Instrumentation & Diagnostics: First Thoughts on a Damping Ring Beamsize Monitor

UCLC subproject

"A Fast Synchrotron Radiation Imaging System for Beam Size Monitoring"

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Introduction

Basic idea: *image synchrotron radiation from damping rings*

- *Snapshots of transverse bunch shape*
- *Measure σ_x, σ_y, distortions, rotations, etc.*
- *Bunch-by-bunch: single bunch resolution*

Motivations:

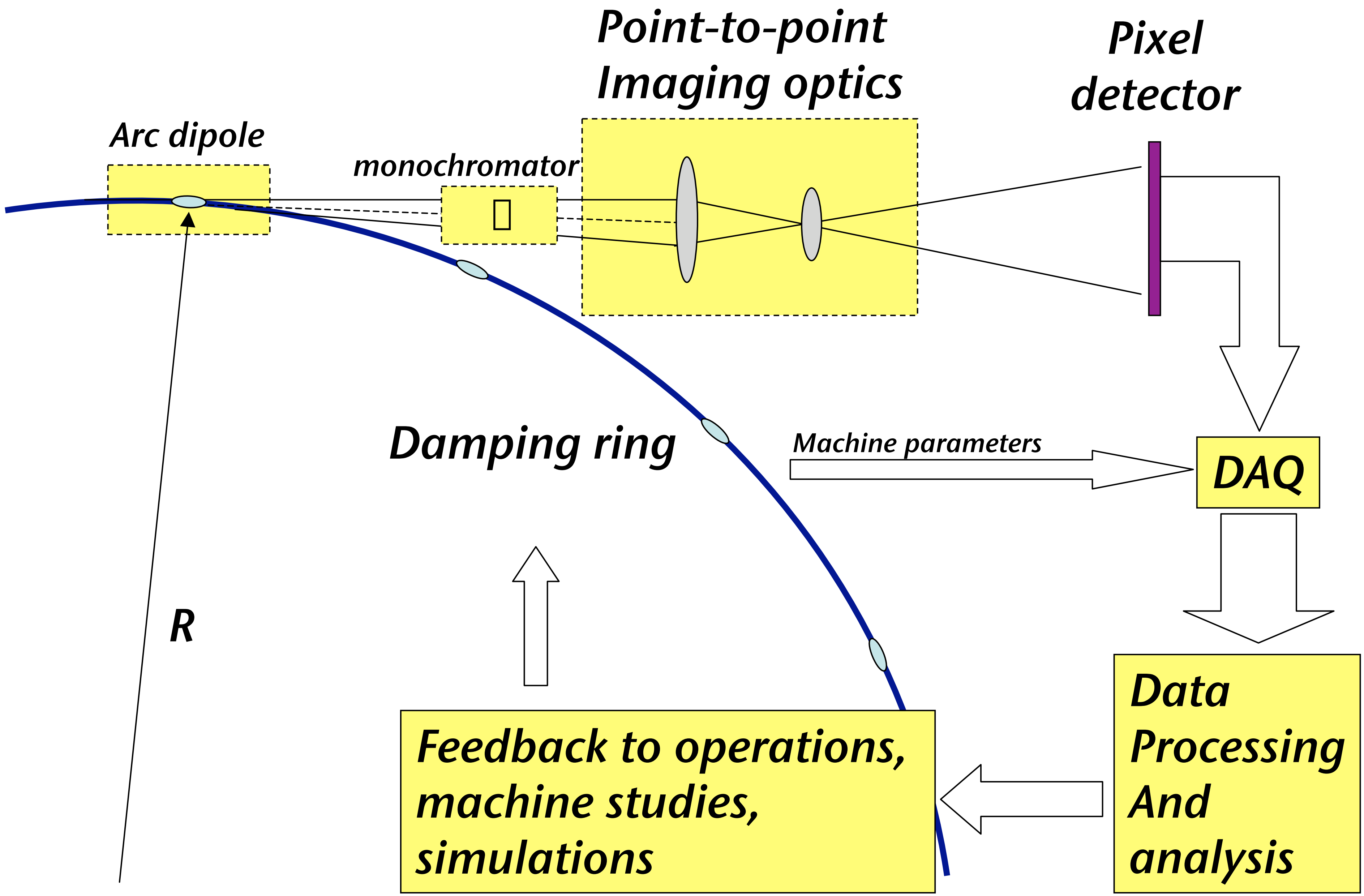
- *"The LC needs two things: RF cavities to make the energy, and beam diagnostics to make the luminosity."*

- *natural way to contribute*
  - *Particle detectors - familiar technology (but xray optics new)*
  - *Small scale - suitable to university setting, small group*
  - *Possibility to use CESR as test bench*
  - *Availability of nanofabrication facility*

- short project description: Damping Ring beam size monitor

- Detailed project description: The beam height in the damping ring will be about 4 microns. We need to nondisruptively measure this on an individual turn in the ring. Traditionally this is done with a synchrotron light monitor. The spot here is so small that one must go to very short (x-ray) wavelengths to get the necessary resolution. We would like a conceptual design of some way to do this. It would then be evaluated whether a prototype is needed

Concept:


Point-to-point
Imaging optics
Pixel
detector
Arc dipole
monochromator
Damping ring
Machine parameters
DAQ
R
Data
Processing
And
analysis
Feedback to operations,
machine studies,
simulations

Design Issues for a fast imaging system

- ***Transverse resolution:*** *image quality*
  - *Small bunch dimensions (5x50um) □ magnification (>20)*
  - *optics: defects & limitations. Various technology choices.*
  - *Diffraction from small source □ xrays >1keV ok.* $\square y \sim \square(E_c E)^{-1/2}$
  - *Transverse motion of bunch during snapshot (~R/□² < 1□m)*
  - *Photon statistics (100? 1000? 10,000?) Moments.*
  - *S/N in electronics chain*

FOCUS

- ***Longitudinal resolution:*** *single bunch resolution* ***(z=ct)***
  - *□t between bunches (1.4 ns: assume worst case)*
  - *absorption depth in detector* $e^{-x/\square}$ $(\square \sim E_{\square}^{5/2} / \square Z^5)$
  - *signal collection time* $\square t \sim \square / v_d = \square\, t_{det} / \square V_{dep}$
  - *R,C of collection & switching circuits*

    $C_{det} \sim$ *(pixel area) /* t_{det}

SHUTTER SPEED

- ***Complicated TRADEOFFS □ OPTIMIZATION required***

Optical System (Telescope)

Monochromator:

single □ helpful in design;

widens choices: eliminates chromatic aberrations as concern

reduces flux: BW = dE/E = 1.4×10^{-4}

Collimators, Attenuators, choppers:

will be needed…

Telescope:

Critical Design Issues:

- *Magnification*
- *Transmission*
- *Aberrations (scattering, surface quality, diffraction,…)*
- *Thermal load*

Technology Choices for Optics

FRESNEL ZONE PLATE

+ in use at KEK ATF

- manufacturing tolerances are tight

** could be done here at nanofabrication facility*

DIFFRACTIVE LENSES

+ available ~off the shelf

- absorption, scattering, mechanical tolerances

SPECULAR REFLECTION

- *challenging surface quality requirements ~nm;*
- *complicated…*

Nominal Damping ring parameters

Quantity	"TESLA"	"NLC"
Beam Energy (GeV)	5.0	1.98
gamma = E/mc^2	9784	3875
e+ per bunch	2E10	1.9E10
bunch length: sigma_z	6mm	4mm
circumference	17km	223m
Number of turns	500	6700
Time in Damping ring	28ms	5ms
Damping time	4ms	1ms
Rep rate	5Hz	180Hz
time per turn	57us	743ns
interbunch spacing	20ns	1.4ns
bunch length: sigma_t	20ps	13ps

Quantities evaluated at center of bend dipole:

dipole bend field (T)	0.194	1.53
bend radius (m)	86.	4.3
critical energy (keV)	6.4	8.0
diffraction lim. @ 1keV(um)	4.1	1.4
vertical beta func (m)	27.	5.5
horizontal beta func (m)	2.5	1.5
gamma * vert emittance (m)	2E-8	2E-8
gamma * horz emittance (m)	8E-6	3E-6
bunch size: sigma_x	45um	34um
bunch size: sigma_y	7um	5.3um

Important Time Scales

- *Plenty of time between cycles*
- *Single bunch image challenging*
- *intra-bunch tomography: really challenging... impossible?*

- *Determines available xray spectrum. Must choose optimum E.*
- *evaluated at xray energy E=1keV; scales as ~$E^{-1/2}$*

- *Requires significant magnification (Need optical system anyway)*

Xray Flux Estimates

- *Consider low and high xray energy (just above L3, K edges in Arsenic)*
- *Assume monochromator BW acceptance = dE/E = 1.4x10^{-4};*
  no other attenuator or chopper
- *Use Jackson's definition of critical energy (spectrum peaks at ~ E_{crit}/6)*

Case I: Eγ = 1.4keV

Critical Energy = 6.232 keV

Detected Photon Energy E = 1059.4 eV

x = E/Ecritial = 0.17

Diffraction Limited Resolution 4. μm

Relative to Peak intensity = 0.96

Energy per snapshot = 22. MeV

Photons per snapshot = 20596.

Case II: Eγ = 12.2 keV

Critical Energy = 6.232 keV

Detected Photon Energy E = 12152. eV

x = E/Ecritial = 1.95

Diffraction Limited Resolution 1.2 μm

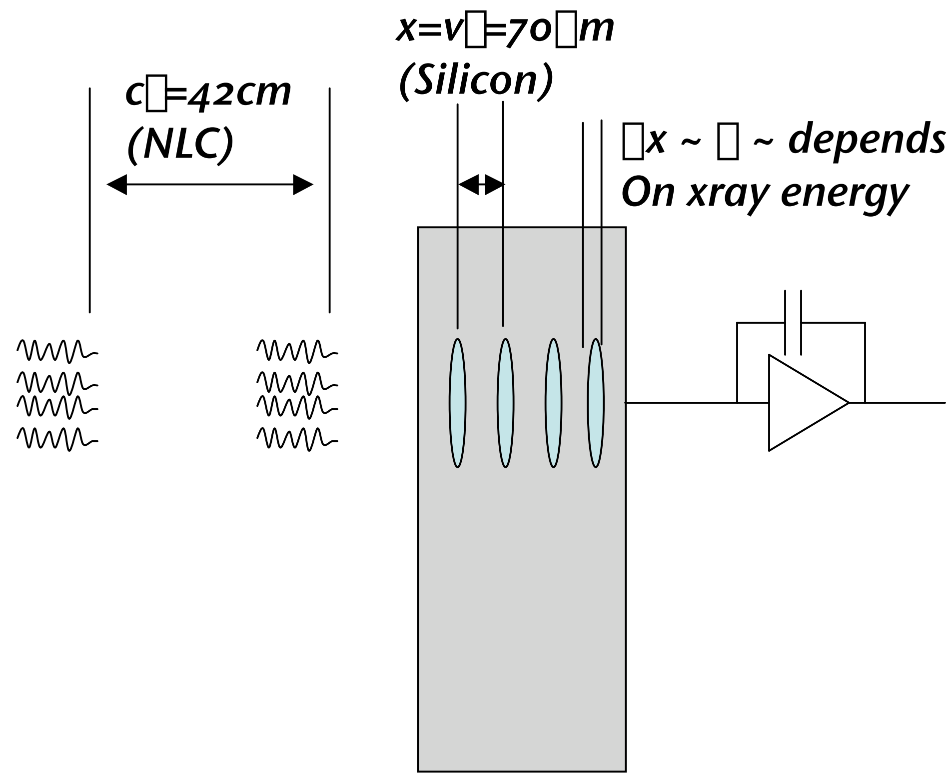
Relative to Peak intensity = 0.061

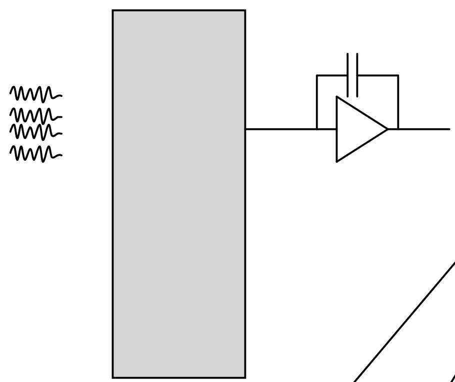
Energy per snapshot = 16. MeV

Photons per snapshot = 1302.7

Detector Issues

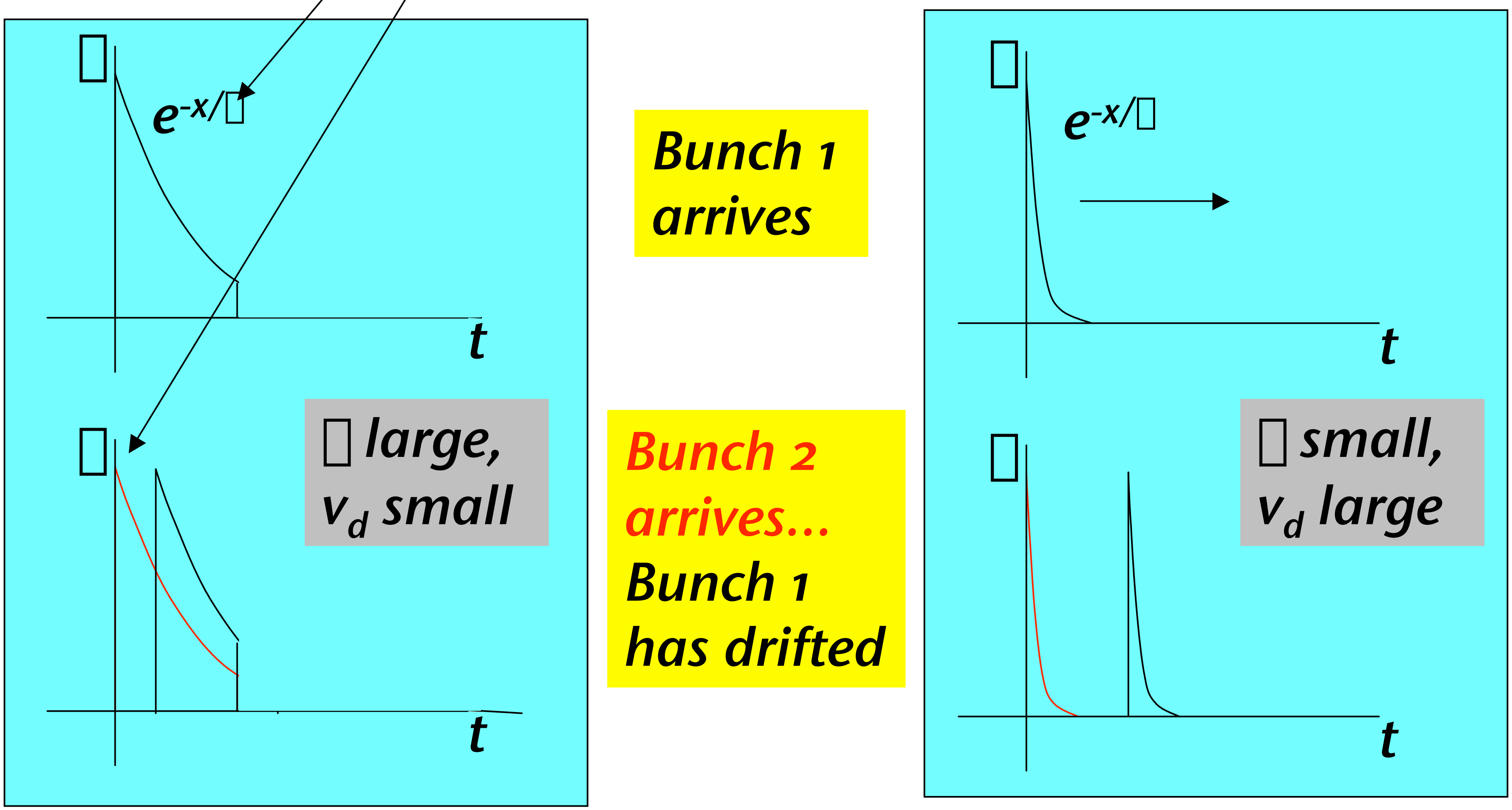
- *solid state pixels… small array, perhaps 16x32*
- *challenges*
  - *Speed requirements*
  - *Radiation dose*
- *Key factors to consider:*
  - *Xray absorption length*
    - *Xray energy*
    - *Choice of semiconductor*
  - *Mobility (use electrons)*
    - *Choice of semiconductor*
    - *Temperature*
  - *R, C of detector and external circuits!*
- *Optimum material? GaAs. Silicon…*





Pulse Pile-up in detector

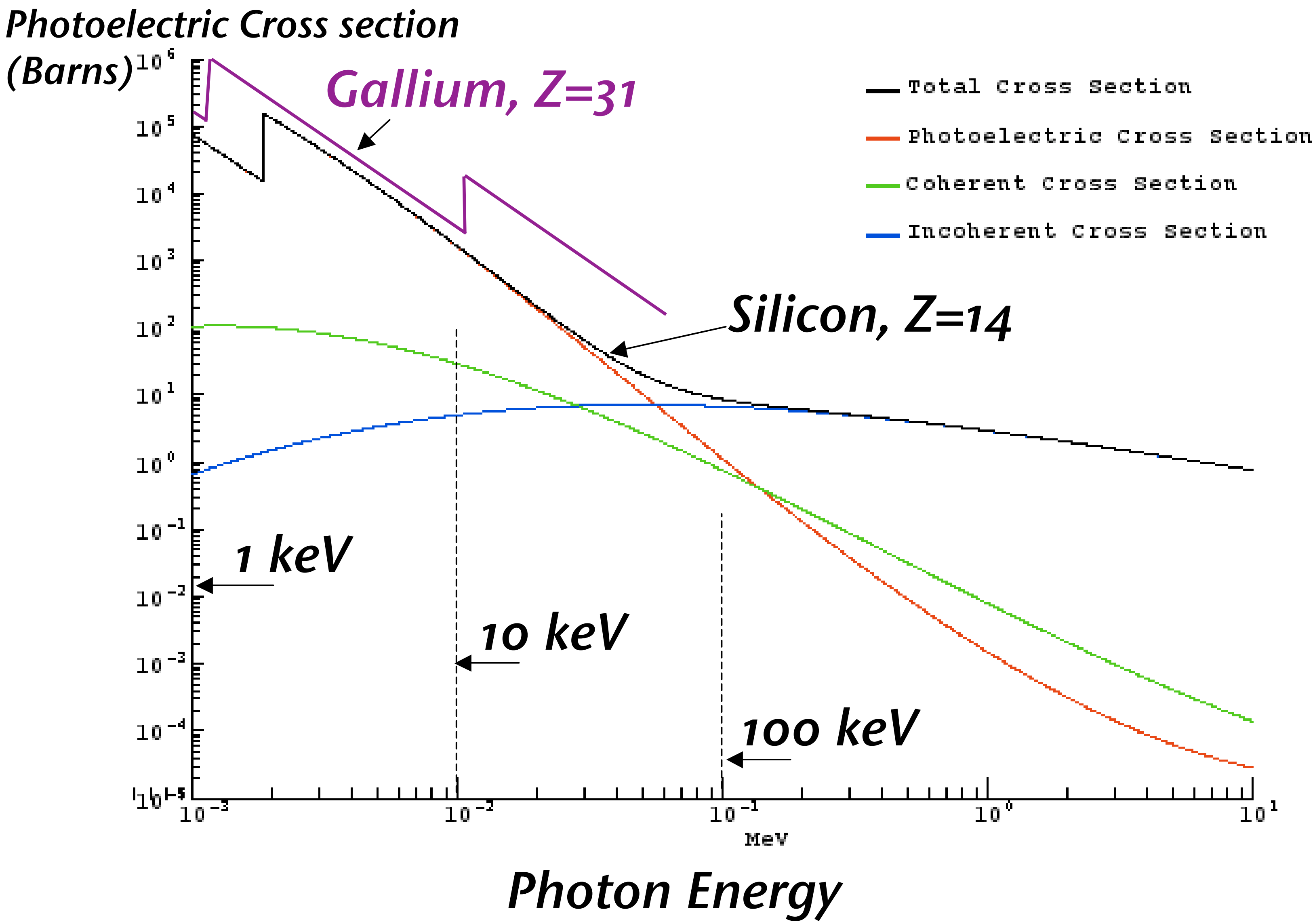
- *Absorption length determines pulse length*
- *Drift velocity determines separation*



Silicon and GaAs properties

Quantity	Silicon	GaAs
density (g/cm^3)	2.3	5.3
<Z>	14	32
K-edge	1.84keV	10.4keV, 11.7keV
Xray Absorption length@		
2keV	1.6um	0.6um
12keV	242um	12um
dielectric const	12	13
band gap	1.12eV	1.42eV
energy to liberate one pair	3.6eV	?
electron mobility (cm^2/sV)		
@300K	1450	8400
@77K	22000	130000
breakdown field (kV/cm)	30kV/cm	40kV/cm
e- Drift Vel @3.3kV/cm	50um/ns	290um/ns
Bunch separation - TESLA	1000um	5800um
Bunch separation - NLC	70um	406um

Photoelectric Cross Sections



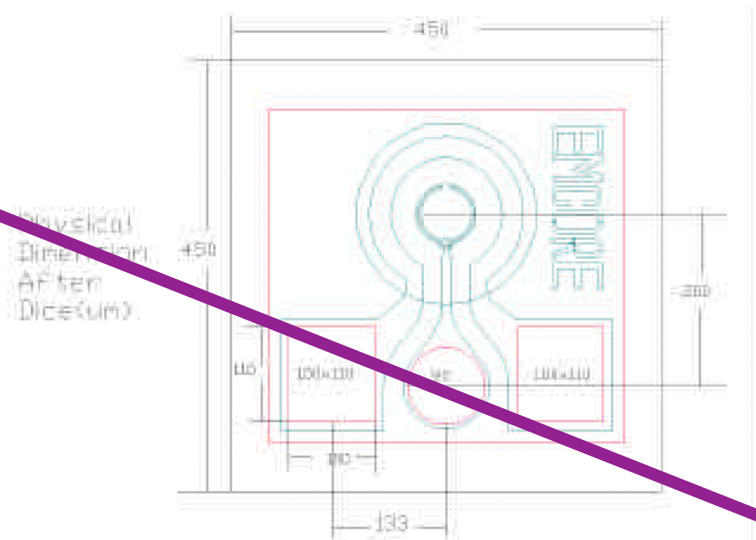
10 Gbps GaAs PIN Photodiode*

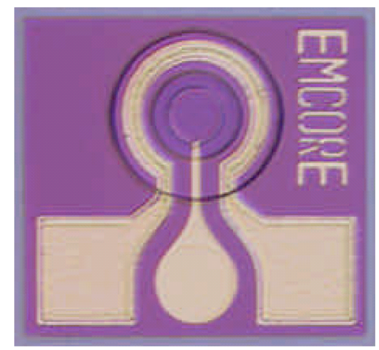
Product Description

EMCORE's 10 Gbps Gallium Arsenide (GaAs) PIN photodiode is designed for multimode fiber applications. Utilizing EMCORE's own state-of-the-art MOCVD wafer foundry and device fabrication facility guarantees a reliable high volume fabrication source of package ready die to meet the growing needs of fiber optic component manufacturers. Excellent device performance and robust operation makes this the superior device for high speed multimode optical communication applications.

Features

- Data rates of 10 Gb/s
- Excellent responsivity
- Large aperture size
- Low capacitance
- Low dark current





Fast enough for single bunch resolution already

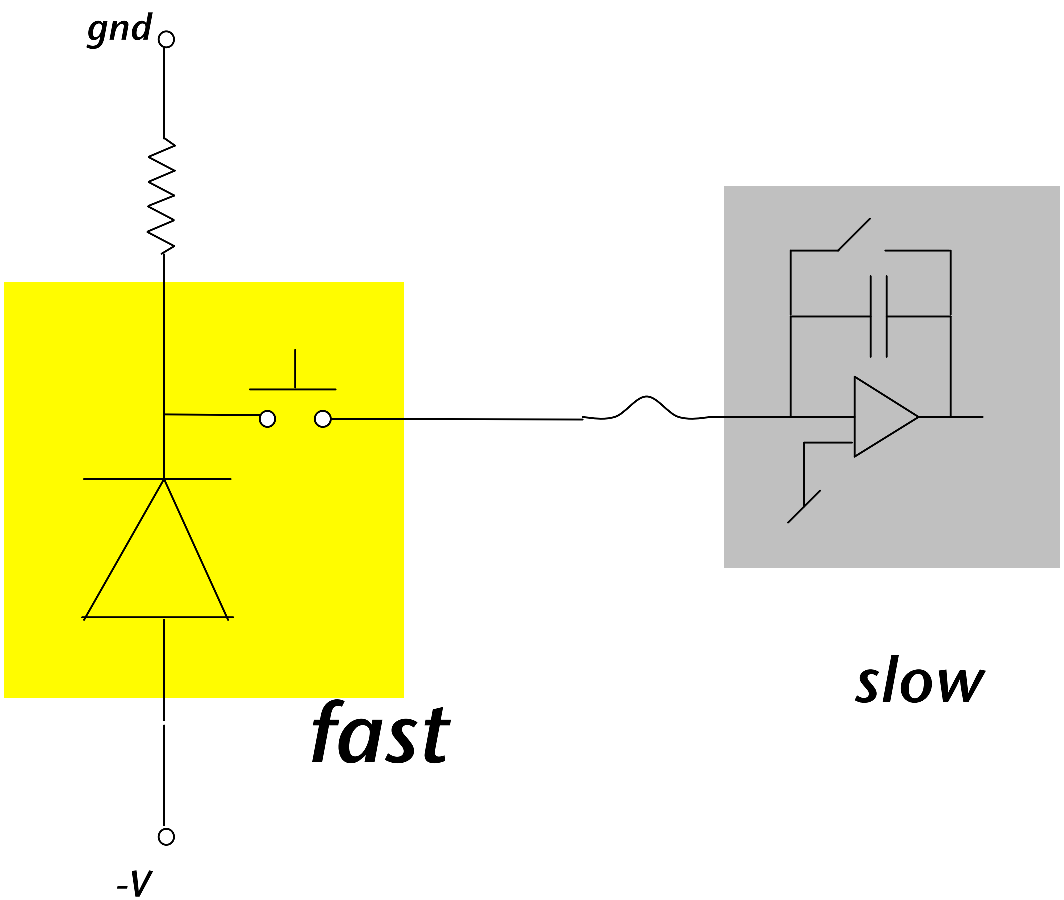
Product Specifications

Electro-Optical Characteristics (T = 30°C)

	Conditions	Min.	Typical	Max.	
Speed	-1.6 V		8.5		
Responsivity	3 to -26 dBm, 850 nm Epoxy coated, n=1.6		.5		A/W
Active Area (aperture)	-		60		µm
Rise/Fall Time	20% / 80%, -1.6 V bias		30/35		ps
Dark Current	-1.6 V, -70 dBm		<.2	1	nA
Capacitance	-1.6 V, 1 MHz		.28		pF
Reverse Breakdown	1 µA	20	50		V
Reflectivity	Epoxy coated, n=1.6			1	%

Concept

- *Fast detector,*
- *Fast switch,*
- *Slow amplifiers*



Some Issues:

- *RC constants*
- *Integration*
- *Gate pulse*
- *switch on/off characteristics*
- *Chg injec.*

Radiation Damage, Thermal Power, etc…

Case I: E□= 1.4keV

Critical Energy = 6.232 keV

Detected Photon Energy E = 1059.4 eV

x = E/Ecritial = 0.17

Diffraction Limited Resolution 4. μm

Relative to Peak intensity = 0.96

Energy per snapshot = 22. MeV

Photons per snapshot = 20596.

Xray mean free path = 0.32 μm

Mass	= 18.4×10^{-6} g
Dose Rate	= 13.5×10^{3} kRad/sec
Thermal Load	= 2.49×10^{-3} Watts
Temp rise per sec	= 410. degC
Drift Velocity	= 280. um/ns
Collection Time	= 2.3×10^{-3} ns

Case II: E□= 12.2 keV

Critical Energy = 6.232 keV

Detected Photon Energy E = 12152. eV

x = E/Ecritial = 1.95

Diffraction Limited Resolution 1.2 μm

Relative to Peak intensity = 0.061

Energy per snapshot = 16. MeV

Photons per snapshot = 1302.7

Xray mean free path = 11. μm

Mass	= $646. \times 10^{-6}$ g
Dose Rate	= 281. kRad/sec
Thermal Load	= 1.81×10^{-3} Watts
Temp rise per sec	= 8.49 degC
Drift Velocity	= 280. um/ns
Collection Time	= 7.9×10^{-2} ns

- ***Clearly chopping/shuttering will be required!***
- ***Higher energy xrays appear to be preferable.***

Status and outlook...

- *explore parameter space, identify key issues*

- *simple simulations of signal development, image properties*

- *optical system proto-design... have ESFR software*

- *detector+shutter proto-design. Simulations...*
  need engineering help

- *test structures....*