Detectors for X-ray Science

Heinz Graafsma
<2006: European Synchrotron Radiation Facility
>2006: DESY-Hamburg

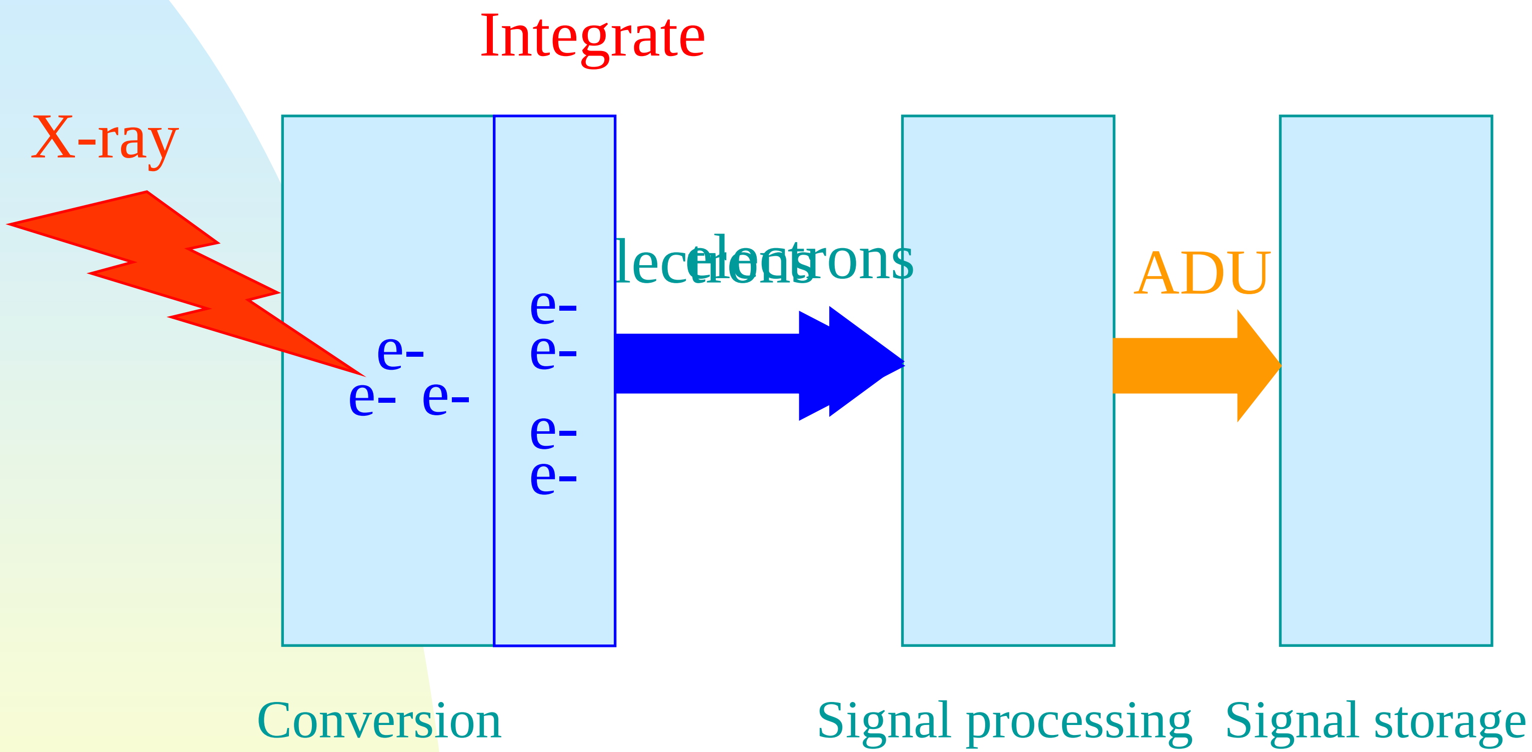
X-ray Science?

- **Medical Imaging**
- **Security and safety inspection**
- **Non-destructive testing**
- **Space Science**
- **Analytical tool in home lab**
- **Storage rings**
- **XFELS**
- **...**

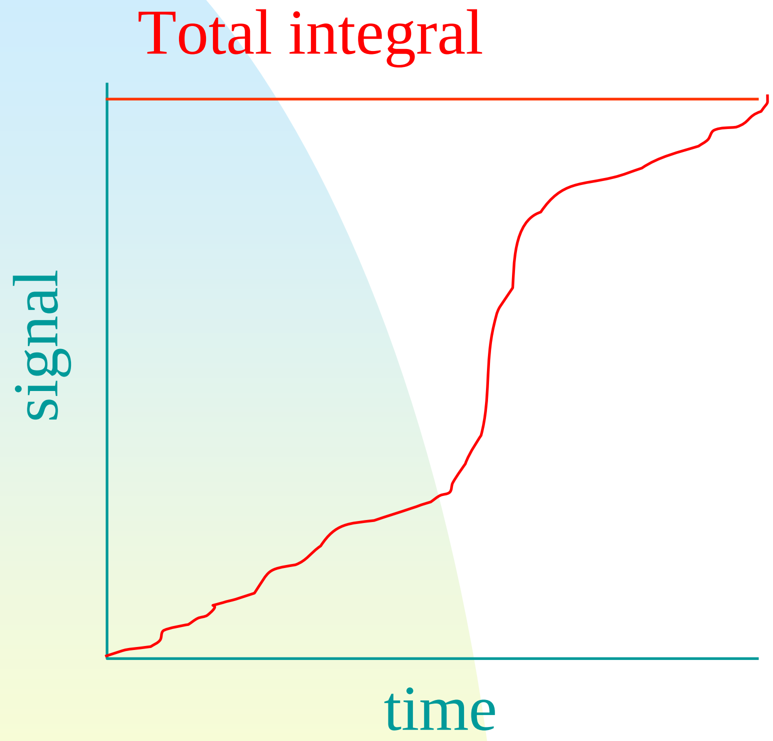
What will be covered?

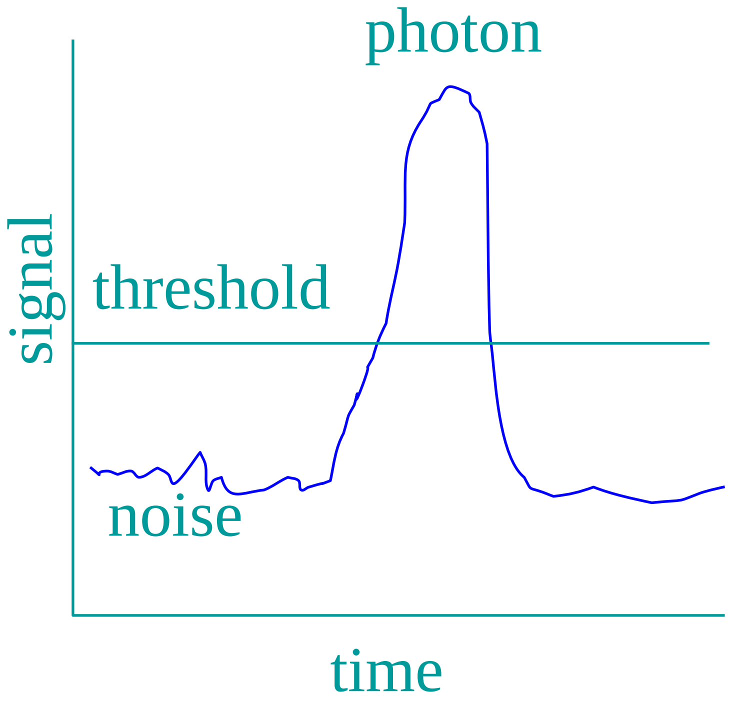
- **Detectors for Storage Rings “today”**
- **Detectors for “tomorrow”**
- **Detector requirements for XFEL’s**
- **Summary**
- **Remarks**

Today versus Tomorrow
Integrating versus Counting



Integrating versus Counting

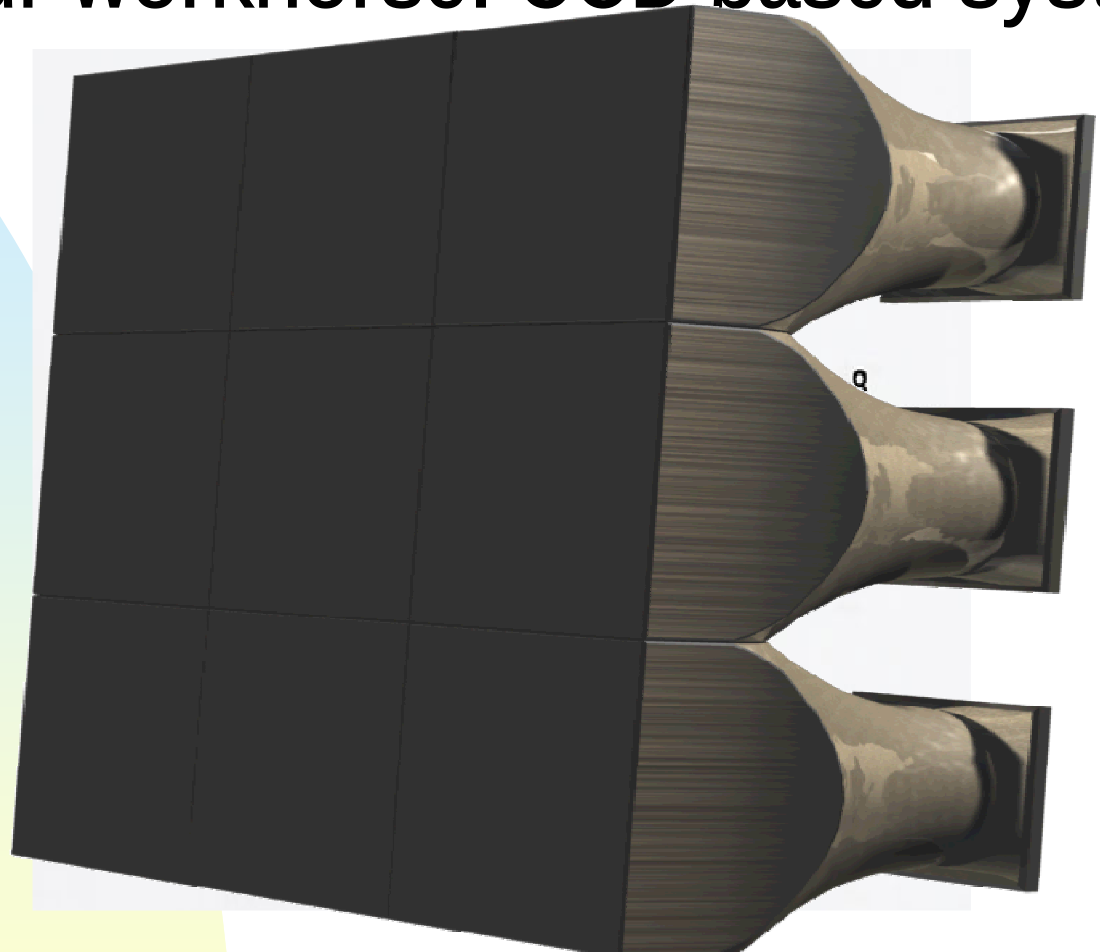




What really counts is the Signal-to-Noise ratio: S/N

Detectors for SR today:
« Take what you can »

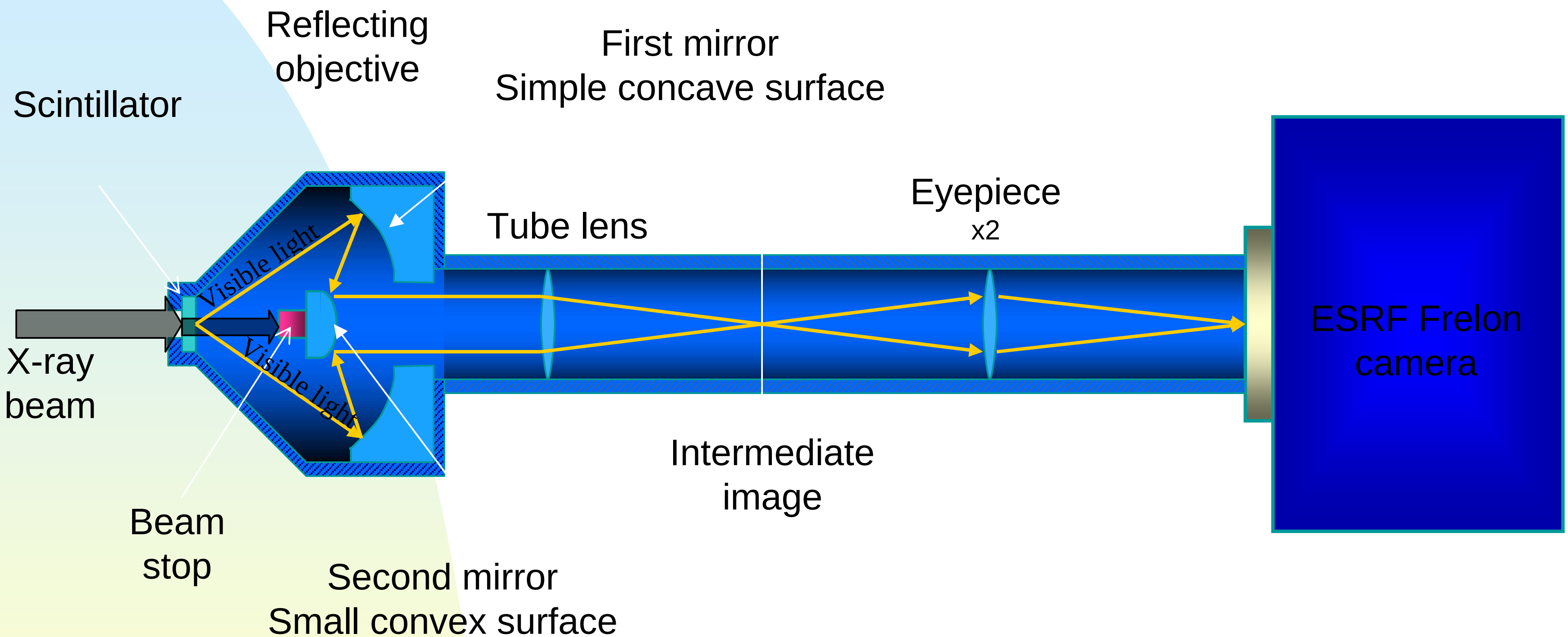
Our workhorse: CCD based systems



– **Indirect detection**
==> losses & spreading

– **Integrating detector**
==> noise & information loss

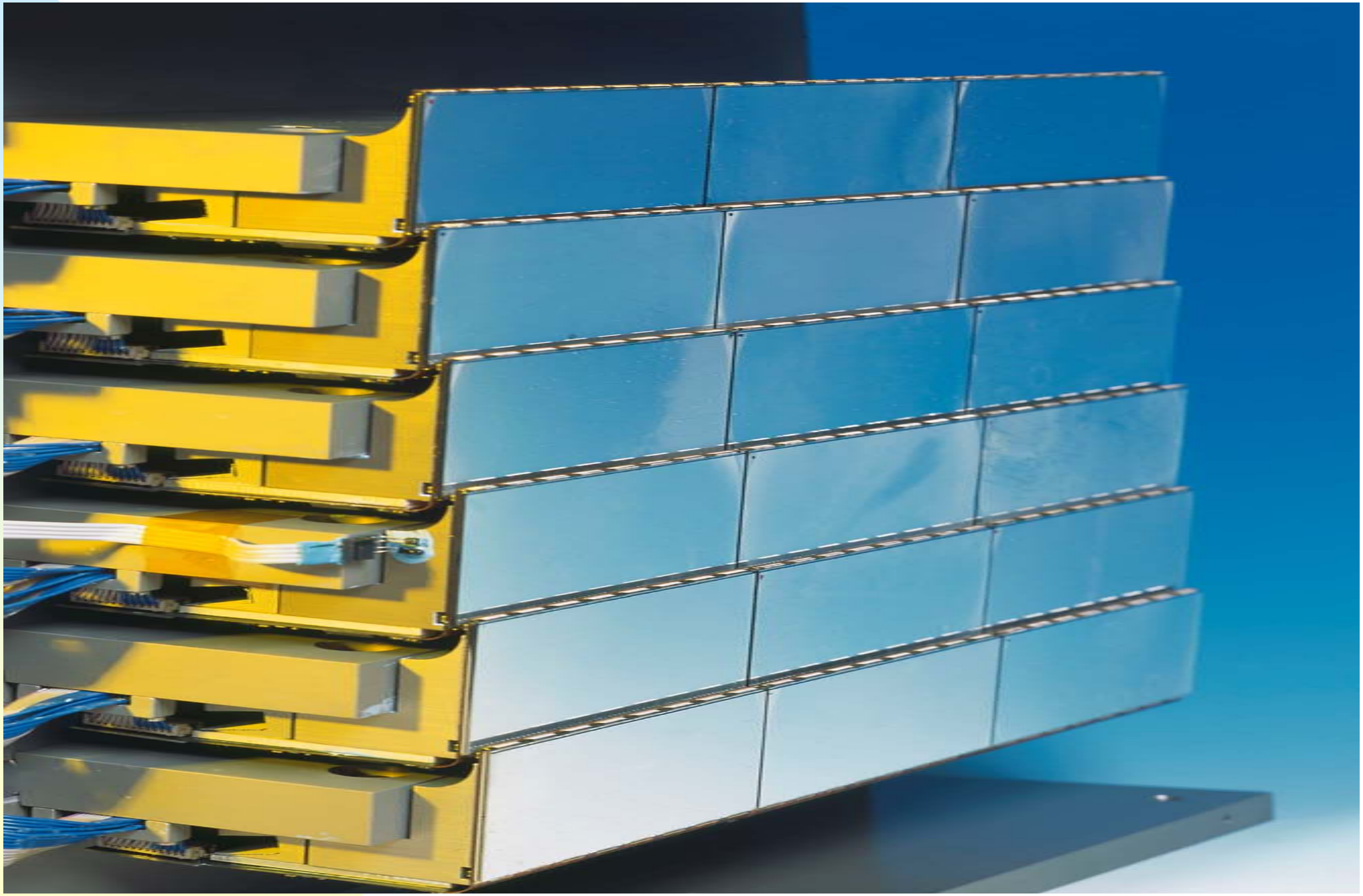
High resolution imaging with CCD's



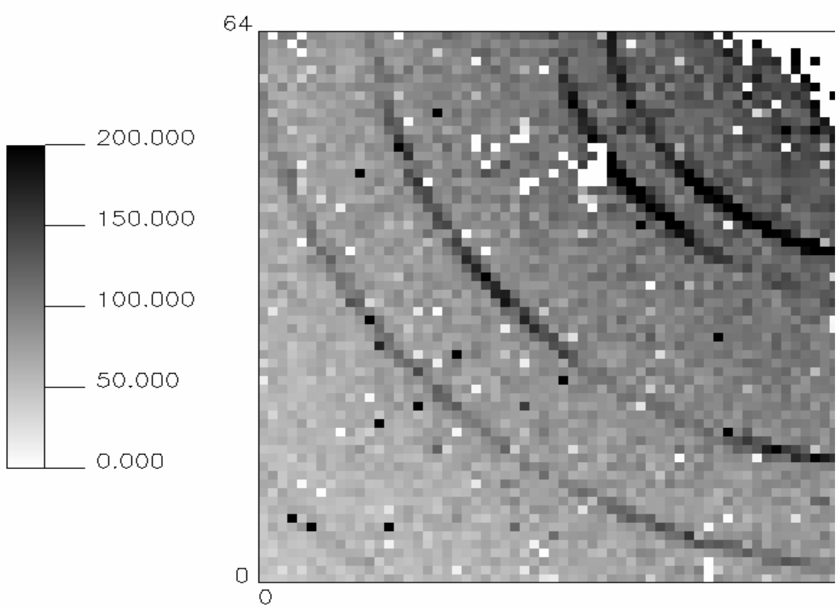
Scintillator is very inefficient

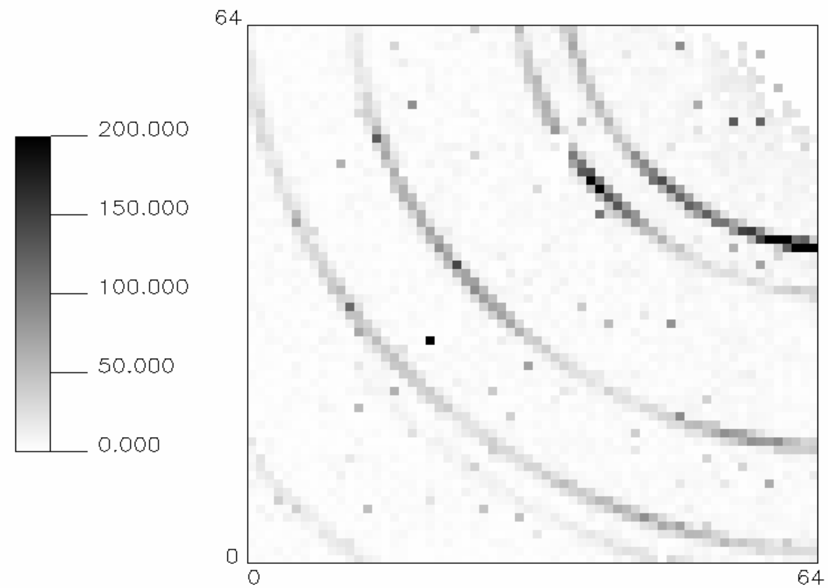
Full tomo dataset in 10 sec.

Pixel Array Detector

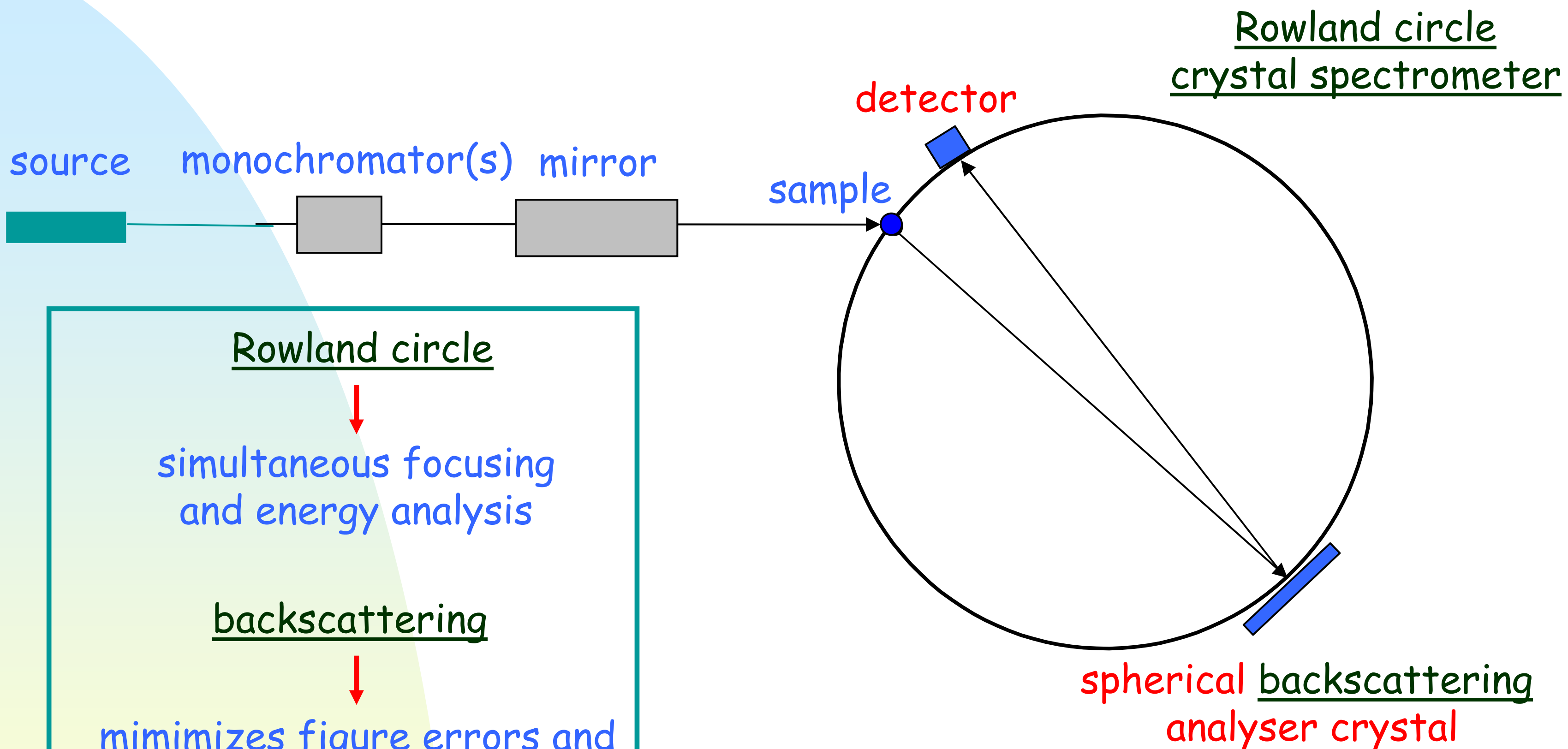


Really low noise:





High-resolution IXS spectrometers: basics



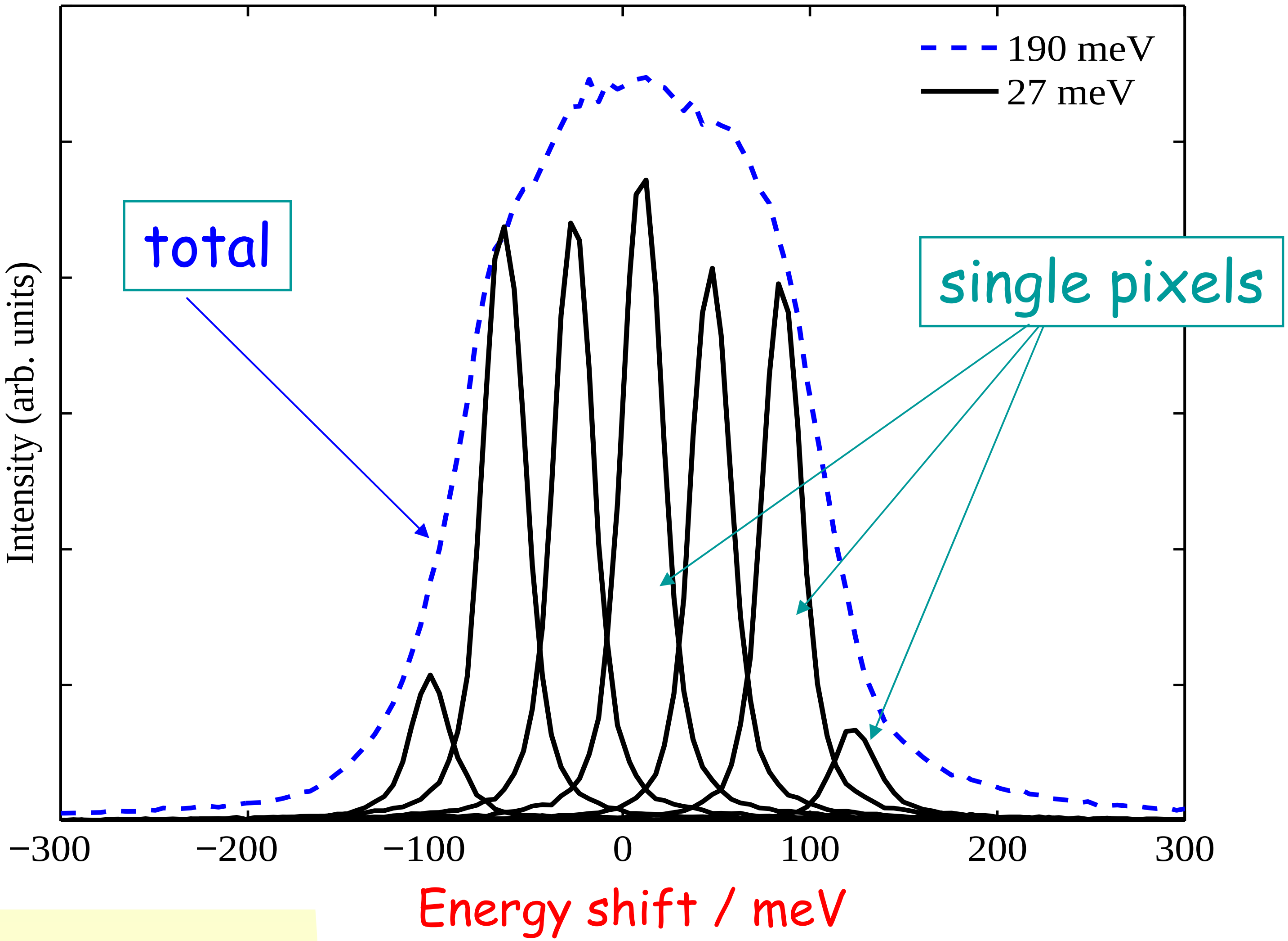
Rowland circle
↓
simultaneous focusing and energy analysis

backscattering
↓
mimimizes figure errors and geometrical contributions

critical components:

- spherical analyser
- detector

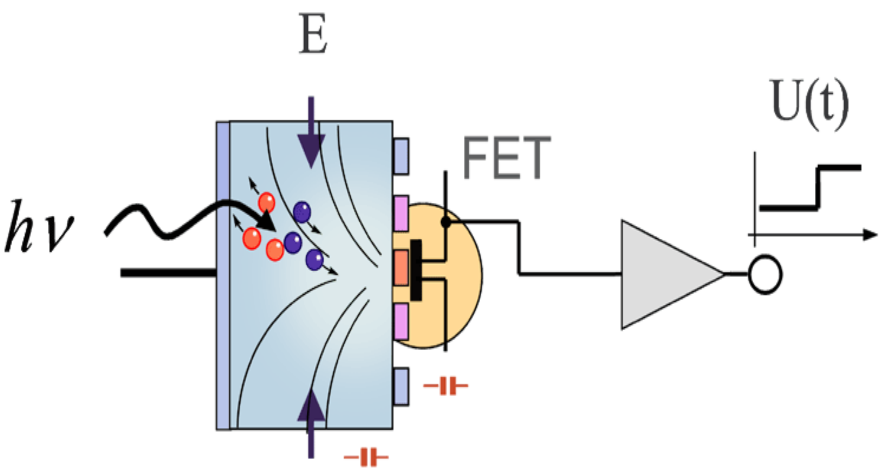
Resolution (ΔE)



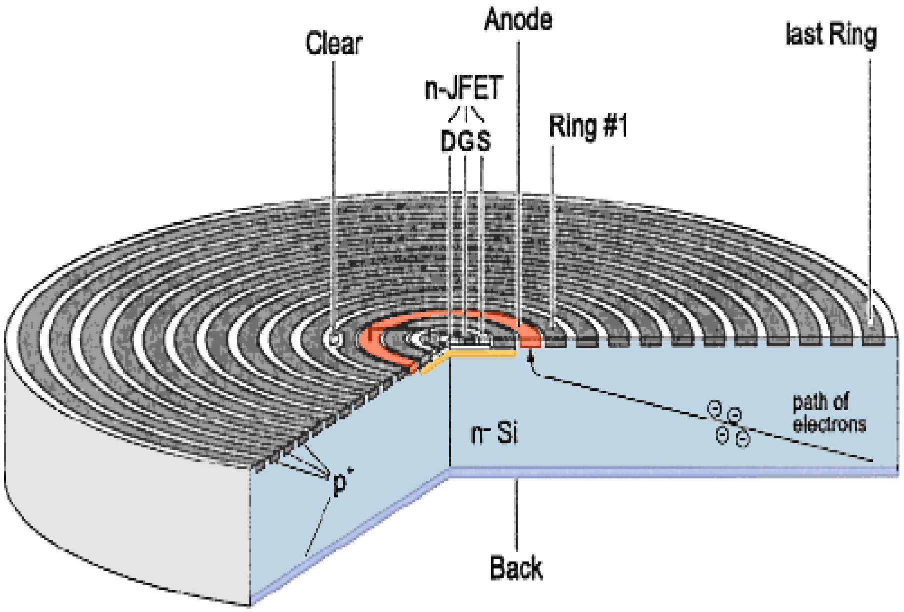
Problems to overcome:

- **Radiation tolerance**
- **Charge sharing**
- **Yield**
- **4 side-butting (3D connectivity)**
- **High Z sensors (GaAs, CdZnTe)**
- **This can all be overcome by enough critical mass → COLLABORATION!**
- **Limited energy resolution**

Energy Resolving Detectors
Silicon Drift Detectors:



$$n_e = h\frac{\nu}{\varepsilon}$$



AVALANCHE PHOTODIODE

- Energy range : 3 keV < $E_{X\text{-ray}}$ < 30 keV (limited by thickness)
- Counting rate: ~ 10^7 cps
- Dark noise: ~ 0.01 cps
- Energy resolution: ~20 % @ 24keV
  ~39% @ 12keV
- **Time resolution: ~ 1ns**

AVALANCHE PHOTODIODE

Acquisition system

ACE (APD Controller Electronic)

Head = APD + Pre-amplifier

- Hamamatsu
  - 5x3mm² 135 μm available
  - ϕ=3mm 135μm (proto)
- EGG
  - 5x5mm² 110μm
  - 10x10mm² 110 μm

Acquisition system : ACE (APD Controller Electronic)

- Principle of use: amplitude (mV) ⇔ energy(eV)
  - 1 counter, 2 thresholds (high and low) for level discrimination
  - Counter with low level only = integral counter.
  - Counter with low-high level = counter in energy range.

Detectors for tomorrow?
“make what you need”

1. Parallel readout CCD’s
2. Hybrid (counting) Pixel detectors
3. Si Drift Detectors
4. Avalanche Photodiode arrays
5. Diamond based detectors

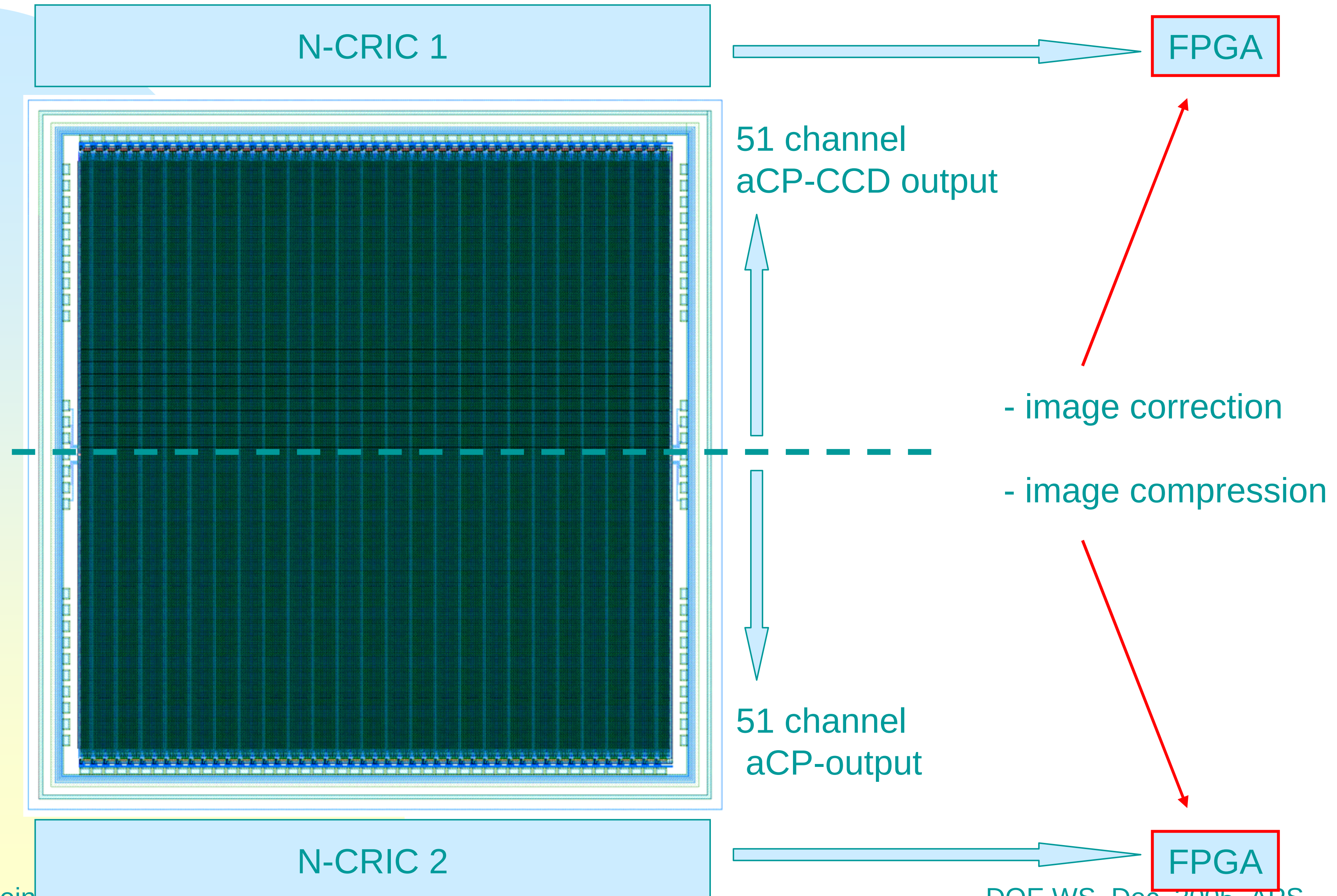
Fast CCD-based Systems for Detection of X-rays and Electrons

H. A. Padmore[1], C. Bebek[2], M. Church[1], P. Denes[3], J. Glossinger[1], S. Holland[2], H. von der Lippe[3] and J. P. Walder[3]

Lawrence Berkeley National Laboratory
[1] ALS, [2] Physics and [3] Engineering Divisions

- **CCDs for synchrotron radiation x-ray research**
- **Development of optical CCDs at LBNL**
- **Column Parallel CCDs**
- **Status report**

Prototype (almost) Column Parallel CCD Readout Structure



What are the Detectors for tomorrow?

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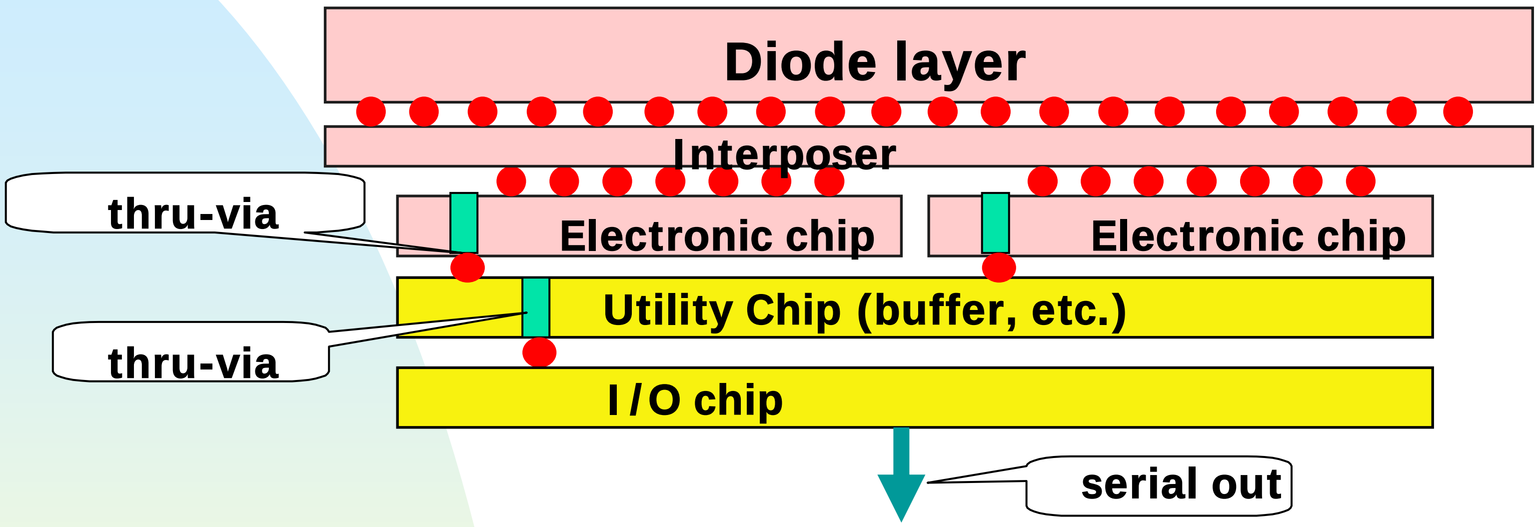
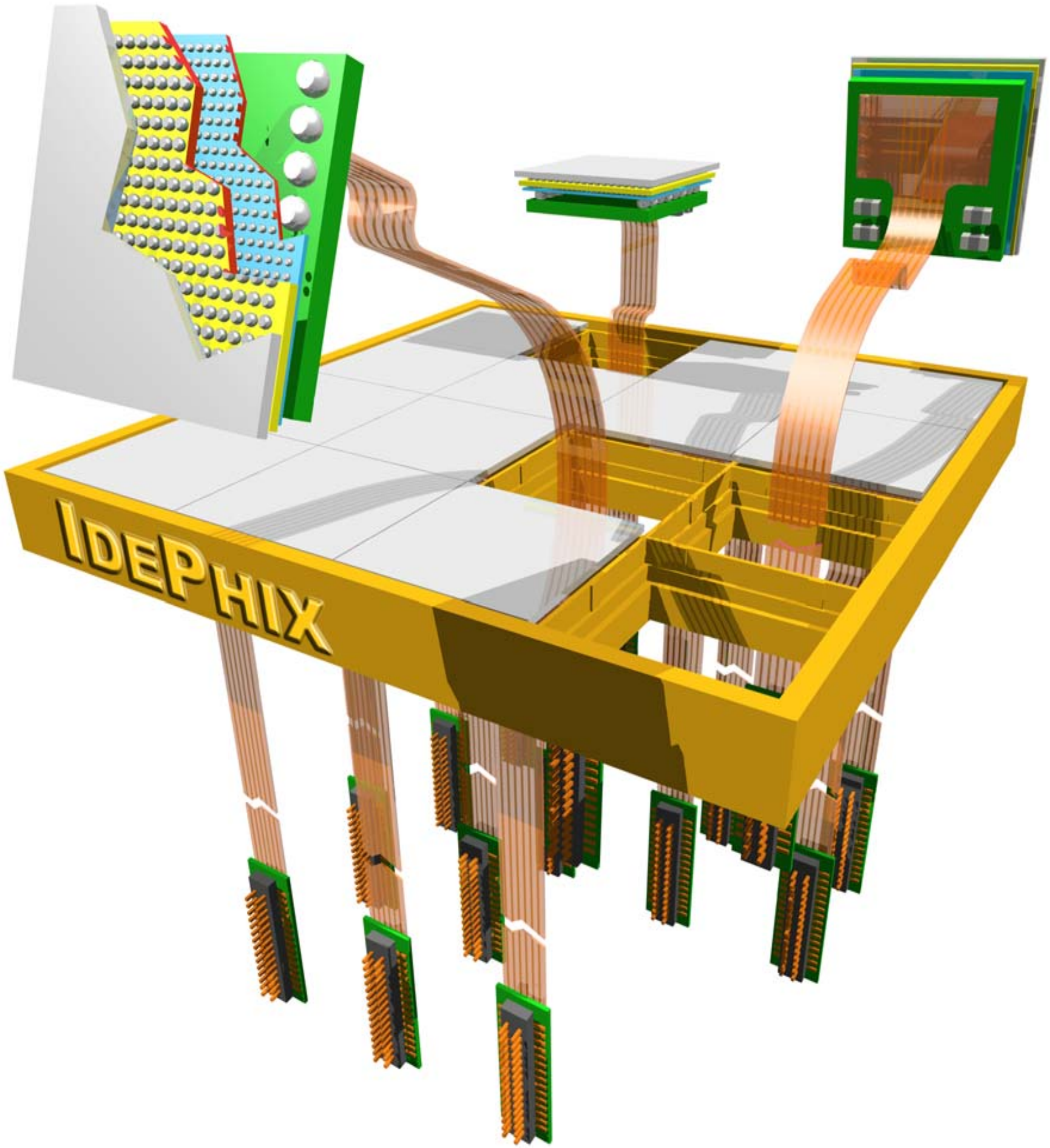
Next Generation Pixel Array Detectors



- More functionalities (dubble buffering, XPCS, energy resolution,…) (ex. MEDIPIX-3)
- Fully four side buttable (large areas)
- Extreme Radiation hard design
- **Different Diode layer materials (GaAs)**



IDEPHIX

What are the Detectors for tomorrow?

1. **Parallel readout CCD's**
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4. **Avalanche Photodiode arrays**
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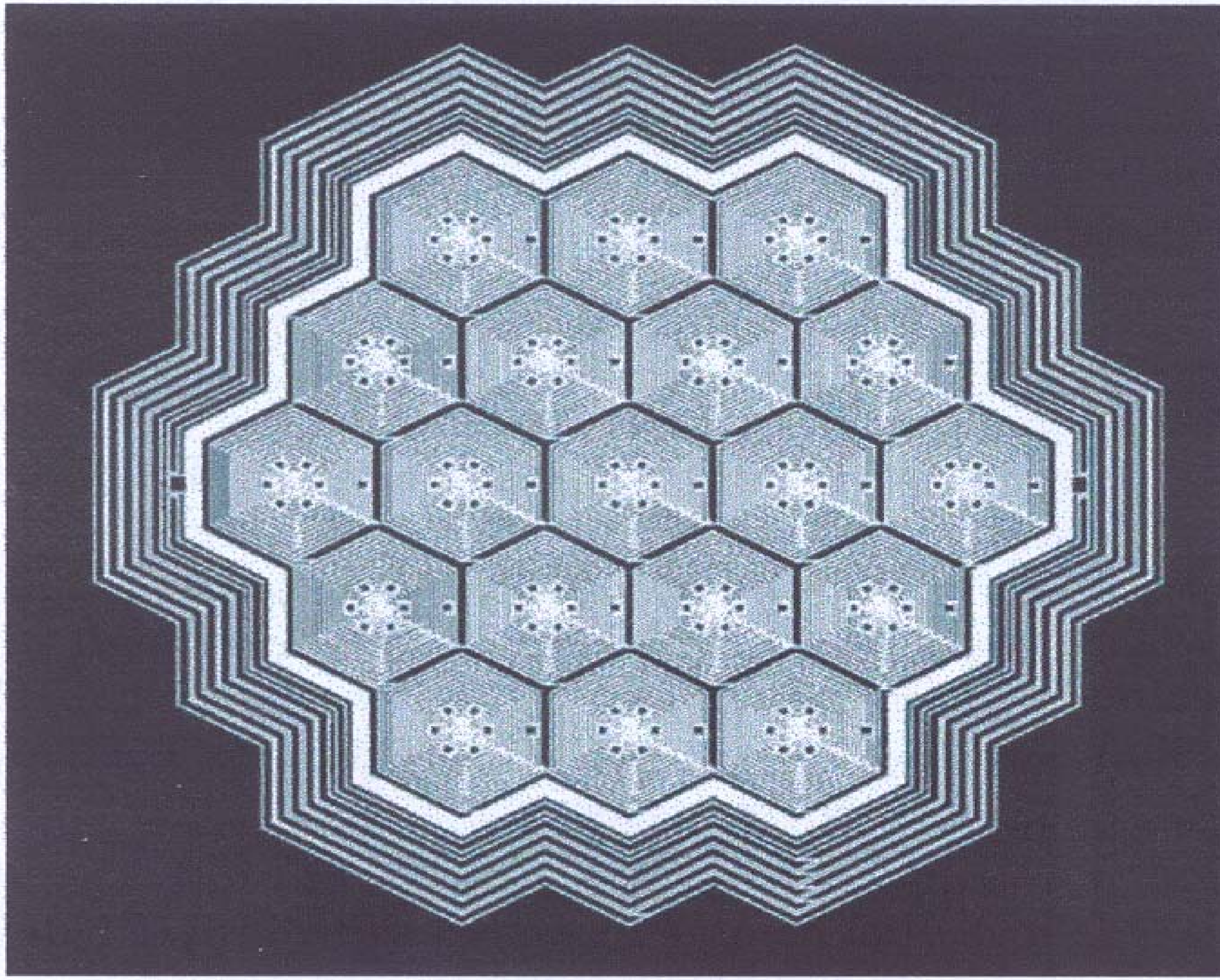

Fig 10: Multichannel drift detector consisting of 19 hexagonal 5mm2 SDDs.

The PN-CCD principle

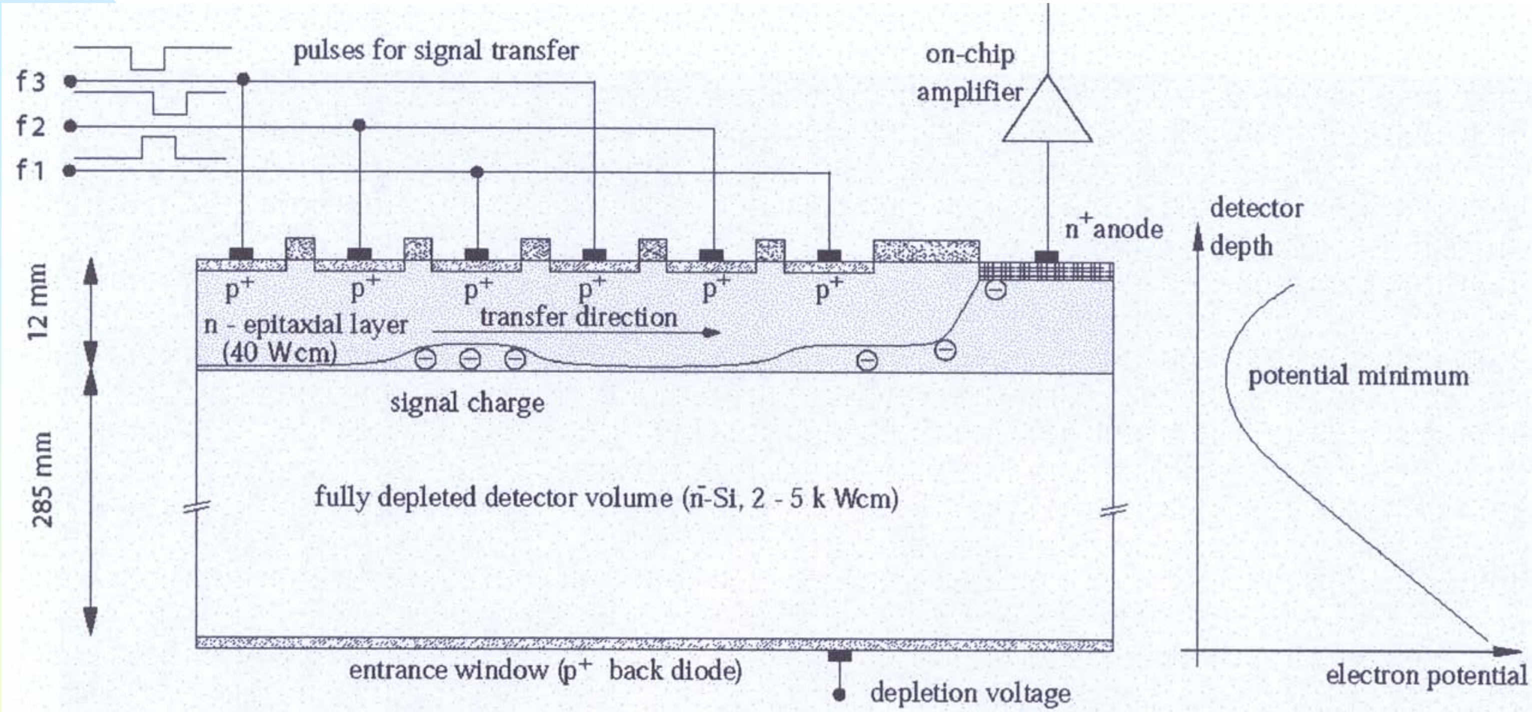

Fig.13: A schematic cross section through the pn-CCD along a transfer channel. The device is back illuminated and fully depleted over 300µm thickness. The electron potential perpendicular to the wafer surface is shown on the right hand side.

Table 3: Comparison of expected properties of pn-CCDs in ROSITA with those reached at XMM. The energy resolution (FWHM) refers to incident X-rays of the $Mn\,K_\alpha$ line at 5.9keV and $C\,K_\alpha$ measured at temperatures around -100 °C .

Property	XMM	ROSITA	XEUS
Status	Operating in orbit	Produced and tested	Prototypes tested
type	full frame	frame store	DEPFET pixel sensors
Format	400x384	256x256	1024x1024
pixel size	15x150 μm^2	75x75 μm^2	50x50 μm^2 or 75x75 μm^2
readout noise	5 electrons	3 electrons	1 electron
sensitive thickness	295 μm	450 μm	450 μm
frame rate	15 frames/sec	20 frames/sec	200 (1000) frames/sec
readout speed	350 ns/pix	100 ns/pix	50 ns/pix
energy resolution at Mn $_{K\alpha}$ (5.9keV)	140 eV	130 eV	125 eV
Operating temperature	-100°C		
energy resolution at C $_{K\alpha}$	130 eV	80 eV	45 eV
energy range	0.15 keV - 15 keV	0.1 keV - 20 keV	0.05 keV - 20 keV

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Why diamond?

Z = 6 → low specific X-ray absorption/beam scattering

High charge carrier saturation velocity (~3×10^{7}cm/s) and low dielectric constant (5.5)

-> fast pulse response (~nsec in practical devices)

wide bandgap energy (5eV), excellent thermal/mechanical properties

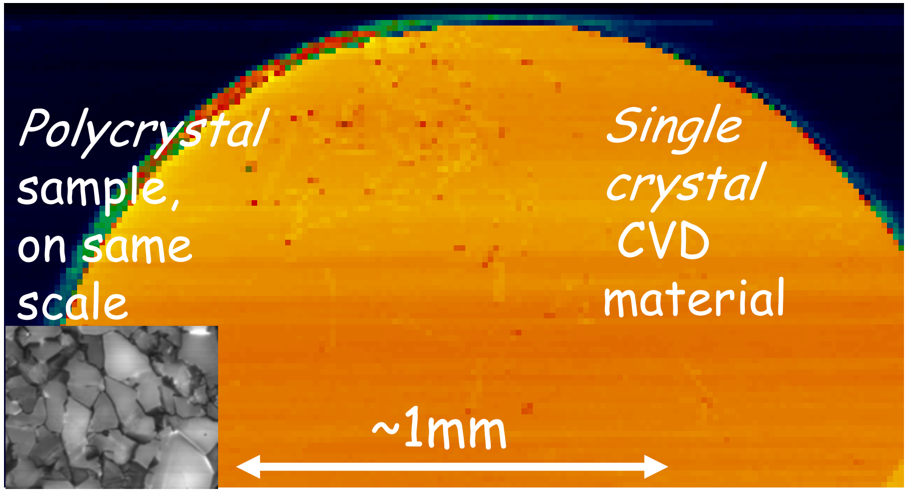
-> low leakage currents at high temperature, high heat load 'white' beam monitoring possibility

why *single crystal* material ?

no grain-boundary artifacts

charge-carrier lifetime >50nsec

-> 100% charge signal collection over ~mm distances)



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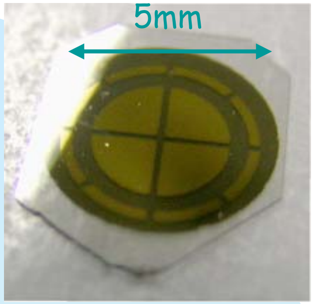
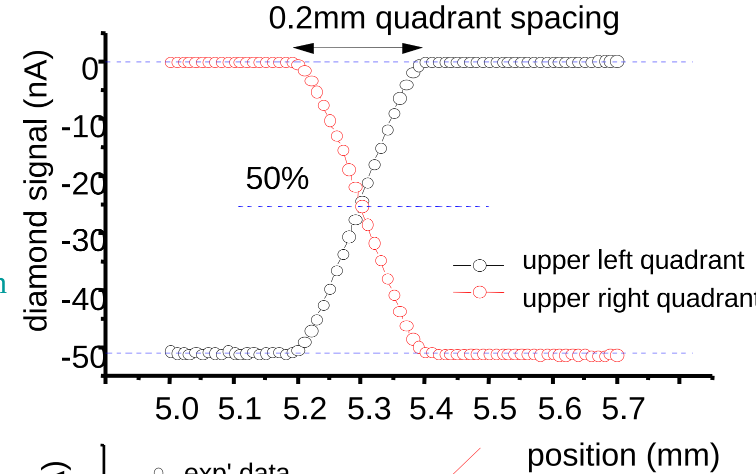
X-Ray BPM tests of ***single crystal CVD*** diamond plate at (ID21, May 2005)

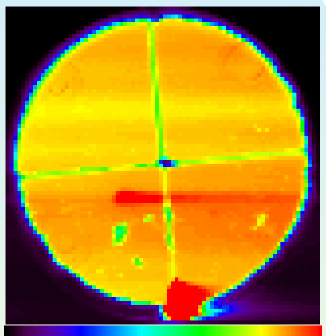


Element-Six CVD diamond plate, 100µm thick,

50nm Cr-Au contacts

Linear crossover position response to 200um (pinhole) beam

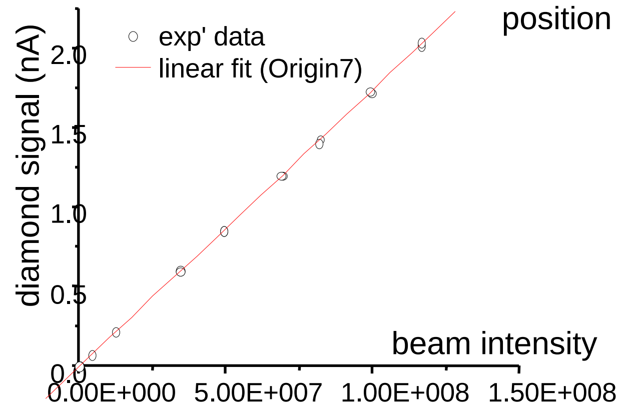




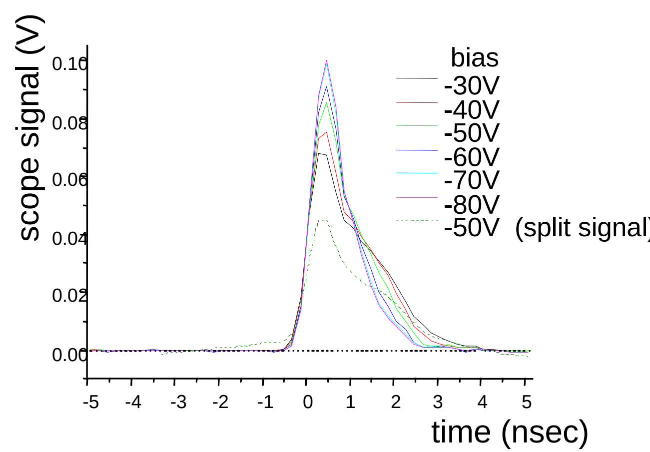
X-ray uniformity map with 7.2keV beam, 10^8 ph/sec, 1x0.4μm^2 :

image contrast is from the diamond signal current

Signal linearity with beam intensity over 4 decades



Signal time response for *single* X-ray bunch (32 fold aver.)



Conclude:

- Viable as BPM/intensity monitor operated in dc or RF modes, spatial resolution << µm
- Possible white beam, bunch-by-bunch monitor (tests in planning)

Detector requirements for XFELs

- **Integrating Pixel Detectors, with single photon sensitivity**

Introduction: Characteristics of XFEL radiation

Photon energy	**X-rays: 3 up to 15 keV (λ= 1Å)**
	(soft X.: 200 up to 2000 eV)
Photon per pulse	**10^{12} *(up to 10^{14})***
Divergence	**< 1 up to few 10 µrad**
Source appearance	**~ 100 µm (diffraction limited)**
Bandwidth	**~ 0.1 %**
Pulse duration	**100 – 300 fs (probably decreasing)**
Repetition rate	**Macro-Bunch (MB): 10 – 120 Hz**
	single bunches within MB: ≤ 5 MHz

Short pulse high energy radiation from spontaneous emission

Photon energy	***100 – 400 keV***
Photons per pulse	***~10^8 / 0.1%bw***

Requirements: Imaging

Pixel Size [μm]	**30**	(<30)
Number of Pixels	**1k x 1k**	(2k x 2k)
Need for tiling	**yes**	
Signal rate/pixel/bunch	**up to 10e5**	
Single photon resolution	**yes**	
Photon energy range [keV]	**8-12**	
Quantum efficiency	**>0.8**	(1)
Environement	**vacuum**	
Timing	**120Hz** (LCLS)	

Resources (1)

Cost estimate (R&D programme) for **two 2-D detector systems based on two different technologies: Active Pixel Sensor (APS) and Hybrid Pixel Sensor (HPS).** Both systems provide a pixel-size of about 100 microns and are supposed to be compatible with the XFEL time structure. In each case a two step development process is assumed: i) Design and development of a small (e.g. 4-K or 128-K) prototype system with a subsequent extension to a ii) full scale 1-M detector. It is furthermore assumed that the minimum duration of the respective project generations is 4 years (i) and 2 years (ii), respectively. The data are based on a study carried out at DESY.

System 1:	**APS 4-K**		**APS 1-M**	
Program duration	at least 4 years		at least 2 years	
Costs	Capital (kEuro)	Personel (FTE)	Capital	Personel
Total	3165	40	1980	15
System 2:	**HPS 128-K**		**HPS 1-M**	
Program duration	at least 4 years		at least 2 years	
Costs	Capital	Personnel	Capital	Personnel
Total	2220	34	2435	13

Resources (2)

Possible Scenario:

Postpone a technology decision (for a given system) as long as possible. This implies tio develop prototypes of System 1 AND System 2 and decide after the test of the respective prototypes. This approach would yield:

	Capital (kEuro)	Personnel (FTE)	
Total Costs System 1+2:	5385	74	4 years
+ APS 1-M	1980	15	2 years
or HPS 1-M	2435	13	2 years
This results in total costs of :	7365	89	6 years (APS)
	7820	87	6 years (HPS)

Summary: It seems advisable to foresee and reserve funds of about:

7.8 MEuro + 89 FTE covering a period of 6 years (2005 price basis)

Summary

- Parallel readout CCD's: Fast imaging
- Counting Pixel Array Detectors: Many applications
- Silicon Drift Detectors: Imaging with spectroscopy
- Avalanche Photodiode arrays: Fast timing
- Diamonds: Beam monitoring
- Integrating Pixel Array Detectors: XFEL (and others)

Remarks for discussion

- Storage Rings: from Integrating to Counting
- Future detectors are Si-based
- R&D/prototyping is fun and needed, but don't forget production
- Our community should push more materials: GaAs and Diamond
- A push for 3D-hybridization is needed
- Micro-electronics seems to be "covered"
- Detector R&D should be based on Facility Funding!