participated so far in one way or another:

Nick Taylor -- graduate student in General Relativity
Richard Gray -- graduate student in HEP
Laura Fields -- graduate student in HEP
Jake Lee -- undergraduate physics major
Ivan Rankenburg -- graduate student in condensed matter theory

HEP physicists participating in ILC accelerator physics

University contributions to ILC

Summary

- Nondestructive, fast, high resolution beam size monitoring can be provided for low-emittance diagnostics.
- Resolution is sufficient to probe ~10 μm vertical beam size
- High speed detector & readout allows single pass imaging
- Readout system is adaptive and offers flexible operations. Multi-turn averaging is available without any alterations.
- Tests to date have confirmed detector performance; optical elements will be tested in upcoming run.
- Low technical risk. Existence proof at KEK-ATF. Main new element here is speed. Sensor and optical components are readily available, off-the-shelf commercial items.
- Natural upgrade paths exist should circumstances require or suggest improvements.
- CHESS participation has been and continues to be extremely valuable.
- Excellent educational vehicle for students.