Detector Workshop on Synchrotron Radiation Instrumentation
Argonne, Dec. 8, 2005

Silicon Drift Detectors for X-ray Imaging

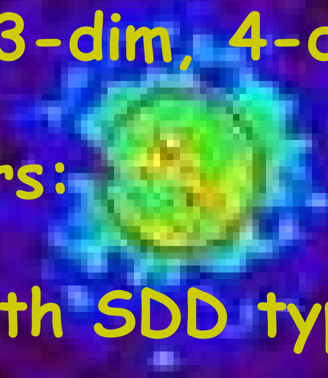
(in close collaboration with Politecnico di Milano: Fiorini, Longoni, Castoldi, Guazzoni, ...)

MPE
Max-Planck Institut
für extraterrestrische Physik

WHI
Max-Planck Institut für Physik
(Werner-Heisenberg-Institut)

PNSensor GmbH

OUTLINE



1. What can Silicon do for X-rax detection !
2. Measuring single X-rays and X-ray intensities (counting)
3. Detector requirements of XFEL, LCLS, and other LS
4. 0-dim, 1-dim, 2-dim, 3-dim, 4-dim measurements
5. Semiconductor detectors: concepts and structures
6. Experimental results with SDD type detectors

   - SDDs, pnCCDs, CDDs, DEPFETs and AApnCCD
7. Proposal of a new high speed imaging detector
8. Summaries

Semiconductors as detector and electronics material

1. **Semiconductors: $E_{Gap} \approx 1 - 3$ eV**
   → small leakage currents
   → low noise, operation @ r.t.

2. **Pair creation energy: w = 2 – 5 eV**
   → large number of signal charges per energy deposit in detector

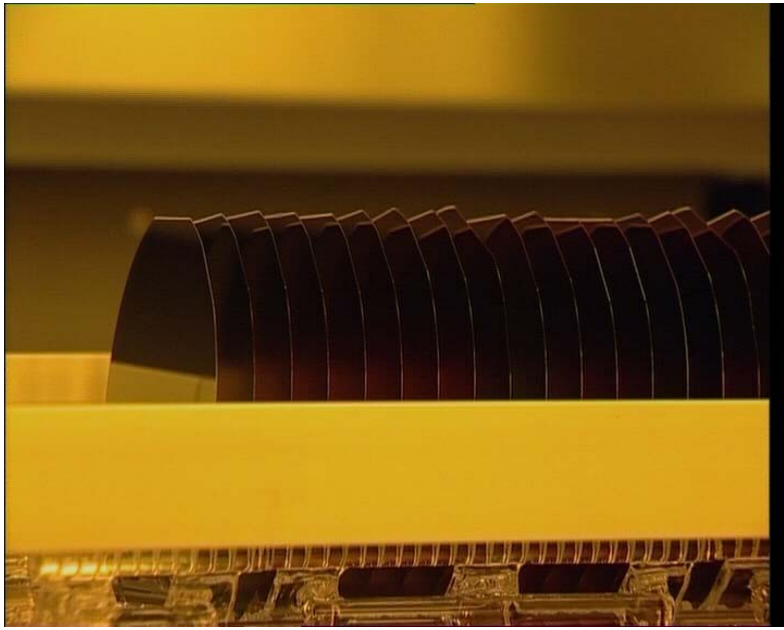
3. **Density: $\rho = 2 - 10$ g cm^{-3}**
   → high energy loss per unit length
   → low range of δ - electrons

This leads to:

good energy resolution
high spatial resolution
high quantum and detection efficieny
good mechanical regidity and thermal conductivity

Semiconductors equally offer:

fixed space charges
high mobility of charge carriers



Single photon counting or intensity measurement (I)

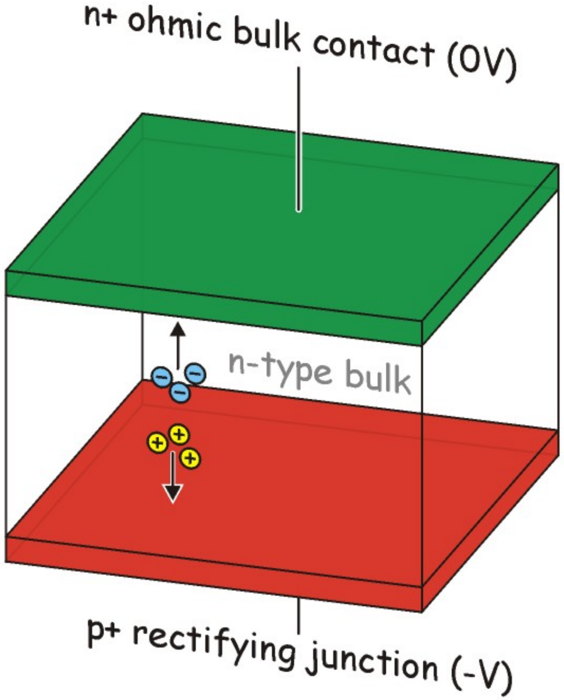
What does the ``final user´´ want to know from the incident photons ??

energy of the (detected) photon [may be]
position [certainly]
''interaction'' time, ``dead´´ time [may be]
quantum efficiency [certainly]
intensity, if not operated in single photon counting mode [certainly]

What can be done with Silicon detecors (in principle)

energy bandwidth: 1 eV < E < 50 keV
energy resolution: 119 eV @ 6 keV, 205 eV @ 20 keV (FWHM), ENC< 5 el.
position resolution: 0.4 μm (rms) @ 6 keV (ENC=5e^-), 0.1 μm (rms) @ 20 keV
image resolution: typically 15 μm (@ 500 μm thickness)
time resolution: typically 100 ps, depending on Q.E. of the system
repetition rate: 1 - 5 MHz depending on capacitance, FET type, R_s, etc
quantum efficieny: QE of > 85 % from 300 eV to 20 keV (2 mm Si)

planar diodes —
measururing single and multiple X-rays



electronic noise

$$ENC = \sqrt{\underbrace{a\frac{2kT}{g_m}C_{tot}^2 A_1 \frac{1}{\tau}}_{\text{thermal noise}} + \underbrace{2\pi a_f C_{tot}^2 A_2}_{\text{1/f noise}} + \underbrace{qI_L A_3 \tau}_{\text{leakage}}}$$

optimum shaping time

$$\tau_{opt} = \sqrt{\left[\frac{2A_3}{A_1}\right]\left[\frac{kT}{q}\frac{C_{tot}^2}{I_L}\frac{2}{3g_m}\right]}$$

» For

- **good resolution**
- **high count rate capability**

the total capacitance must be minimised!!

» Energy to create 1 e – h pair: 3.65 eV (in Si)

- **@ 10 keV: 2740 e⁻ ± 18 e-**
- **conf. lim. from Fano noise:** 10.000 ph.@ 6 keV
- **conf. lim. from Fano noise:** 20.000 ph.@ 10keV

Counting of many X-rays

1.000 X-rays with 10 keV within 100 fs is for the X-ray detector identical to a Gamma – ray of 10 MeV !

i.e. 2.7×10^6 electrons according to $N = E/w \cdot n_x$

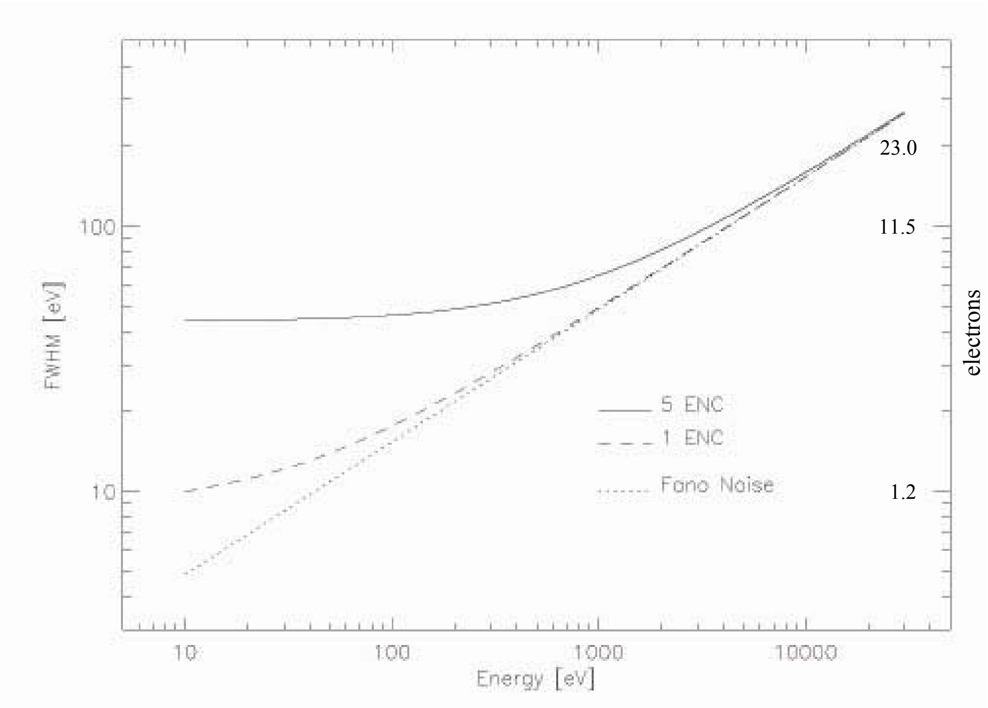
except: for the charge distribution anlong the X-ray flash:

$$I(x) = I_o\, e^{-\mu x}$$

for the higher energies, the signal charges created by the X-rays distribute along a ``tube´´ with a diameters of less than 3 µm in the first 100 fs.

Electrostatic repulsion and diffusion then widens the ``charge tube´´ to up to 20 µm upon arrival at the electron potential minimum in a 500 µm thick detector @ r.t.

Limits of energy and counting resolution of X-rays



$$\mathrm{ENC}^{2}_{\mathrm{fano}} = \frac{F \cdot E}{w}$$

$$\mathrm{ENC}^{2}_{\mathrm{trans}} \approx (1 - \mathrm{CTE})\, \mathrm{N}_{\mathrm{trans}}$$

$$\mathrm{ENC}^{2} = \left(\alpha \frac{2kT}{g_m} C^2{}_{tot} A_1 \right) \frac{1}{\tau} + \left[\left(2\pi a_f C^2{}_{tot} + \frac{b_f}{2\pi} \right) A_2 \right] + A_3 \left(q I_l + \frac{2kT}{R_f} \right) \tau$$

$$ENC^2{}_{tot} = ENC^2{}_{el} + ENC^2{}_{fano} + ENC^2{}_{trans} + \ldots = (1 - 5\ \mathrm{el}^{-})^2$$

Requirements for future XFELs:

Area Detector 1 (integrating detector)

	XFEL	LCLS
single photon resolution	yes	yes
energy range	8 < E < 12 (keV)	0.8 < E < 8 (keV)
pixel size (μm)	100 (50)	100
sig.rate/pixel/bunch	10^4	10^3
quantum efficiency	> 0.8	> 0.8
number of pixels	1024 x 1024 (or 2k x 2k)	512 x 512 (min.)
frame rate/repetition rate	up to 5 MHz	120 Hz
single bunch frame rate	120 Hz (10 kHz)	120 Hz
radiation hardness @ 10keV	yes (10^{15} - 10^{16} per cm^2)	yes (how much ?)
vacuum compatibility	no (yes)	no (yes)
need for tiling	may be (not)	no
preprocessing	no (yes) ?	no (yes) ?
working distance	?	20 – 200 mm

Requirements for future XFELs:

Area Detector 2 (counting detector)

	XFEL	LCLS
single photon resolution	yes	yes
energy range	$8 < E < 12$ (keV)	$6 < E < 24$ (keV)
pixel size (μm)	30	25
sig.rate/pixel/bunch	10^4 (up to 10^5)	10
quantum efficiency	> 0.8	> 0.5
number of pixels	1024 x 1024 (or 2k x 2k)	10^4 x 10^4
frame rate	10 Hz up to 5 MHz	120 Hz
single bunch frame rate	120 Hz (10 kHz)	120 Hz
radiation hardness @ 10keV	yes (10^{15} - 10^{16} per cm^2)	yes (how much ?)
vacuum compatibility	no (yes)	no (yes)
need for tiling	yes	yes
preprocessing	no (yes)	no (yes)
working distance	?	5.000 mm

Requirements for future XFELs:

Area Detector 1 + 2 (counting detectors)

	XFEL + LCLS	pnCCD/DEPFET/CDD
single photon resolution	yes	✓
energy range	0.8 < E < 24 (keV)	✓
pixel size (µm)	25 up to 100	✓
sig.rate/pixel/bunch	10^4	✓
quantum efficiency	> 0.8	(0.4 to 0.6 @ 24 keV) ✓
number of pixels	1024 x 1024 (or 2k x 2k)	✓(in about 3-5 y from now)
frame rate (Hz)	up to 5 MHz	? ? ✓ ? ?
single bunch frame rate	120 Hz (10 kHz)	✓
radiation hardness @ 10keV	yes (10^{15} - 10^{16} per cm^2)	✓
vacuum compatibility	yes	✓
need for tiling (4 sides)	yes	✓
preprocessing	no (yes)	✓
working distance	20 – 5.000 mm	✓

How to do ?

with a

pnCCD and/or

DEPFETs and/or

CDDs

How many charges can be stored in one pixel ?

What is limiting Q.E. ?

What is limiting pixel size ?

What is limiting readout speed and noise?

What limits the total size ?

The Silicon Drift Detector Family

all based on SDD principle - sideward depletion (CHC > 10^6 electrons)

SDDs

sensitive area:
from 1 mm^2 to 55 cm^2

number of read nodes:
from 1 to 360

sensitive thickness:
d = 450 µm
0.1 keV < E < 30 keV

read noise: from 5 e$^-$
@ 5 mm^2 to 12 e$^-$
@ 1 cm^2 and @ -15° C

Count rate per node: 10^6

Avalanche amplifier: ok

Imaging if timing is available

γ-imaging if coupled to scintillators

pnCCDs

sensitive area:
from 1 cm^2
to 36 cm^2

formats: 256x256 up to 400 x 400

pix.size: 36-150 µm□

№ of read nodes: < 768

sensitive thickness:
d = 450 µm
0.1 keV < E < 30 keV

read noise: from 1.8 e-
to 13 e- (@+10°C)

Avalanche amplifier: ok

readout speed: 1200 fps

CDDs

sensitive area:
up to 4 cm^2

№ of read nodes: 400

sensitive thickness:
d = 450 µm
0.1 keV < E<30 keV

read noise: from 15 e-
to 25 e$^-$
@ 100 kfps
and @ 25° C

Imaging: no external trigger needed

Avalanche ampl.: ok

readout speed: 100kfps

DEPFETs

sensitive area:
from .2 cm^2
to .5 cm

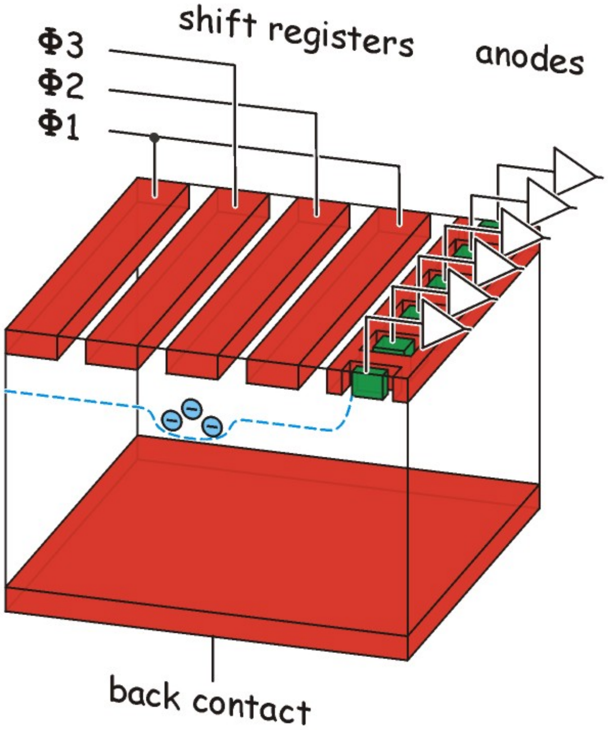
formats: from 64 x 64
to 128 x 128
soon: 256x256 or 512
pix. size: from 25µm□
to 1.000 µm□

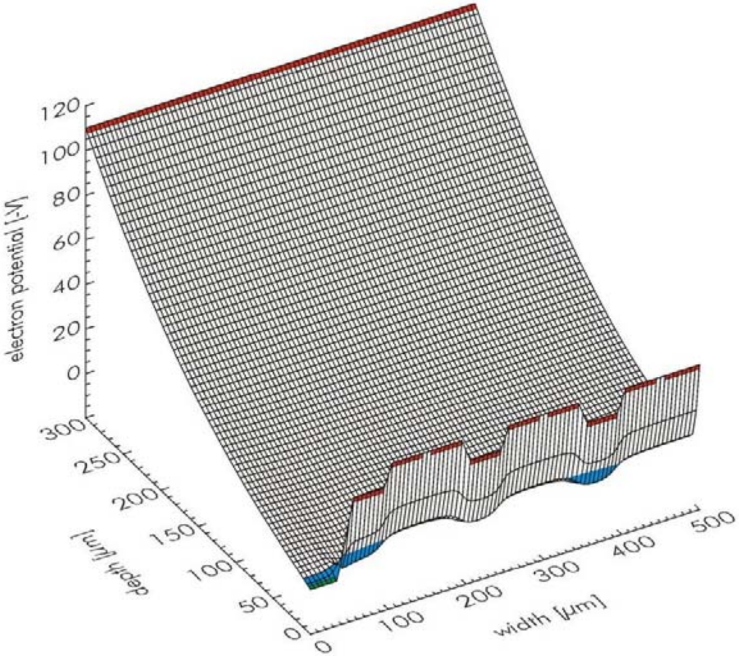
№ of read nodes:
up to 256

sensitive thickness:
d = 450 µm
0.1 keV < E <30keV

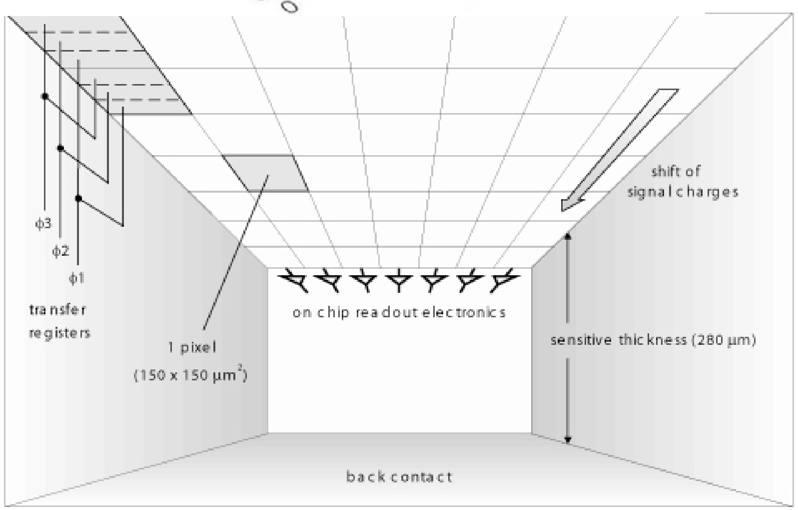
read noise: from 3.6e-
to 10 e- (@+10°C)
readout speed: 1500fps

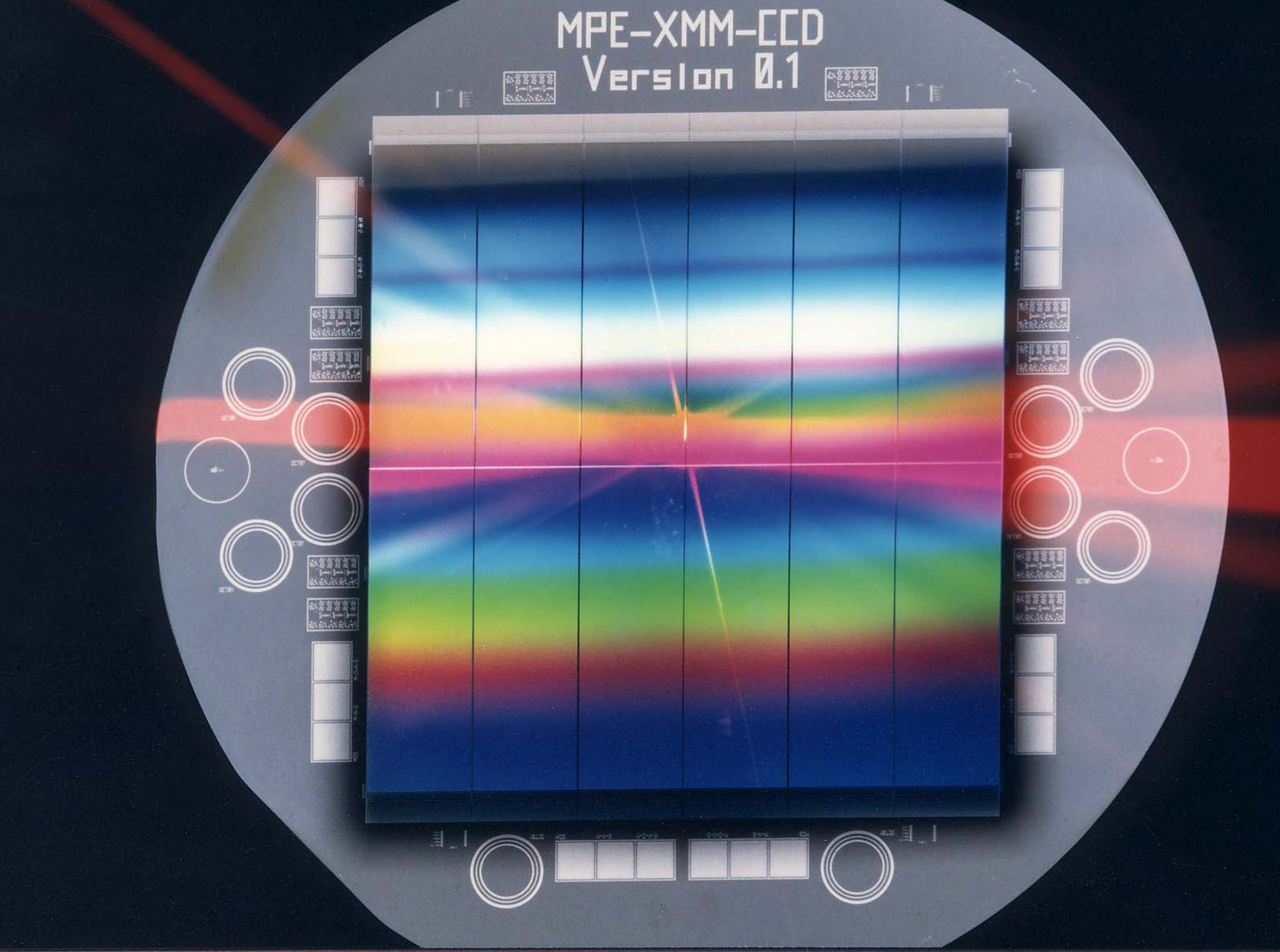
CCD basics

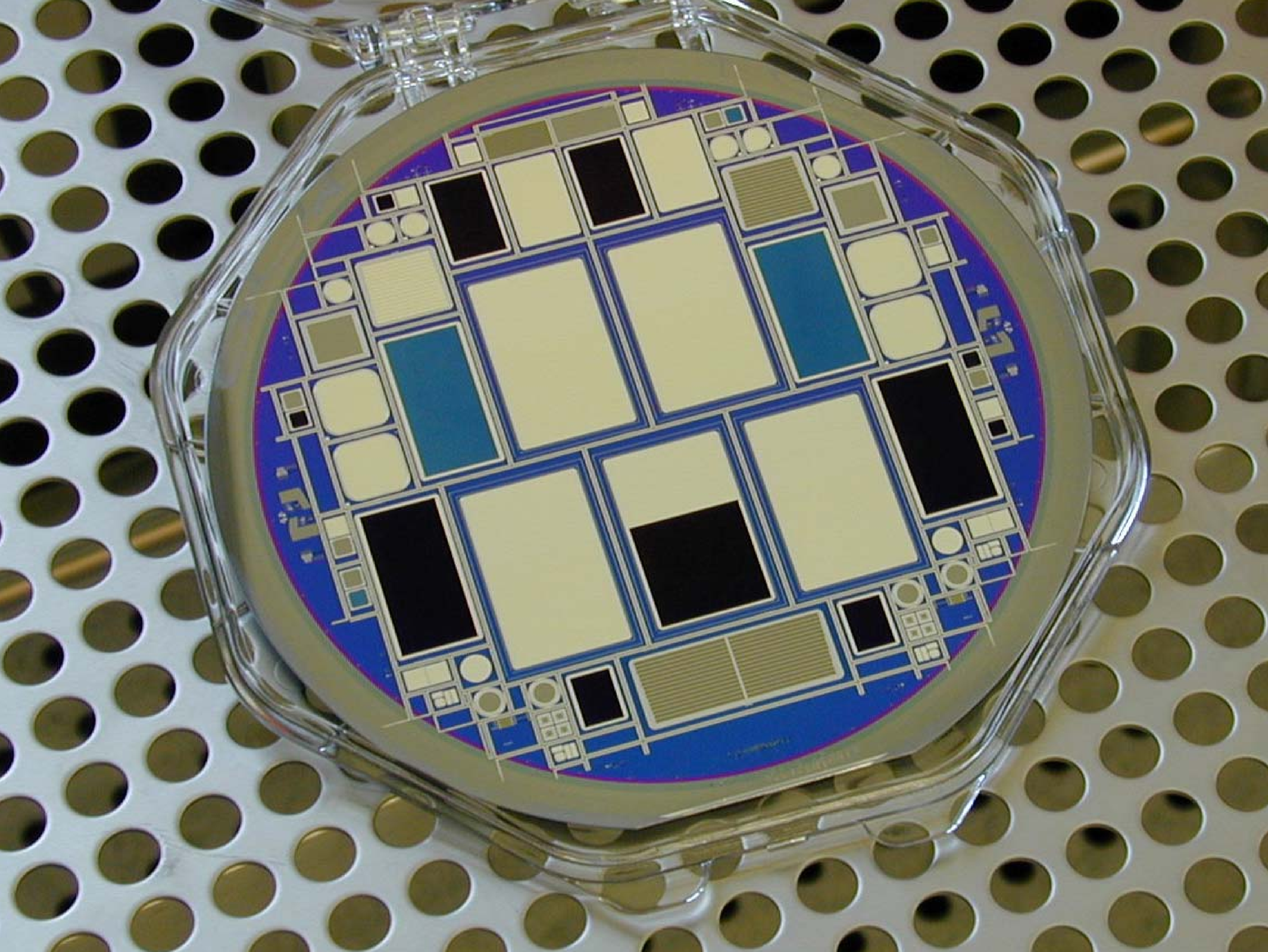


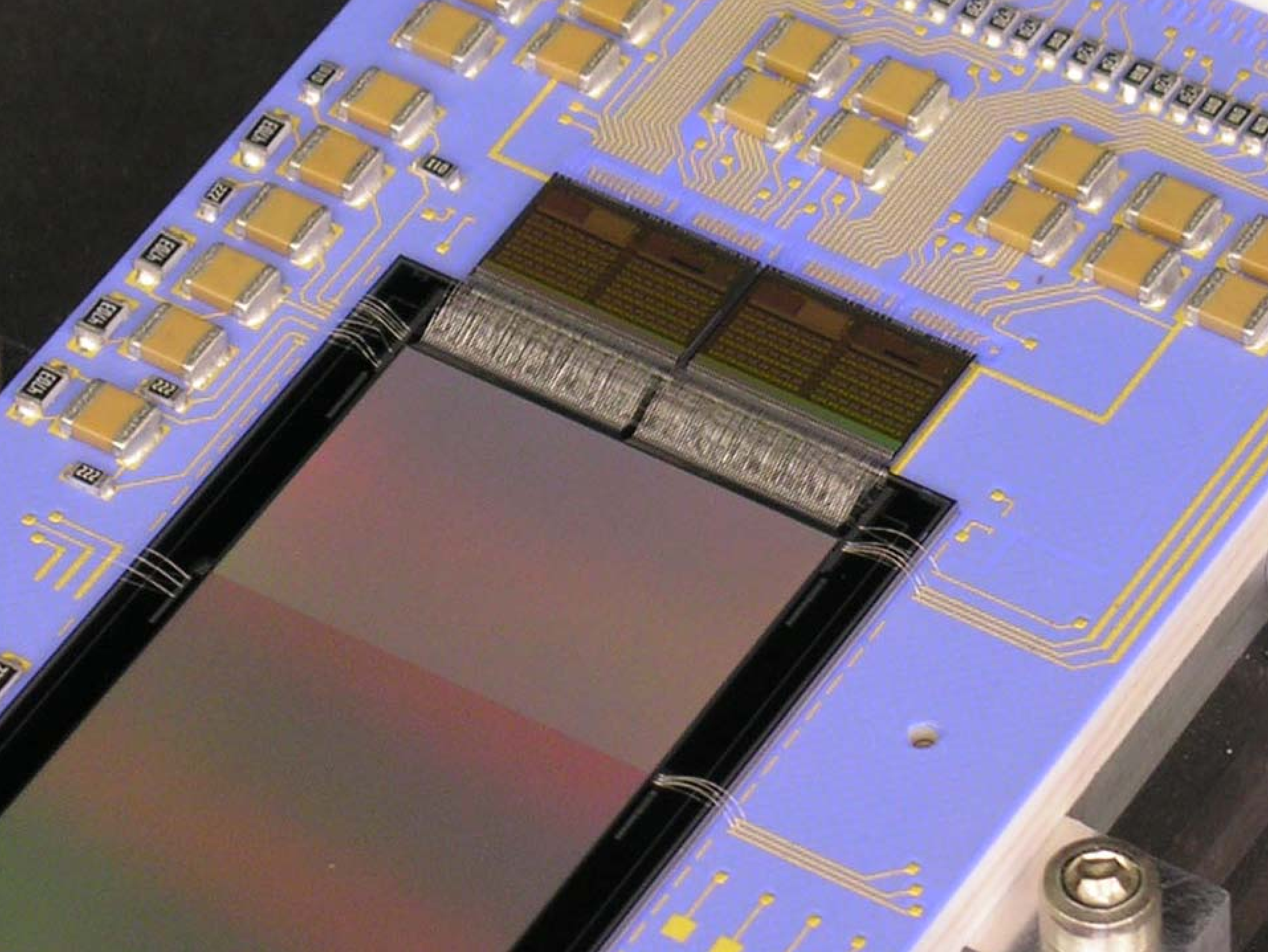


- full depletion (50 µm to 500 µm)
- back side illumination
- radiation hardness
- high readout speed
- pixel sizes from 30 µm to 1 mm
- charge handling: more than 10^6 e^-/pixel
- high quantum efficiency

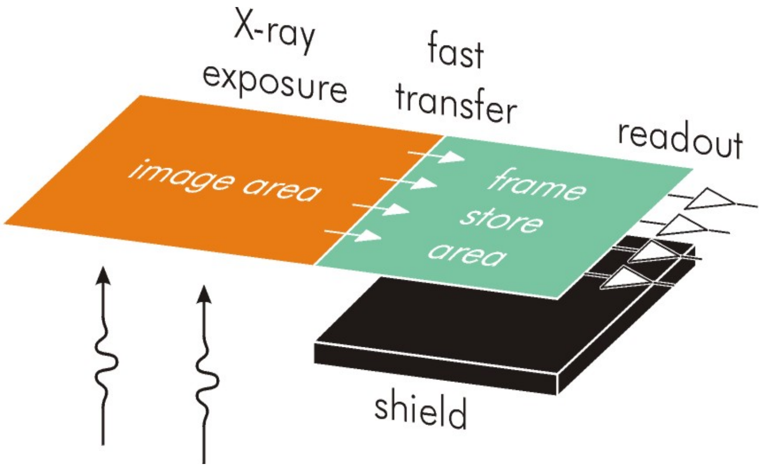


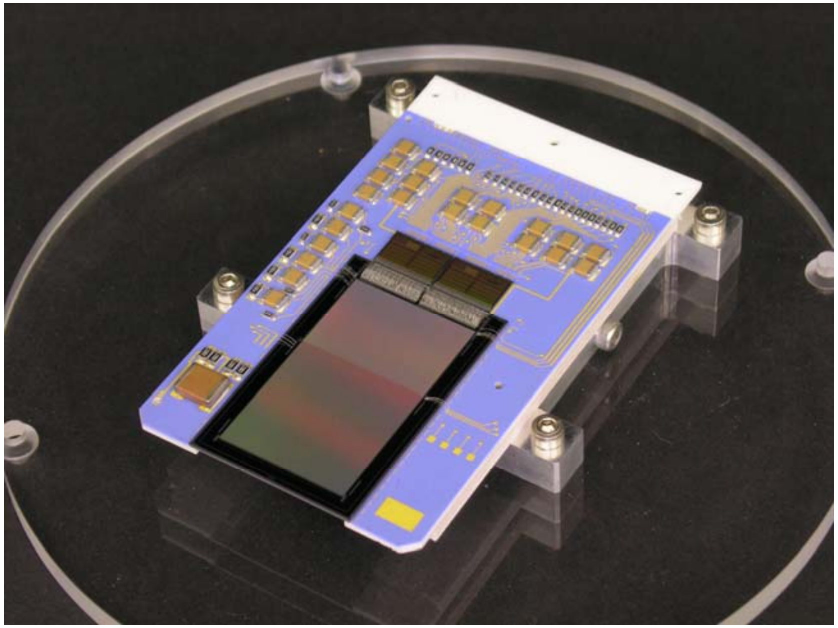

MPE-XMM-CCD
Version 0.1





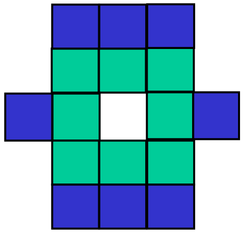
High speed frame store pnCCDs for X-rays, UV light, visible and near infrared light

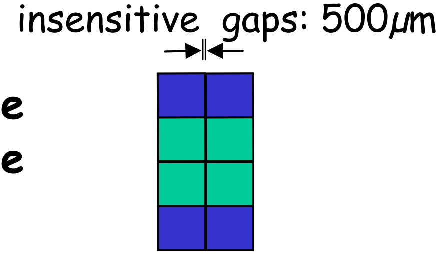




FS pn-CCD for the ROSITA mission (ESA, DLR, ROSKOSMOS)

format	264 x 264
pixel size	75 µm □ image
	50 µm □ image & frame store
	36 µm □ image & frame store
out-of-time	0.1 %





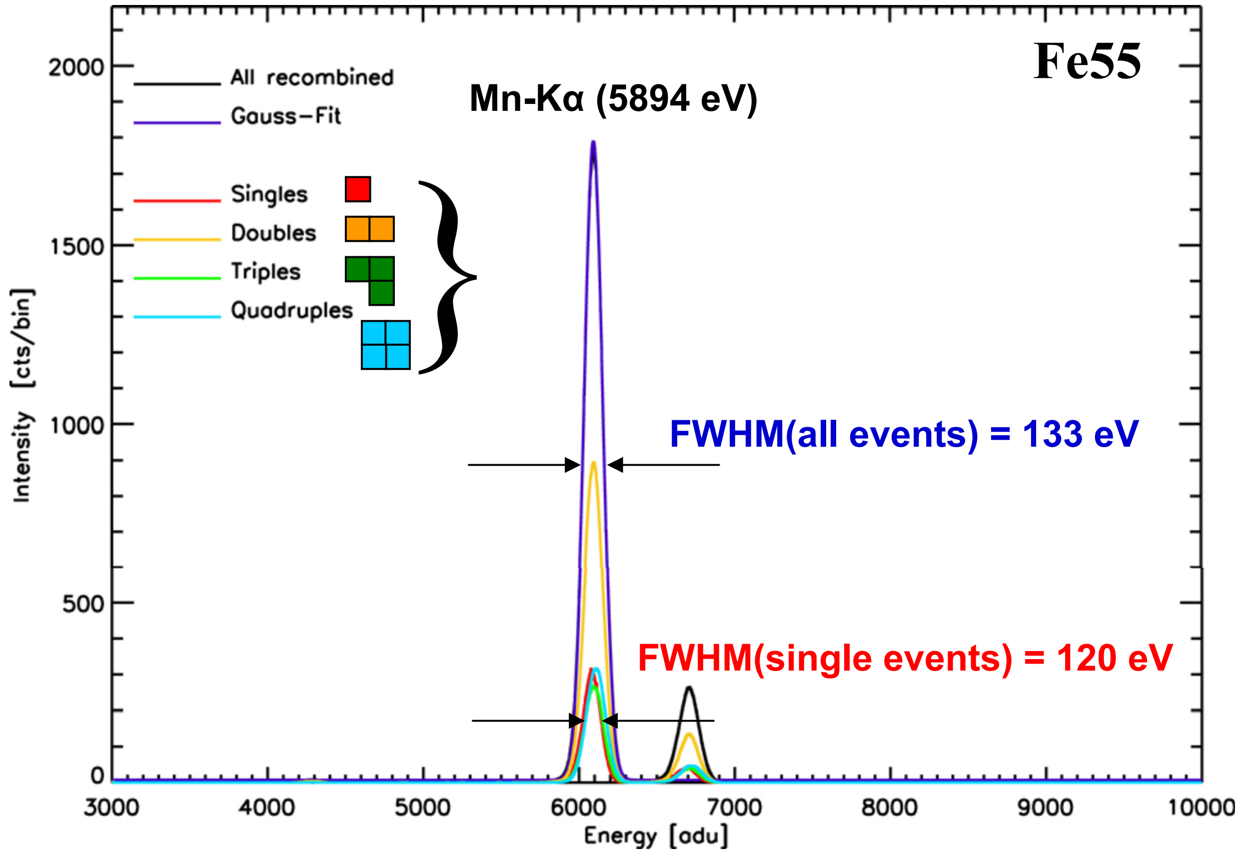
51µm pnCCD with a double-sided readout, mounted onto a ceramic substrate

All measurements were performed
@ - 40 ° C

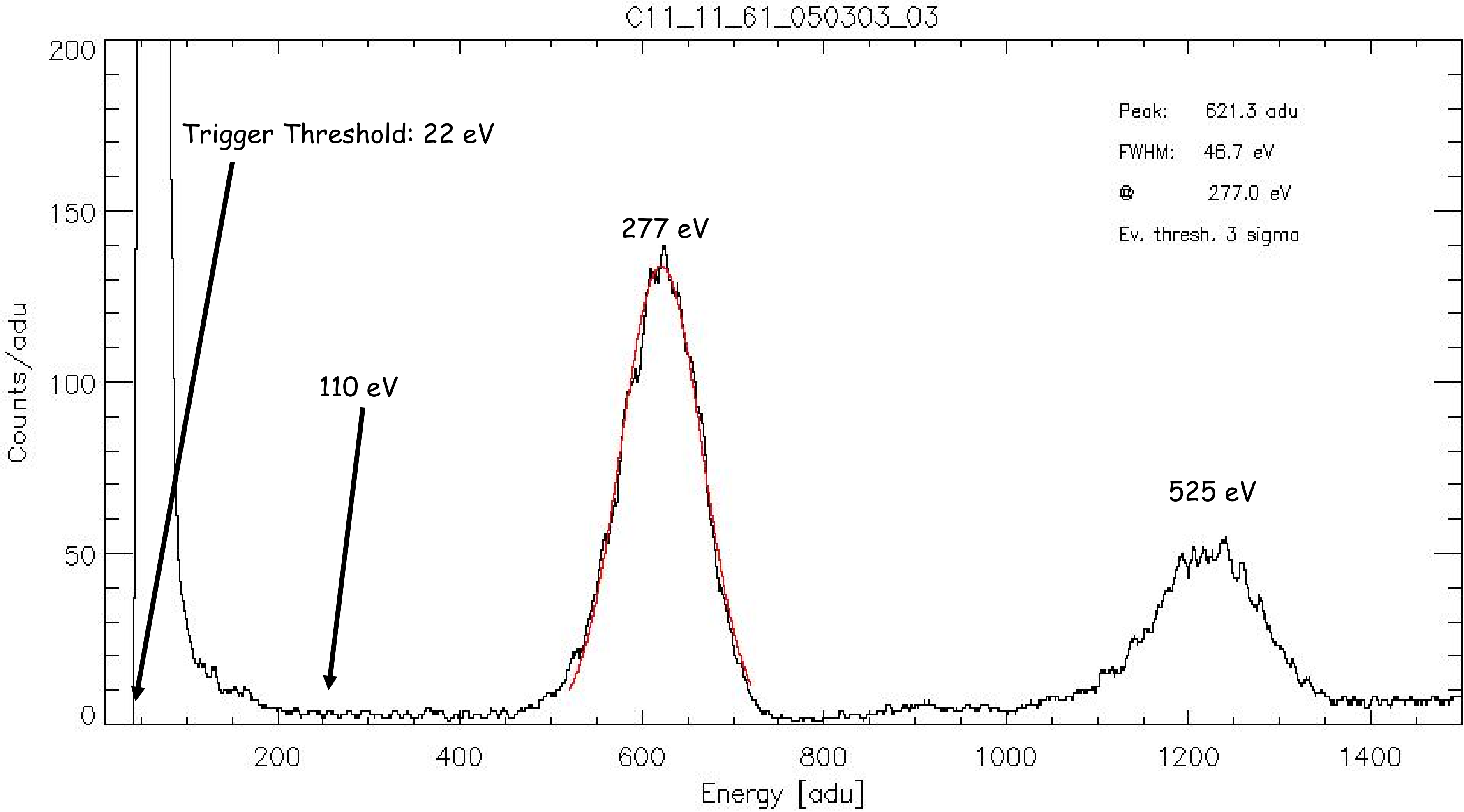
- detector size = 27×13.5 mm^2
- 51 µm ☐ pixel size
- 528×264 pixel in total,
  132×264 in each image & storage area
- readout transfer to both sides
- image transfer time = 30 µs
- OOT probability = 3% @ 1000 fps
- charge transfer loss CTI ≈ 10^{-5}
  i.e. total charge loss < 0.15 %
- charge handling capability > 10^6 e^-
- 100% fill factor
- readout noise vs. frame rate:
  - 1.8 e^- @ 10 .. 400 fps
  - 2.3 e^- @ 400 .. 1.100 fps
- With binning:
  - 2.3 e^- @ 2.200 .. 4.400 fps

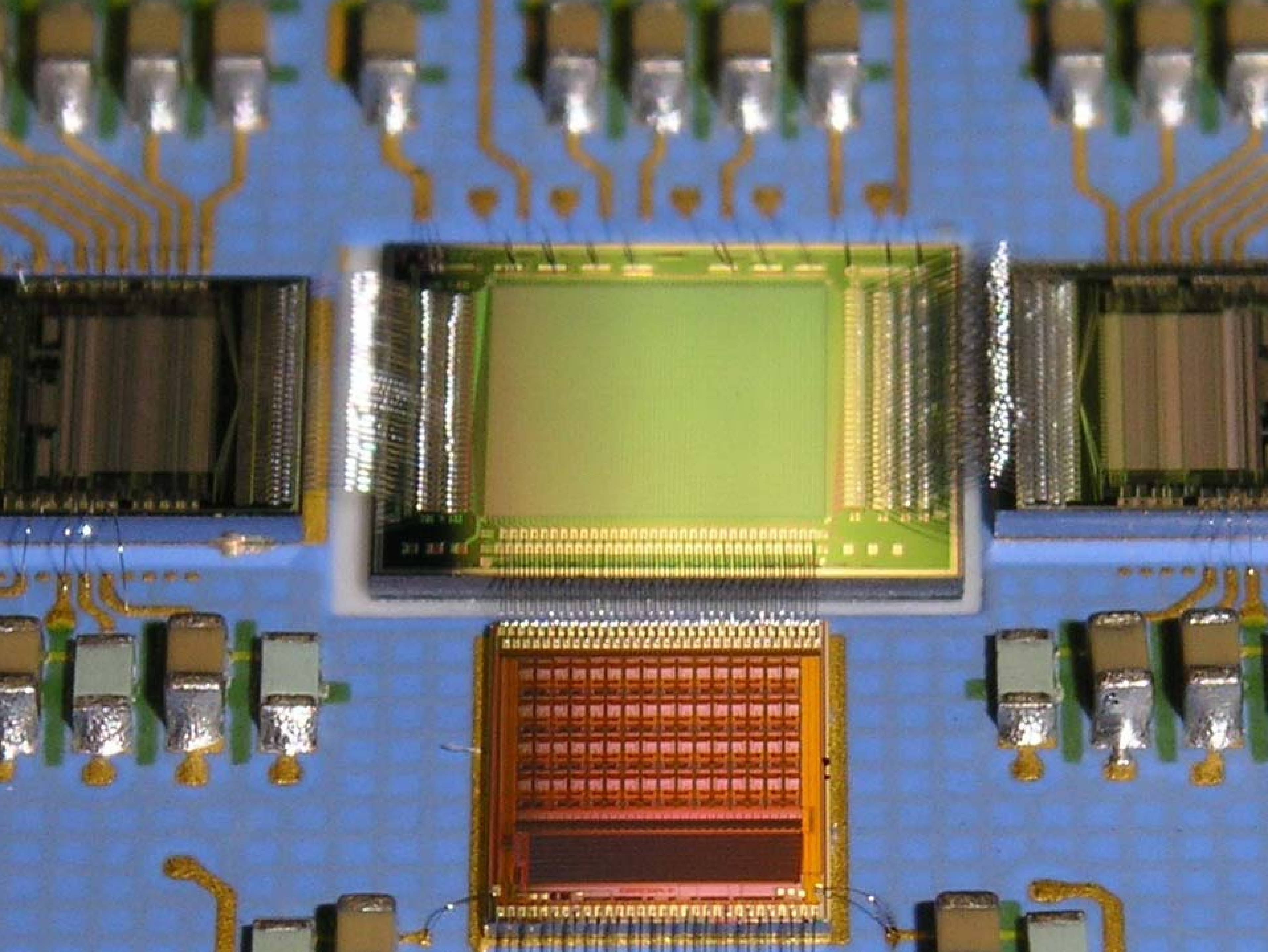
Performance of pnCCDs: spectroscopy Fe55

C11_11_61_050422_01, T = -55°C; 54 ms

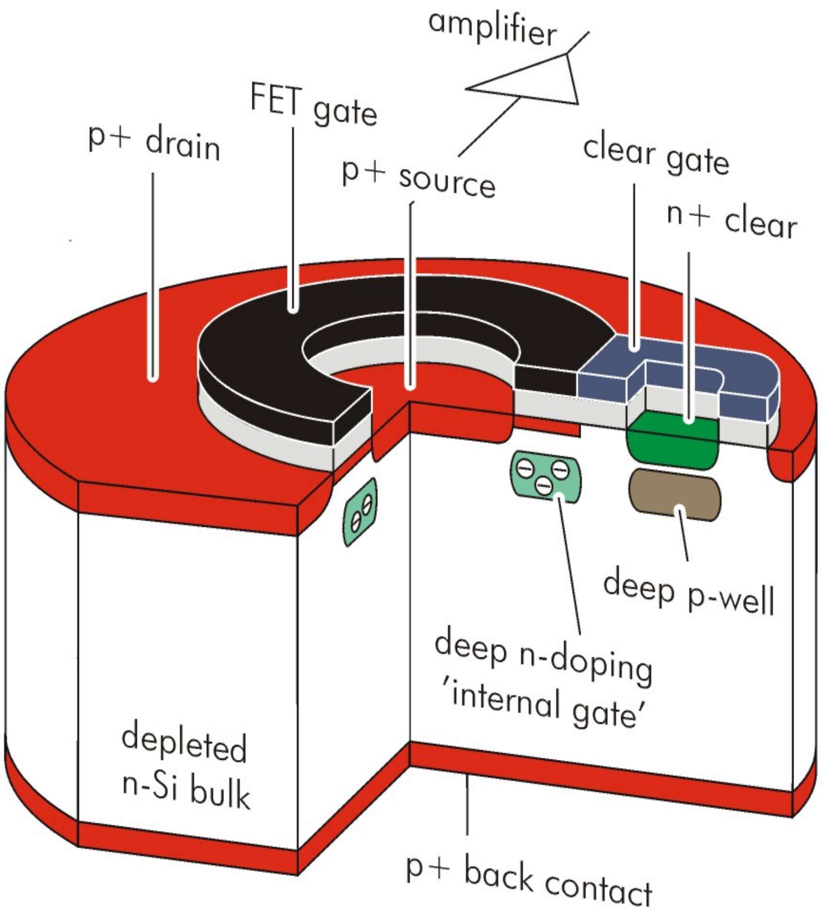


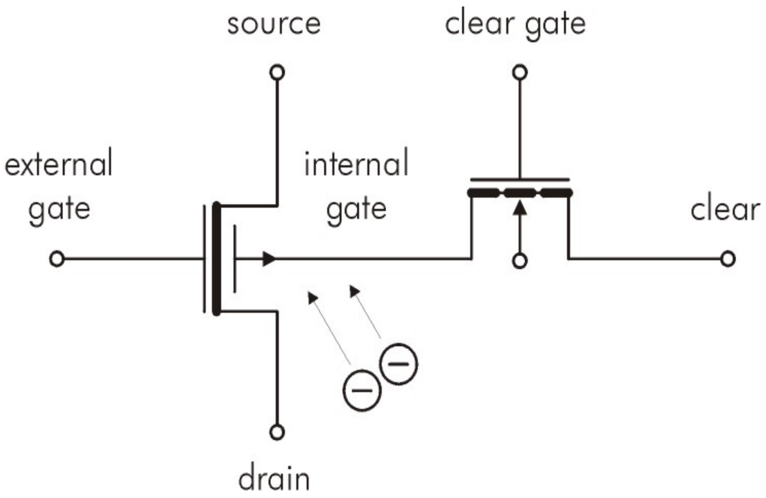
Energy resolution @ C_K of a pnCCD



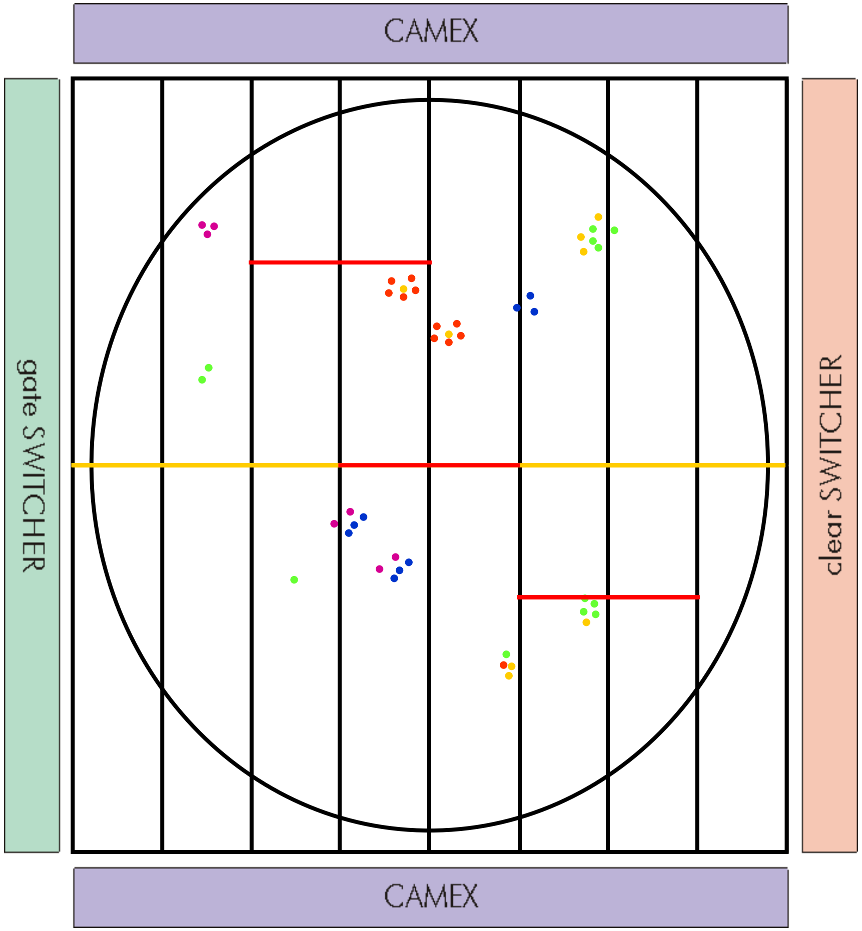


Circular DEPMOSFET pixels





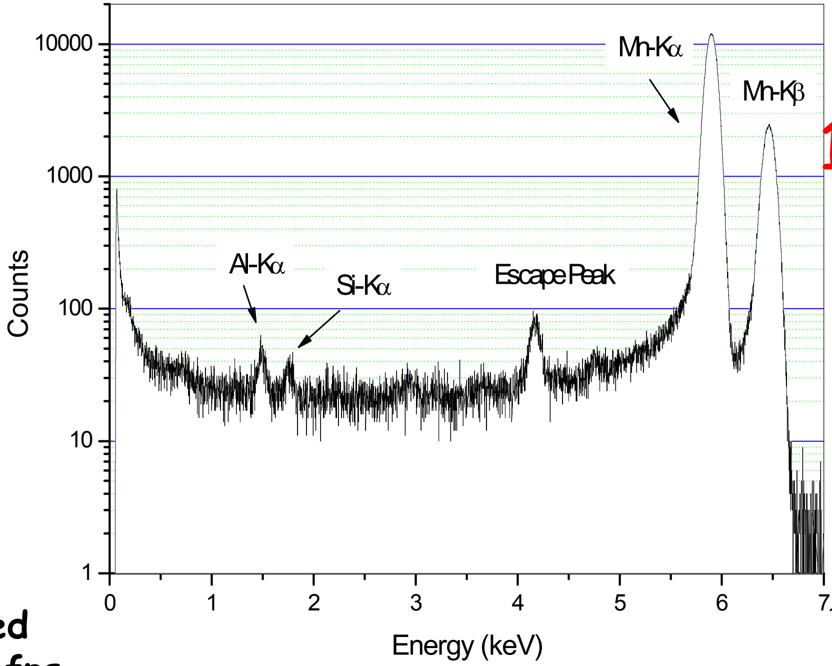
WFI APS setup



XEUS WFI APS:

- Monolithic
- 1k x 1k pixel cells
- 100 x 100 μm^2 size
- Area: 10.4 x 10.4 cm^2
- 16 Sectors of 128 x 512 pixels each
- Row wise readout to both sides (basic mode)
- More flexible readout modes feasible by changing pixel interconnections

Energy resolution of DEPMOSFET arrays @ - 40° C



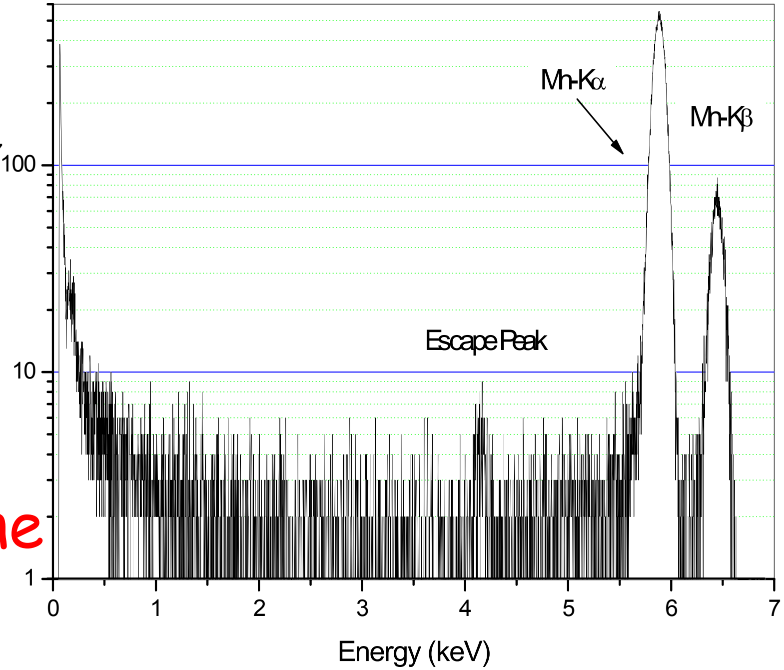
operated @ 300 fps

“Frontside” illumination:
Source illuminates electronic side

Energy resolution:
127 eV FWHM @ Mn-Ka Line
corresponding to 6.4 e⁻ ENC

Energy resolution:
131 eV FWHM @ Mn-Ka Line
corresponding to 6.9 e⁻ ENC

“Backside” illumination:
Source on top of entrance window

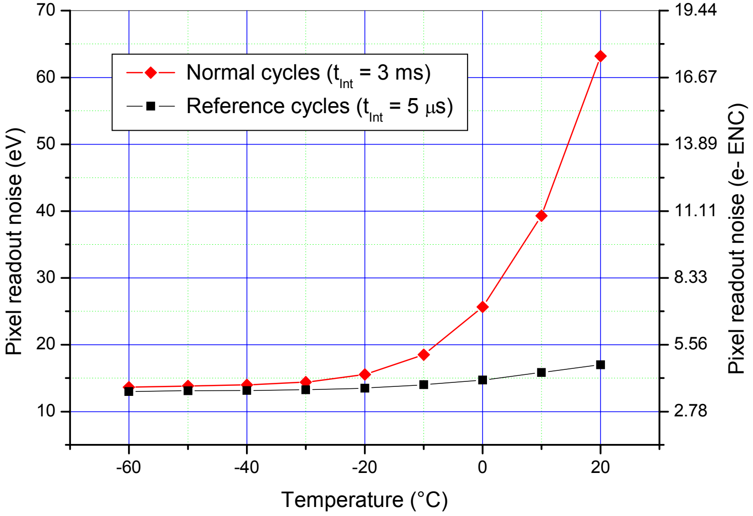


Performance

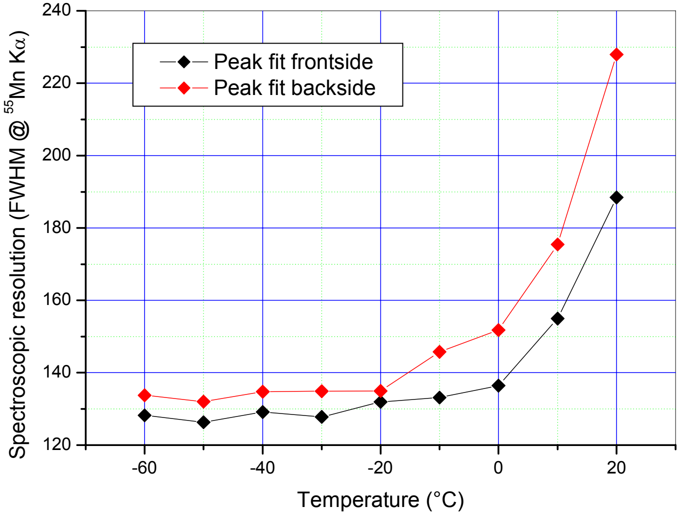
all data were taken
@ 300 fps

Results from ^{55}Mn-Kα peak fits

Readout noise (e$^-$ ENC)



eV FHWM @ Mn- Kα



$$\tau_g = \frac{n_i}{G_{th}} = \frac{q\ d\ n_i}{J_{th}}$$

$$= 800\ ms$$

@ J_{th} = 160 fA/cm^2

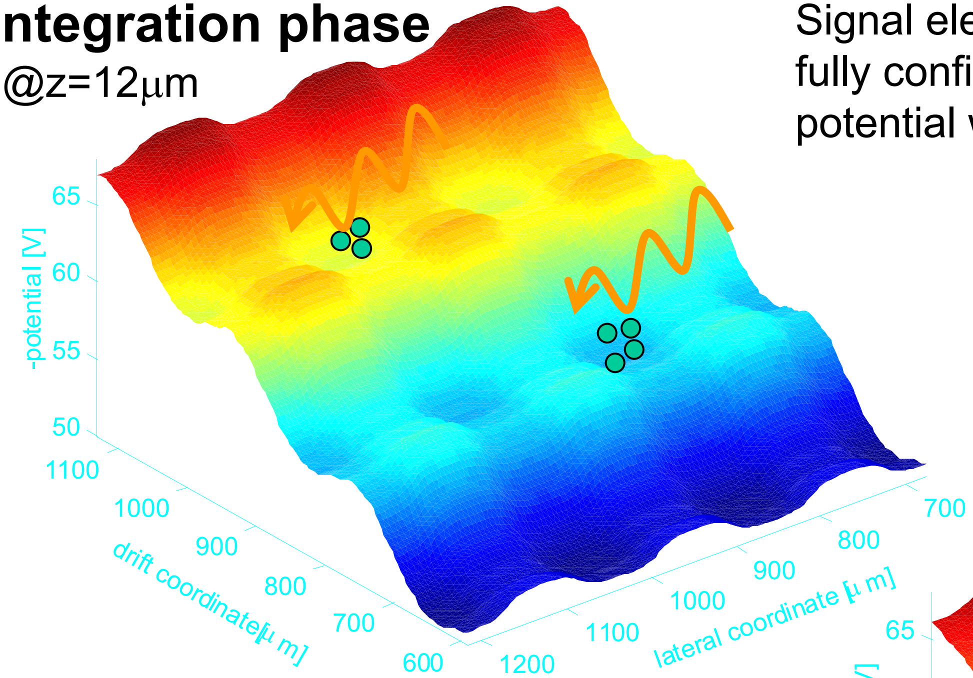
Measured values:

- ➪ 188 eV @ 20° C
- ➪ 127 eV @ -50° C

Controlled-Drift Detector - simulation

Integration phase

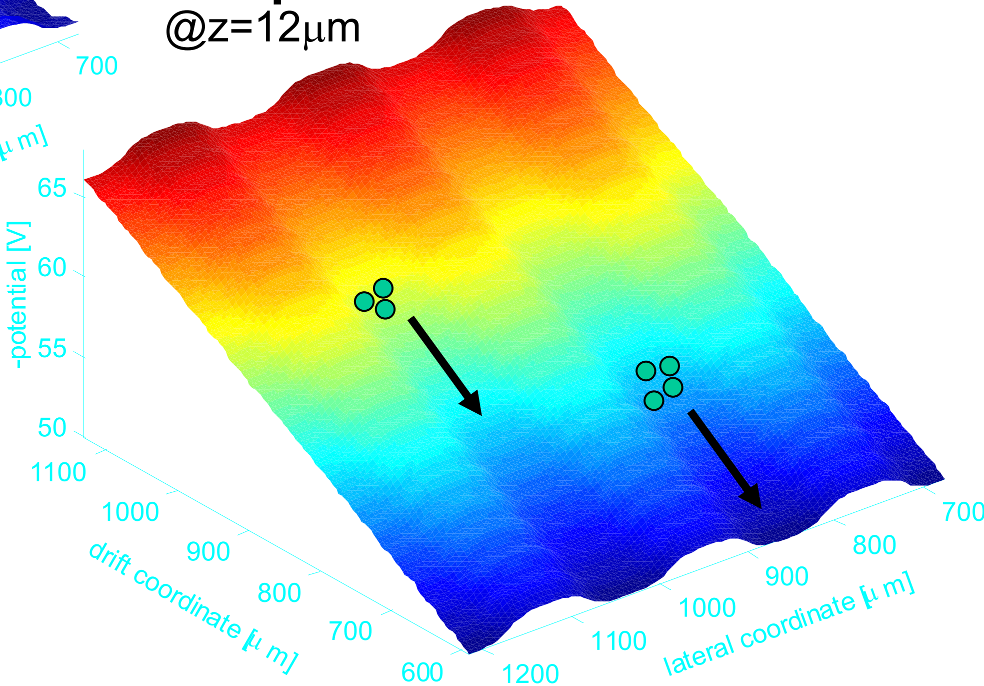
@z=12µm



Signal electrons are fully confined in 3-D potential wells

Drift phase

@z=12µm



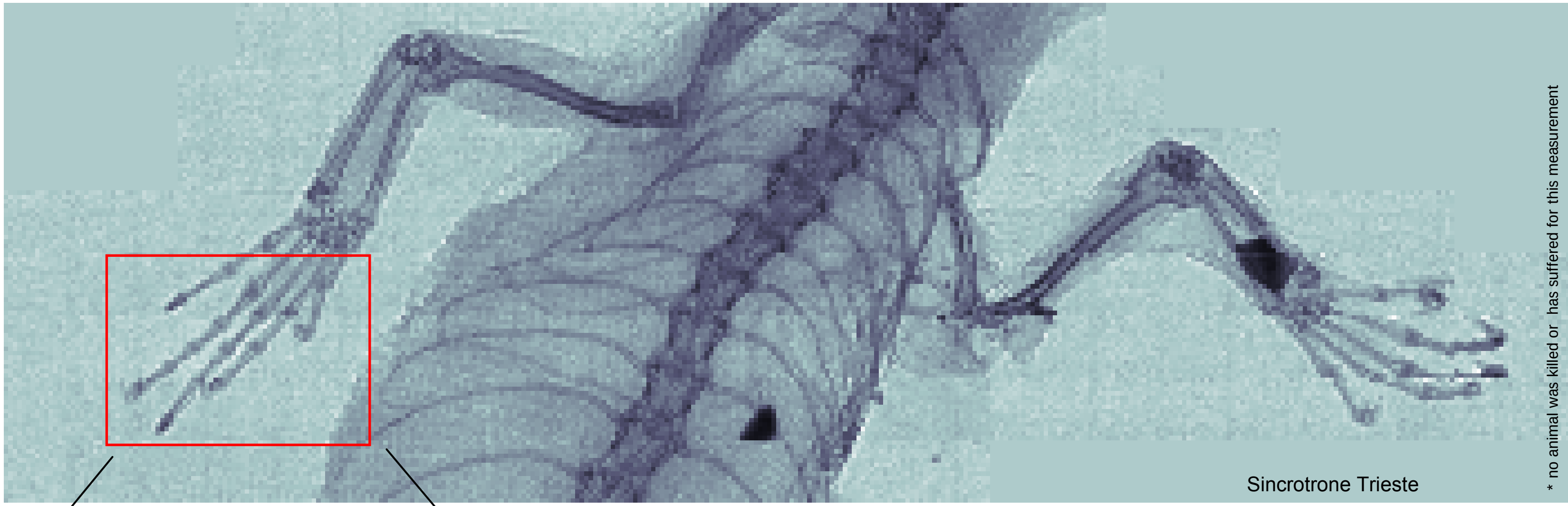
The X-ray position along the drift is obtained from the electrons' drift time

T_{drift}~200 ns / 4 mm

X-ray spectroscopy/imaging tests with CDDs

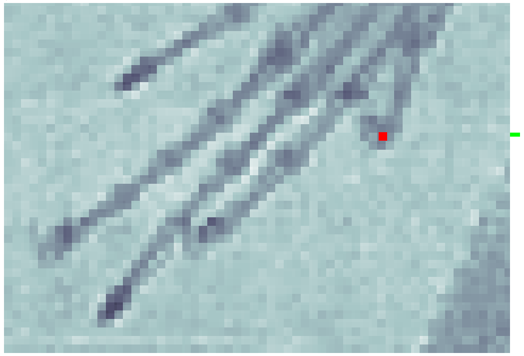
Radiographic image of a lizard...*

pixel size: 120μm, 10^5 frames/s, T=300 K

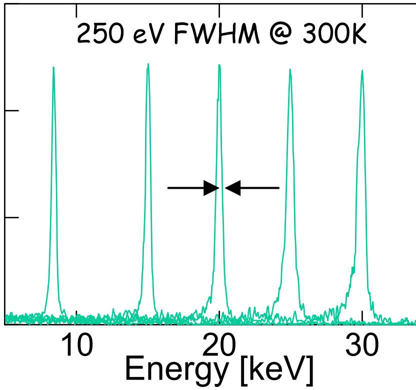


Sincrotrone Trieste

* no animal was killed or has suffered for this measurement

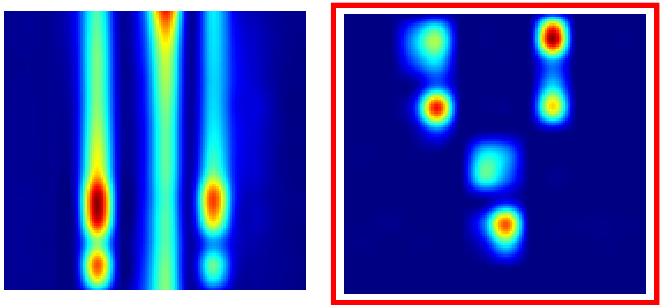


…and spectroscopic analysis of each pixel

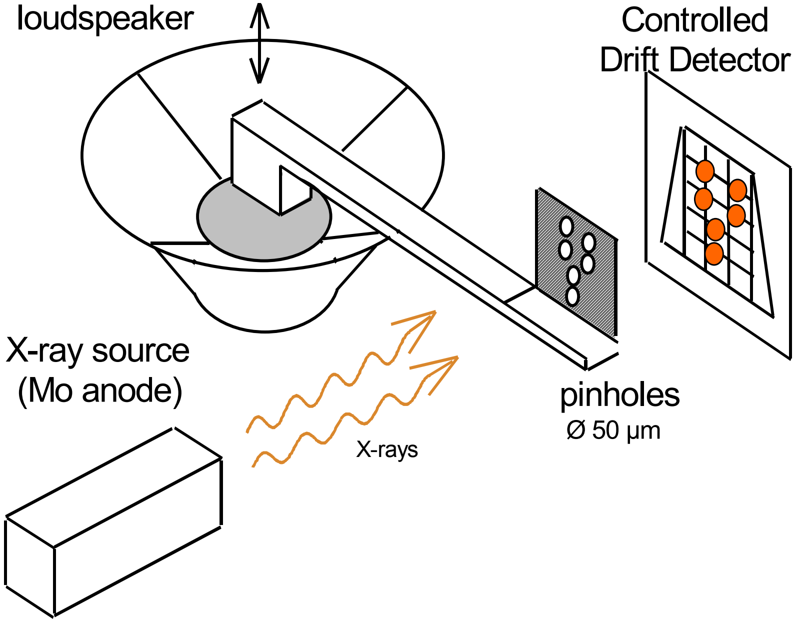


Time-resolved X-ray imaging of repetitive processes

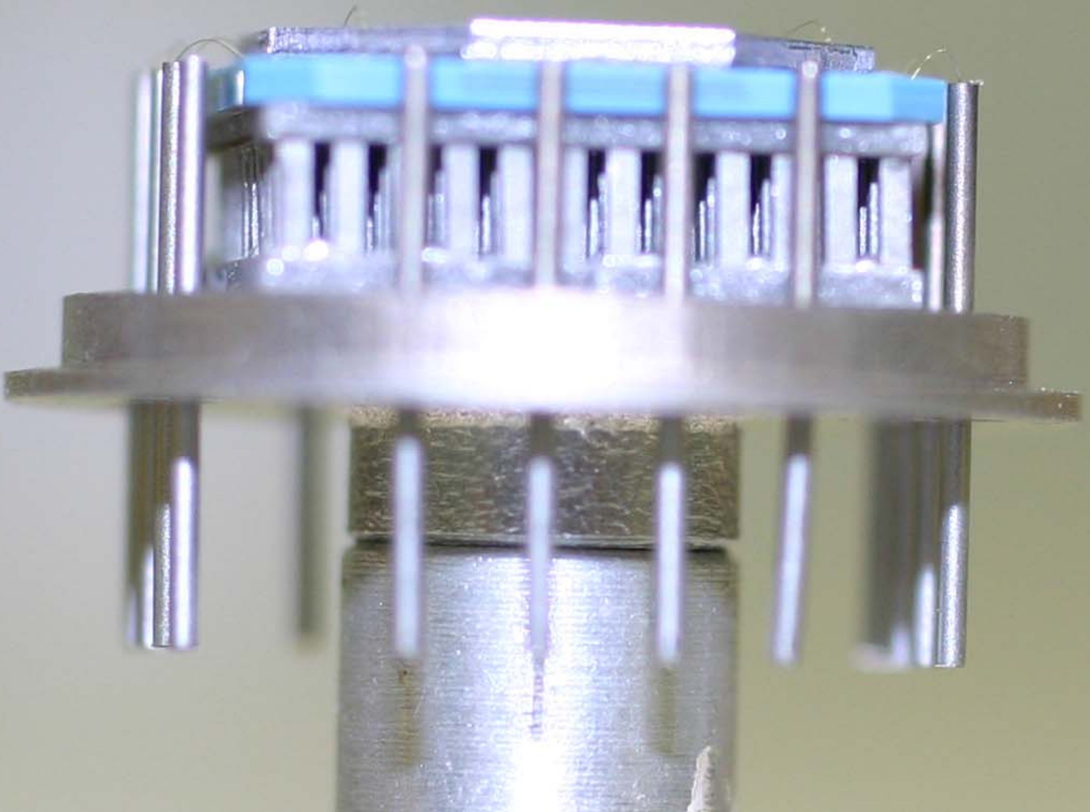
Acquired time-sliced X-ray images



20 µs
time slice



⇒ **Applications in astrophysics, in the biomedical and the industrial fields (e.g. *pump-and-probe* techniques)**



Small and Large Area SDDs

Classic Round SDDs with sensitive area of 5, 10 and 20 and 30 mm2 up to 1cm^2

SDD 5 mm^2

chip 5 x 5 x 0.45 mm^3

SDD 100 mm^2

chip 14 x 14 x 0.45 mm^3

SDD 10 mm^2

chip 6 x 6 x 0.45 mm^3

SDD 30 mm^2

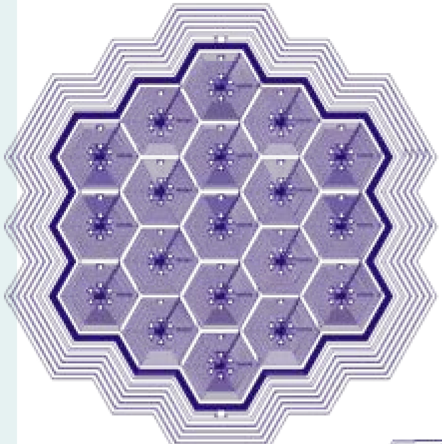
chip 9 x 9 x 0.45 mm^3

SDD 20 mm^2

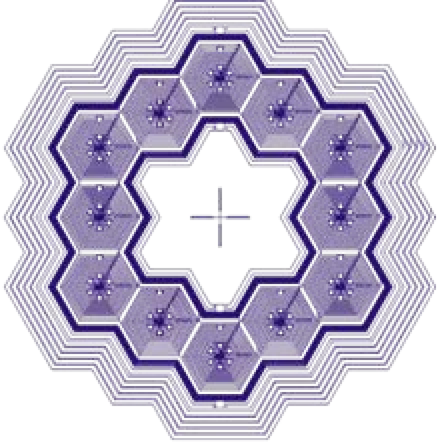
chip 8 x 8 x 0.45 mm^3

Multichannel SDDs

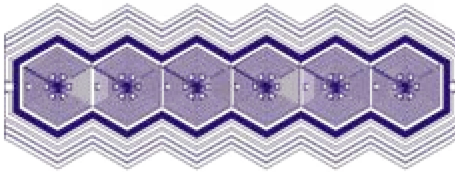
19x5 mm² = 95 mm²



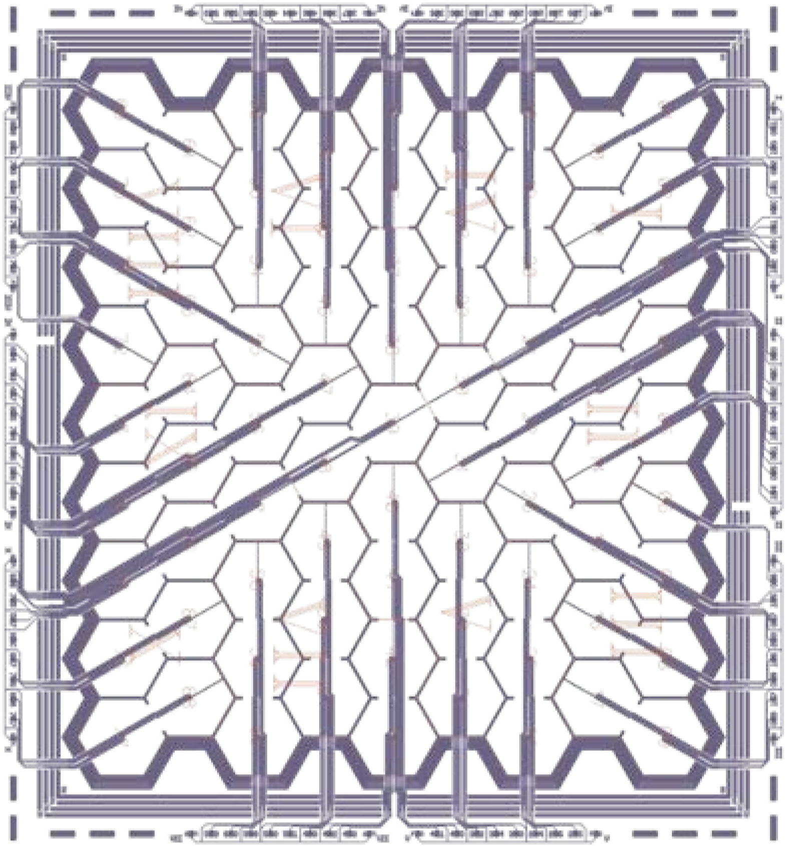
12x5 mm² = 60 mm²

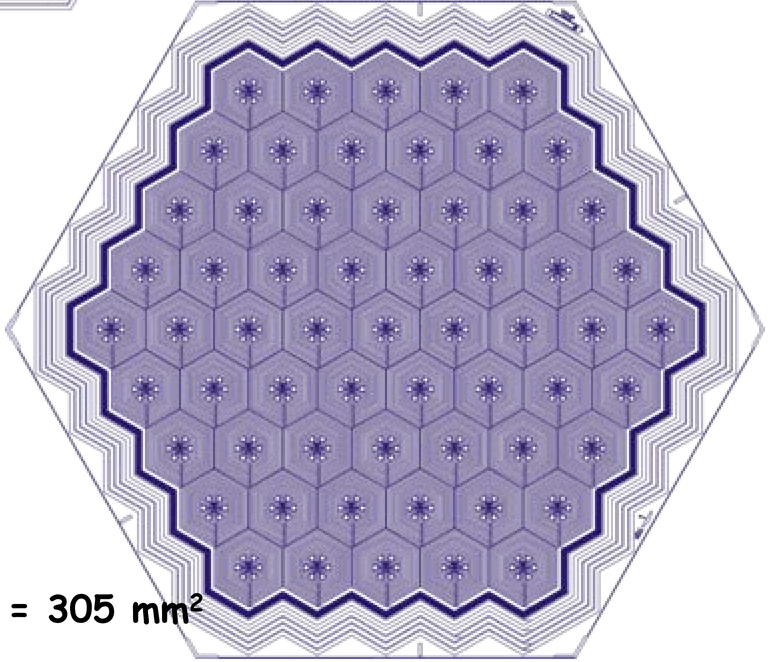


6x5 mm² = 30 mm²



77x7 mm² = 539 mm²





61x5 mm² = 305 mm²

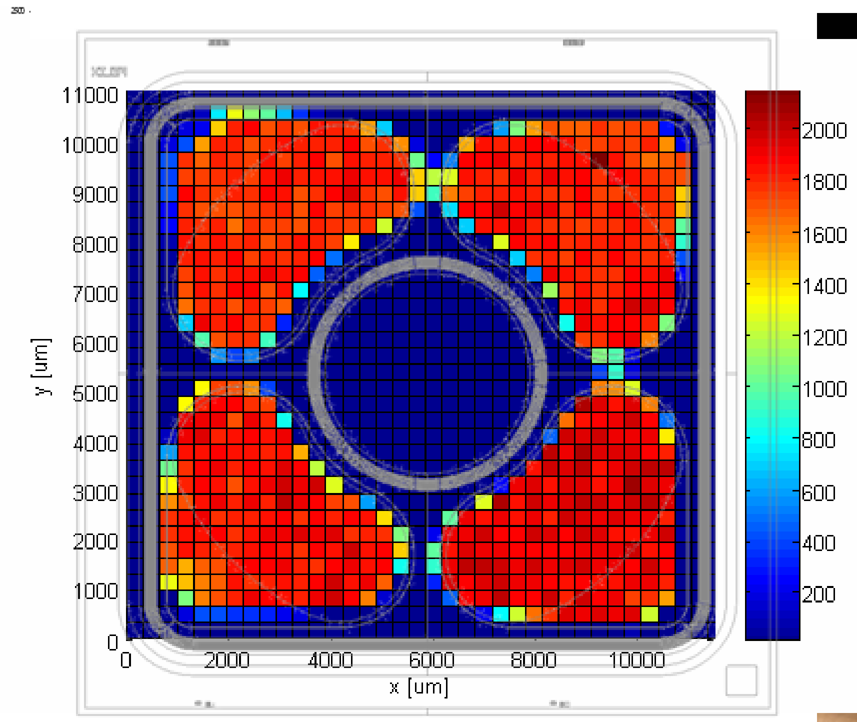
Multichannel SDDs

- "ROCOCO 2"

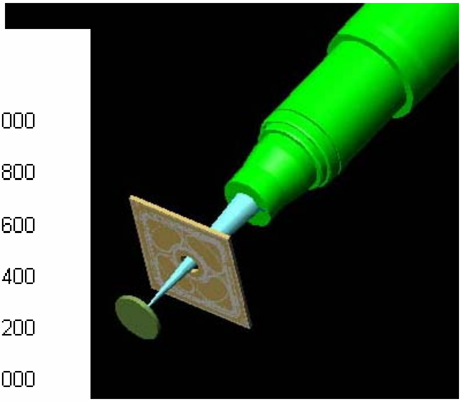
  4 x SD^3 15 mm^2
  monolithic array with center hole

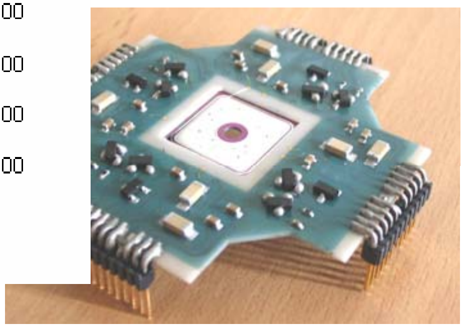
SD^3 4 x 15 mm^2

chip 14 x 14 x 0.45 mm^3



mapping of detection efficiency
lab test, T = -20 °C, τ = 1.0 *μsec*





compact XRF spectrometer for investigation of works of art and archeometry

- polycapillary X-ray fiber
- SDD chip with center hole
- custom electronics

A. Longoni
Politecnico di Milano

interesting option for SEM

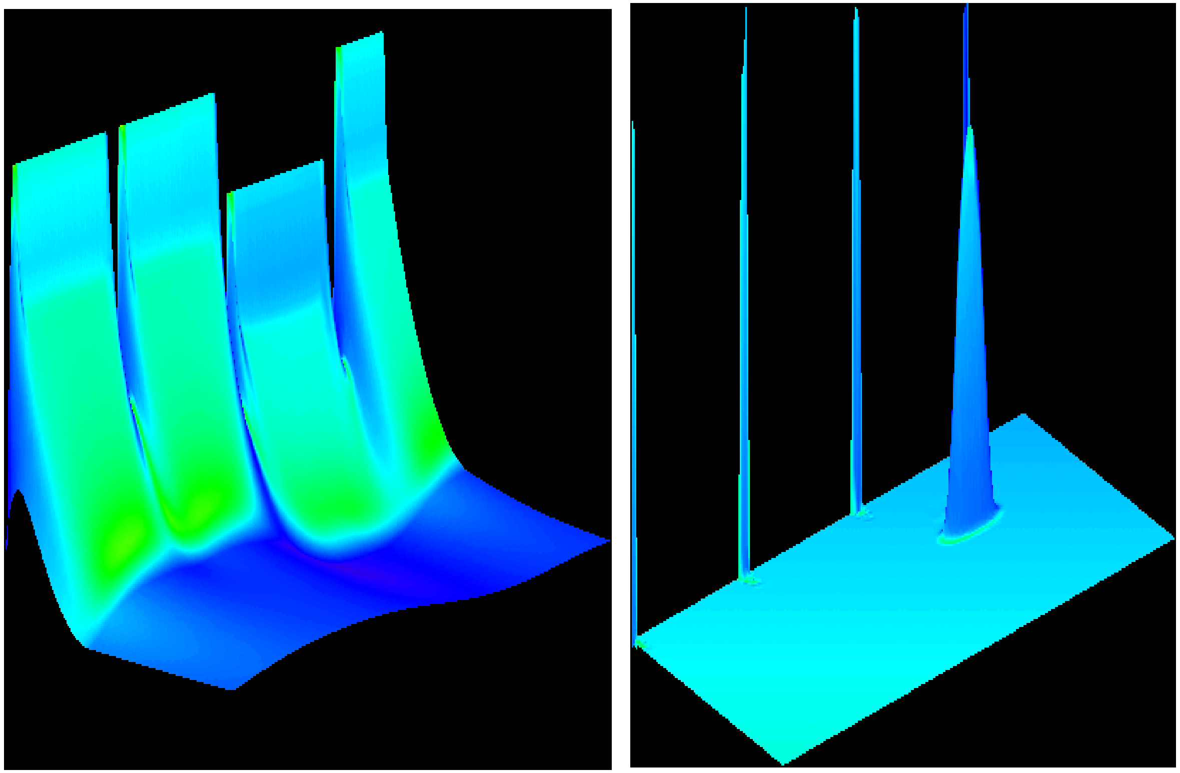
How many charges can be stored in one pixel ?

What determines the charge handling capacity in a pixel ?

pixel volume:
20x50x50 $\mu m^3 = 5 \times 10^4 \mu m^3$

Doping: 10^2 per μm^3

CHC = 5×10^6 per pixel

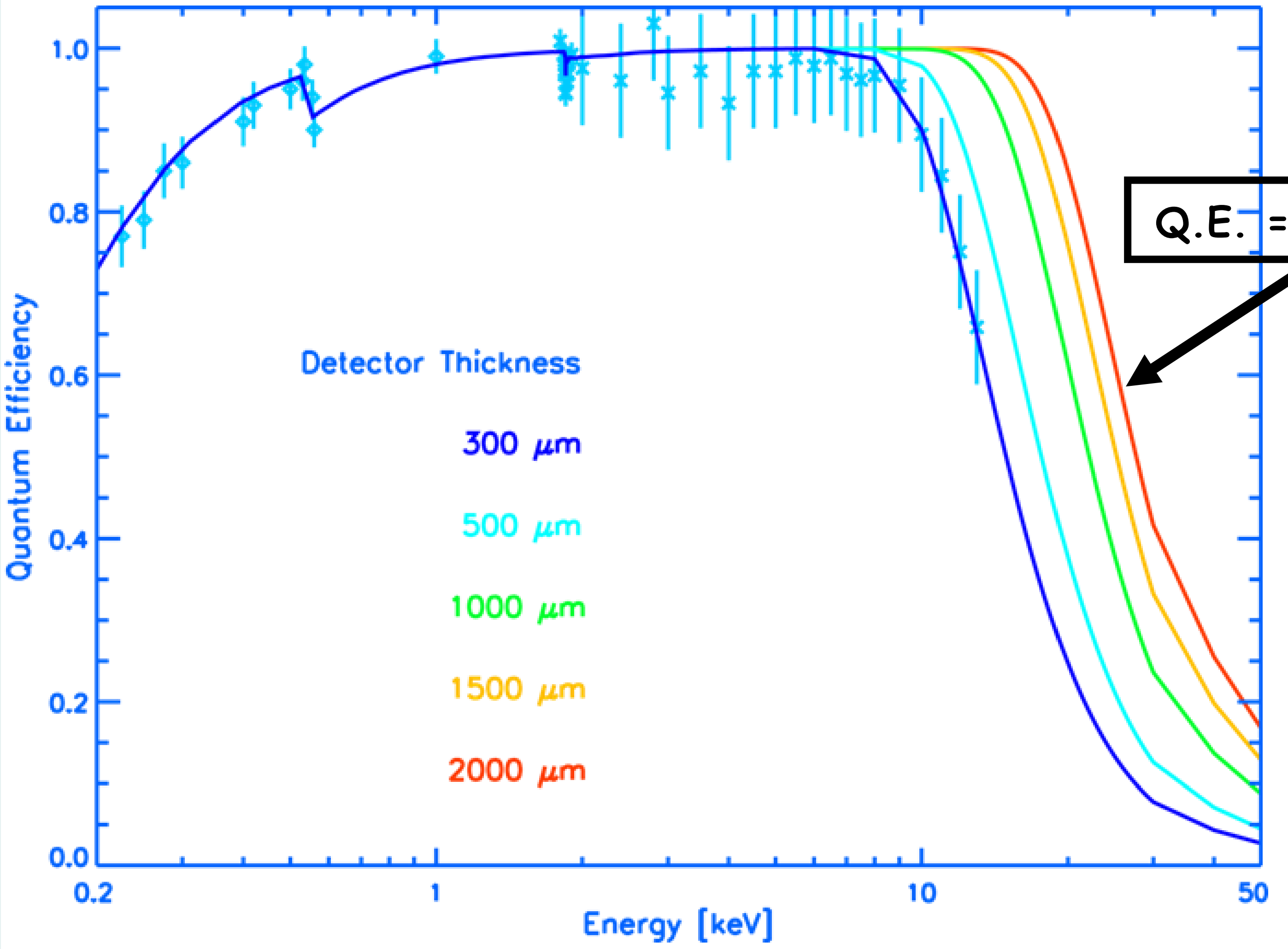


can be **increased** by
external voltages

can be **increased** by **doping**

What is limiting the quantum efficieny ?

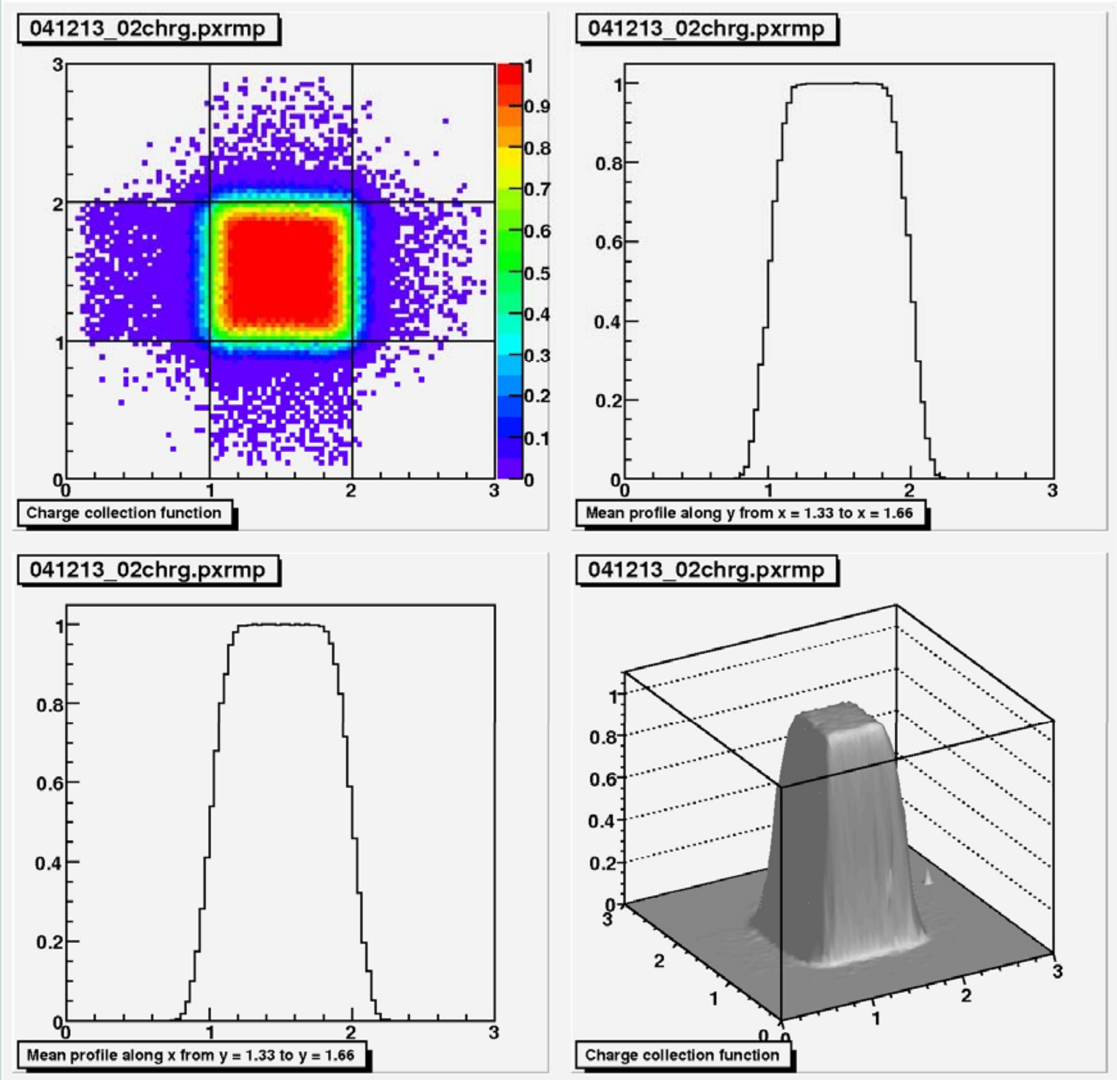
The thickness of Silicon ‼



Q.E. = 60 % @ 24 keV

What limits the pixel size ?

The charge spread function (CSF)



Mesh measurement with 4.5 keV X-rays:
Pixel size: 51 μm

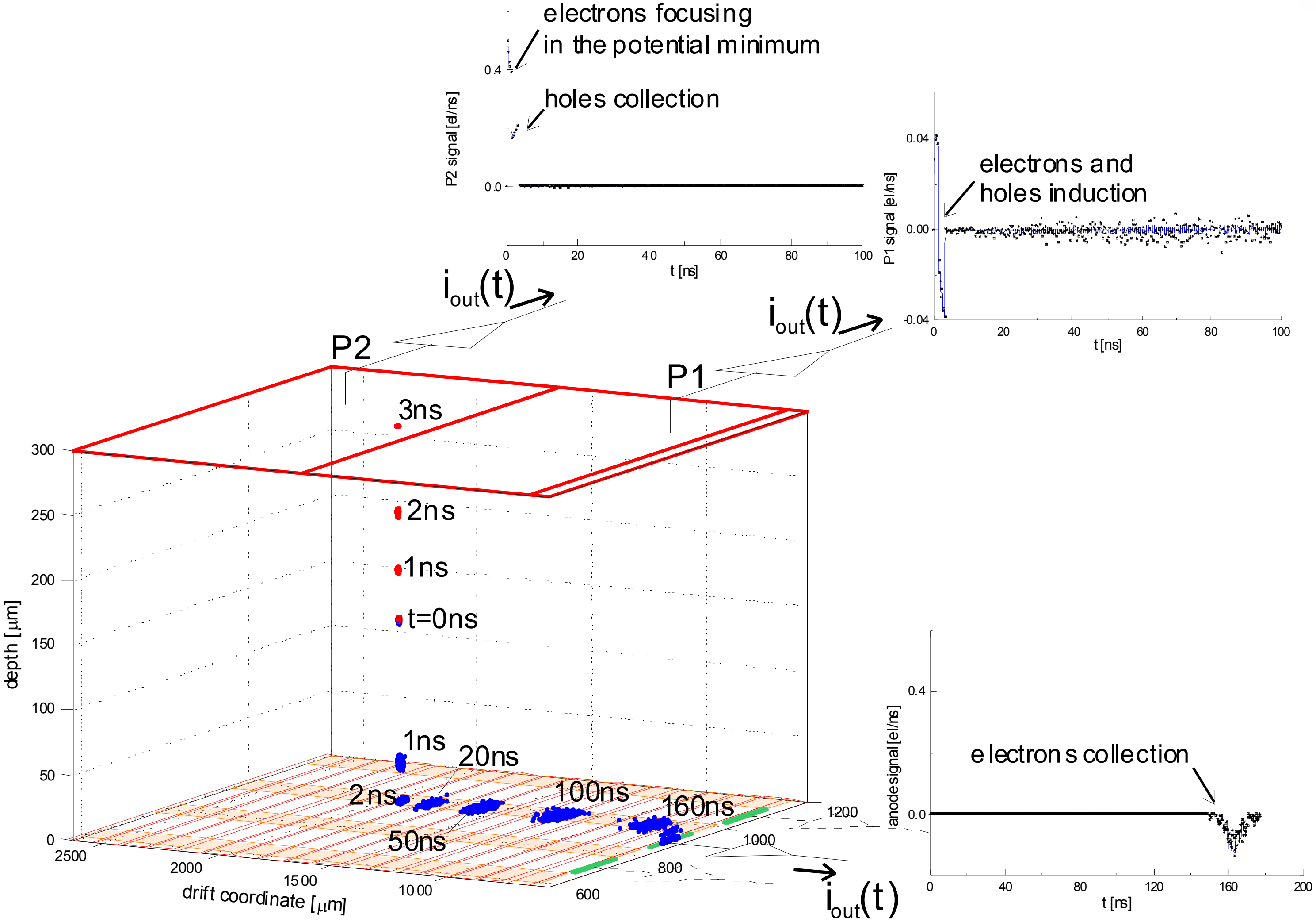
Edge blur (CSF):
(i) ~ 8 μm (rms)
(ii) ~ 20 μm (rms)

@: (i) 500 μm thickness
V_{back} = -90 V
(ii) 1.500 μm thickness
V_{back} = -500 V

work carried out by Nils Kimmel

What limits the ``detection time´´

PHOTON INTERACTION = t_o



electrons focusing in the potential minimum

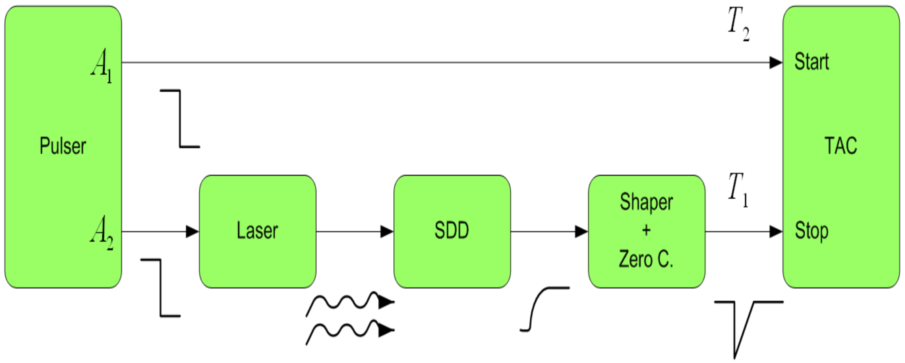
holes collection

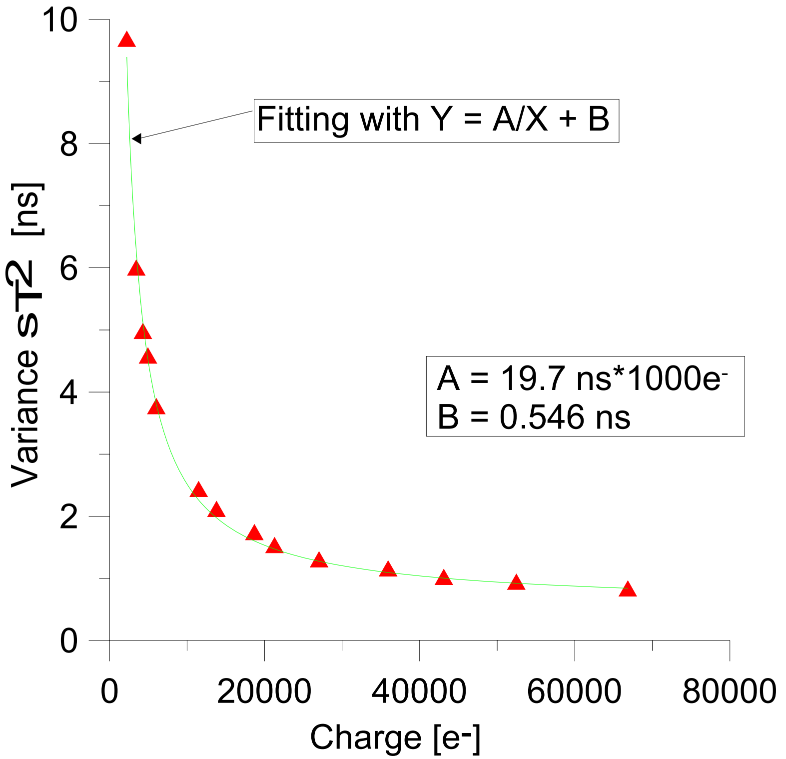
electrons and holes induction

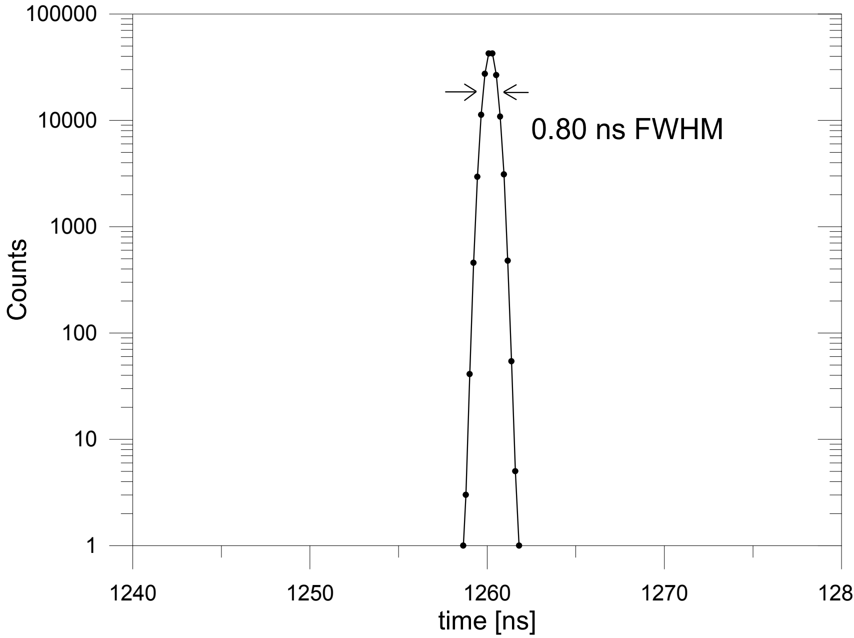
electrons collection

Count rate and timing properties

$$\tau_{opt} = \sqrt{\frac{C_D}{I_{leak}\omega_T}}$$







What limits the total size of a detector chip ?

Availability of large high resistivity (ρ> 10 kΩcm) FZ - Silicon ?

2 inch: 5 %

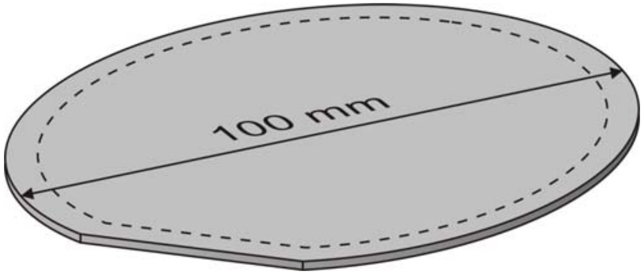
3 inch: 15 %

4 inch: 35 %

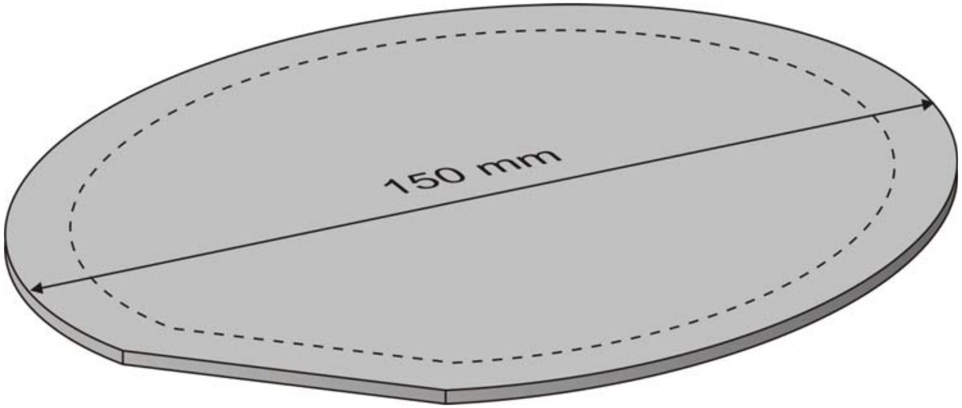
5 inch: 15 %

→ 6 inch: 30 %

8 inch: - commercially available in good quality ? 2007/8
(bulk material, double sided polishing, QA + 2 y)



4 inch wafer (Ø = 100 mm)



6 inch wafer (Ø = 150 mm)

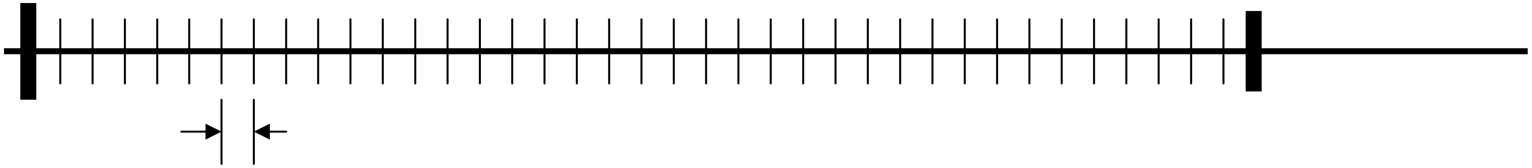
Bunch structure @ the DESY X-FEL

Pulse duration: 150 fs

Δt = 800 μs

99.2 ms
pause

Δt=200 ns to
Δt=12.5 μs

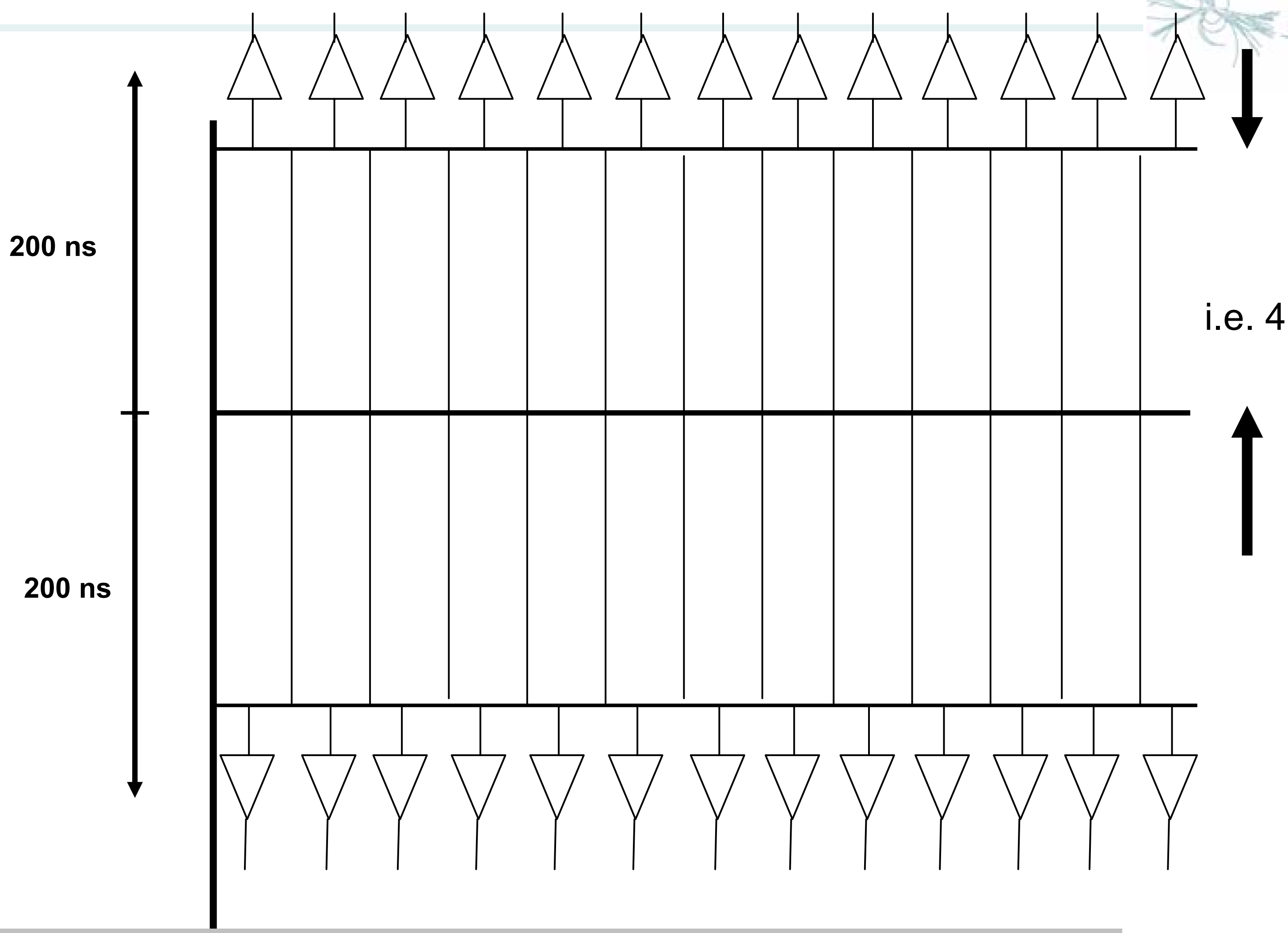


Within 800 μs between 64 and 4096 bunches may occur

Minimum time between bunches: 200 ns
Maximum time between bunches: 12.5 μs

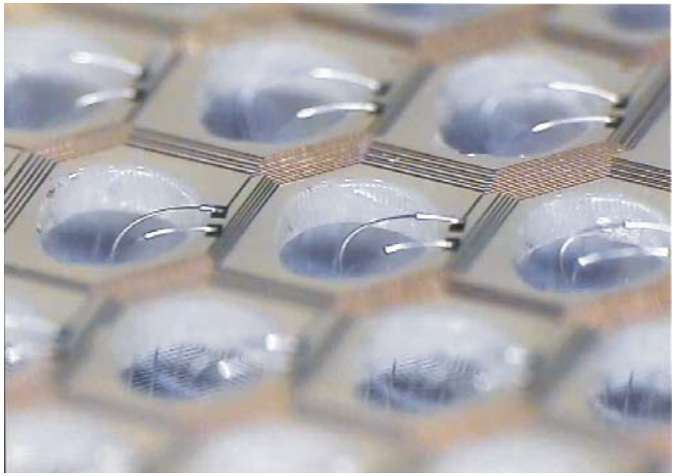
can be chosen by the experiment

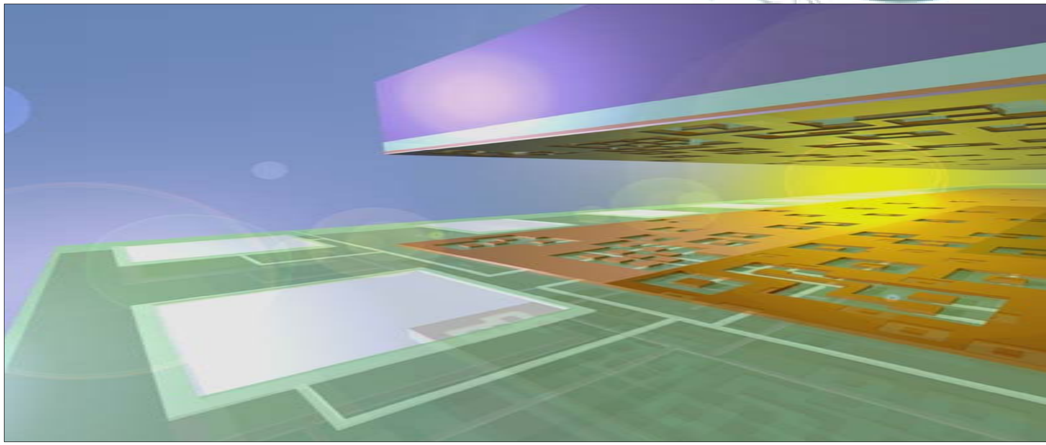
Device Proposal, CDD (non-controlled)

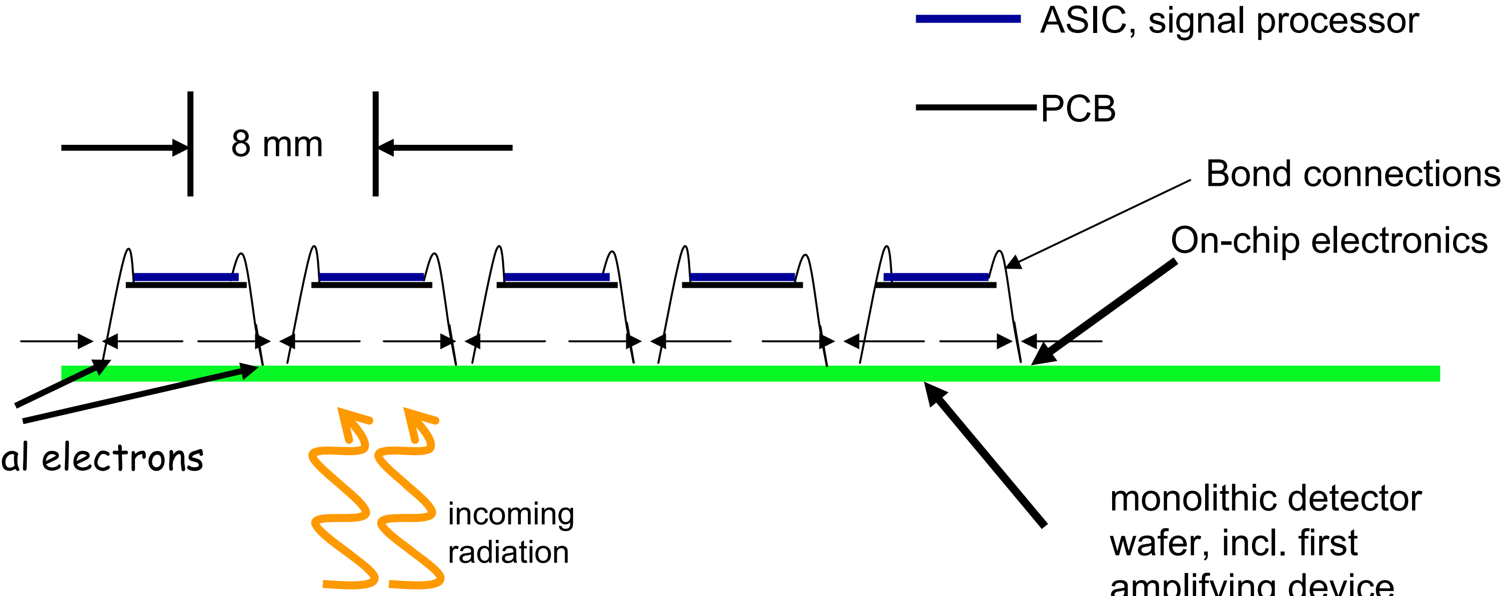


V_{max}≈ 100 µm / ns, V_{exp} ≈ 20 µm / ns That means: Δt= 3 ns, Δx = 60 µm
total $area_{max}$: 80 x n•8 mm², CHC: unlimited (almost)

Basic mechanical structure for the CDD







ASIC, signal processor

PCB

8 mm

Bond connections

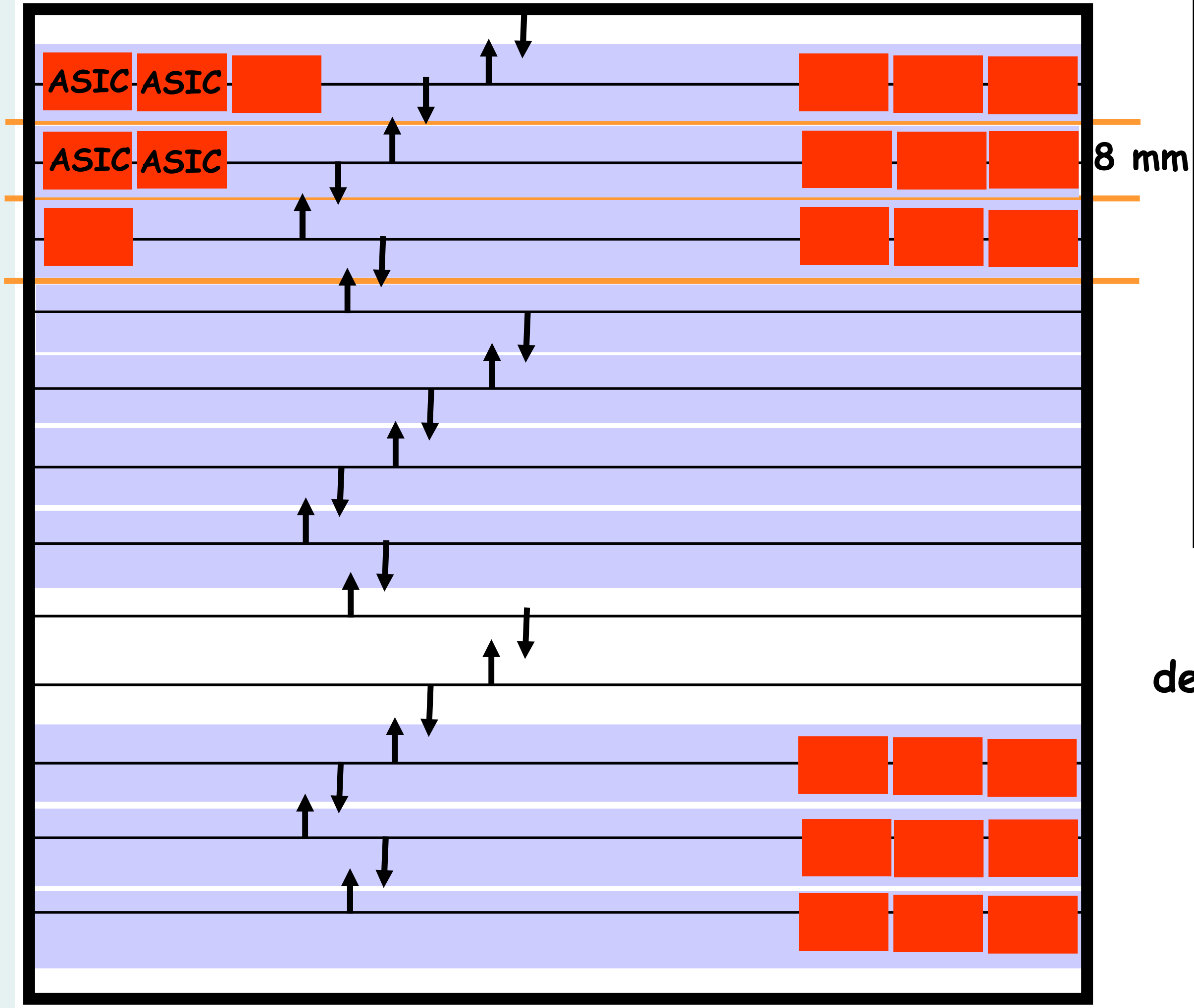
On-chip electronics

Drift of the signal electrons

incoming radiation

monolithic detector wafer, incl. first amplifying device

Top view of CDD detector

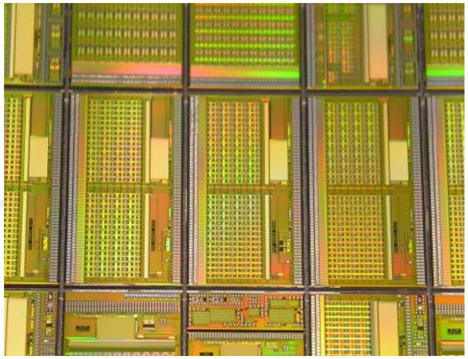


- Drift velocity : $V_n = \mu_n E$
- Vs = 10^7 cm/s in Si at 300 K
- at 15 x 10^3 V/cm
V_s = 8 x 10^6 cm/s
- we plan to operate at
E = 1 x 10^3 V/cm
- Breakdown at E = 40 V/µm
or 400 kV/cm

detector: 1024x1024 pixels
100 x 100 μm^2
120 ASICs needed

up to 200 subsequent time slices of 200 ns each should be recorded before pause

Functions of front end ASIC



Analog and digital electronics per channel:

preamp for slow and fast channel

filter amp. and time resolved S&H, 0 supression

analog storage of ampltitude and time

ADC

e.g. for 128 channels

Analog and digital electronics per channel:

20 x 11 bit if data valid
+ timing information (256 bit)

De-randomizer

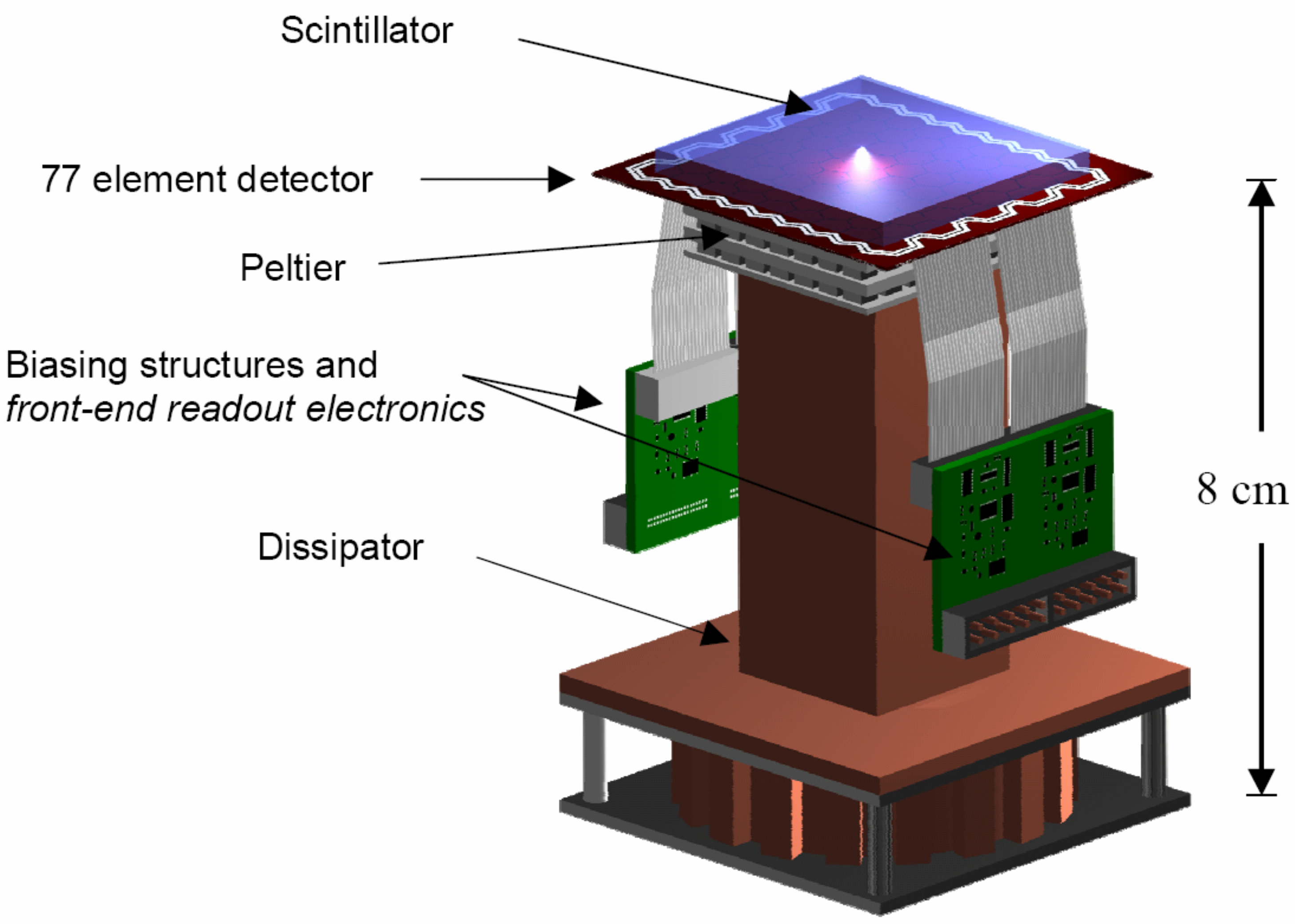
digital memory FIFO (512 kbit)

This would allow the detection for ≈ 2.000 valid subsequent ``X-ray´´ events from 128 channels depending on occupancy of a 1.2 x 0.4 cm^2 large area (e.g. 2 %). This could mean, that e.g. 150 X-ray flashes with 200 ns spacing could be handled before the next pause.

99.2 ms pause

Up to 150 bunches may be digested with 200 ns spacing

4 – side buttable devices



What is different from hybrid pixels

With an imaging pixel size of 100x100 μm^2 we cover a real area of 100 x 4.000 μm^2.

this leads to:

reduced problems for interconnections

extremely low event thresholds

more ASIC area for signal processing

no common mode (baseline) fluctuation

reduced power dissipation

principle allows for further reduction of pixel size without going to technological limits

shaping at 10 ns, ENC_{tot} = 50 e^- (rms), $\Delta t \approx 3$ ns

Threshold: at 5 σ, i.e. 250 e^-, i.e. 910 eV (!)

Summary (I)

- a large variety of pixellized detector systems in various sizes and formats is already available:

  3 side buttable pnCCDs

  2 side buttable DEPFETs

  3 side buttable CDDs

  single channel SDDs and SDD arrays in many sizes and degrees of pixellization

- special fast, large area detectors and low power, high speed analog and digital electronics must be developed to face the special needs of the DESY XFEL.

  The detectors and electronics for the LCLS at SLAC are already available (in principle, not in size, ...)

Summary (II)

- To be done: LCLS case (up to 120 frames per second)

  mechanical design studies
  electrical design studies
  system and software, DAQ, quick look analysis
  detector and front end electronics fabrication
  start with larger formats (4 – side buttable) } **3 -4 years**

- To be done: DESY XFEL case

  see LCLS case + +

  + development of prototypes of uhs
  detector system in the 1 – 5 MHz range } **6 -8 years**

Summary (III)

1. FFpnCCD:
400 x 400 pixel, size 150x150μm^2
i.e. A= 6x6 cm^2, d = 280 μm,
up to 40 frames per second, ENC=5 e

FSpnCCDs:
264x264 pixel, sizes: 75, 51, 36 μm□
2x2 cm^2, 1.4x1.4 cm^2, 0.9x1.4 cm^2, ENC=5 e
up 5.000 frames per second, 450 μm thick

in 2006/7:
formats of 512x512 with 75 μm□ and
51 μm□ will be fabricated on 450 μm in
frame store configuration

Summary (IV)

2. DEPFETs:

64 x 64 and 128 x 128 matrix performs wonderful on 450 µm Si with frame rates of 1000 fps

actual pixel sizes: 25 x 25 µm□ , 75 x 75 µm□ and 1.000 x 1.000 µm□

in 2006/7:

formats of 256x256 and 512x512

with 75 µm□ and 25 µm□ .

in addition: Macropixel with 300 µm□ and 500 µm□ pixel in a 64x64 format will be made.

Summary (V)

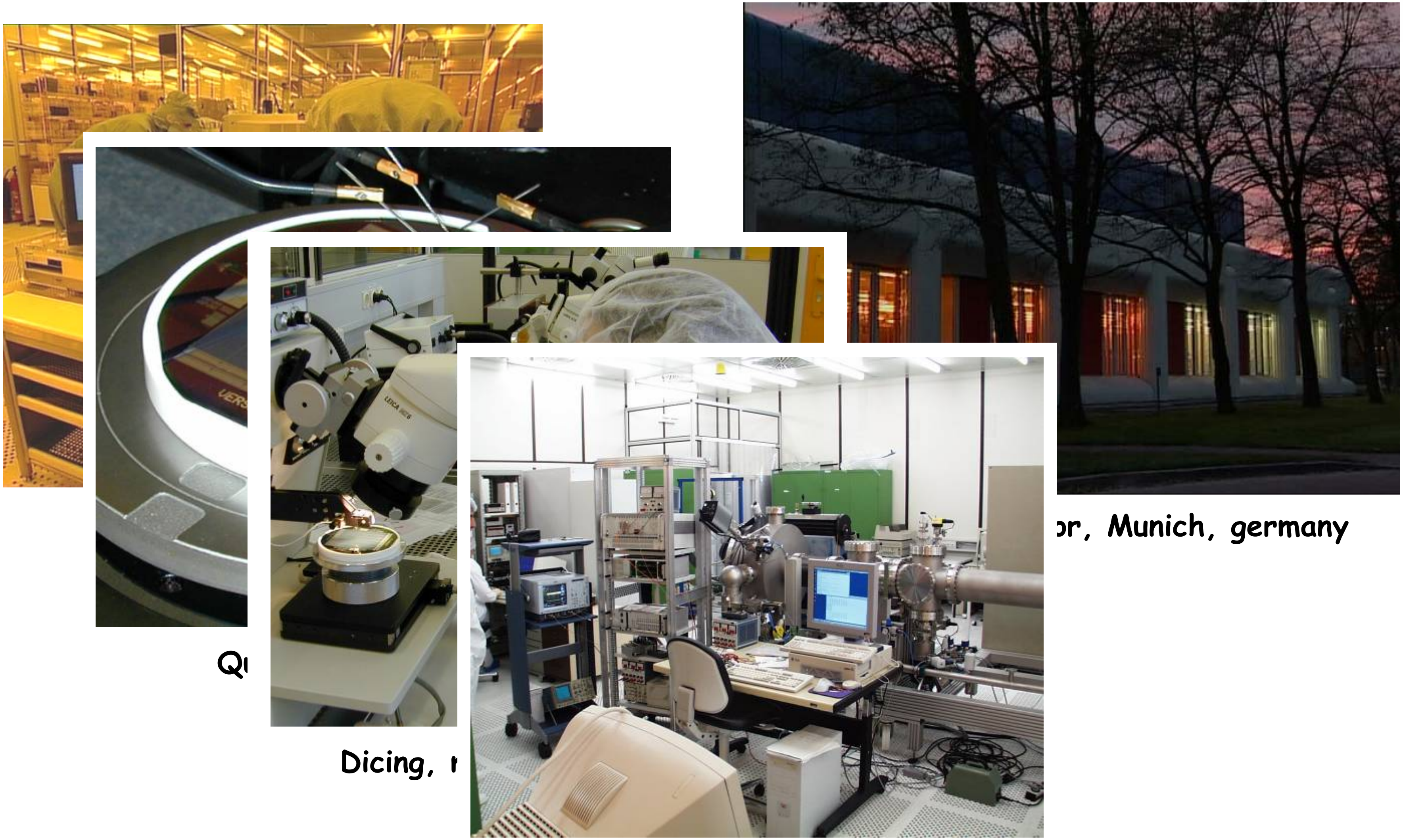
3. CDDs:

2.9 x 1.1 cm^2 is operational
with pixel sizes of 120x80 µm□
They are under test. ASIC electronics
is submitted. 100 k frames have been
performed. Developed as an electronic
collimator for Compton imaging

in 2006/7:

focus on ASIC development .
If interest is sufficient, redisign of CDD
with XFEL parameters. (e.g. size: 6x1.6cm^2
Test of interconnection, thermo-mecha-
nical concept, . . .)

The location

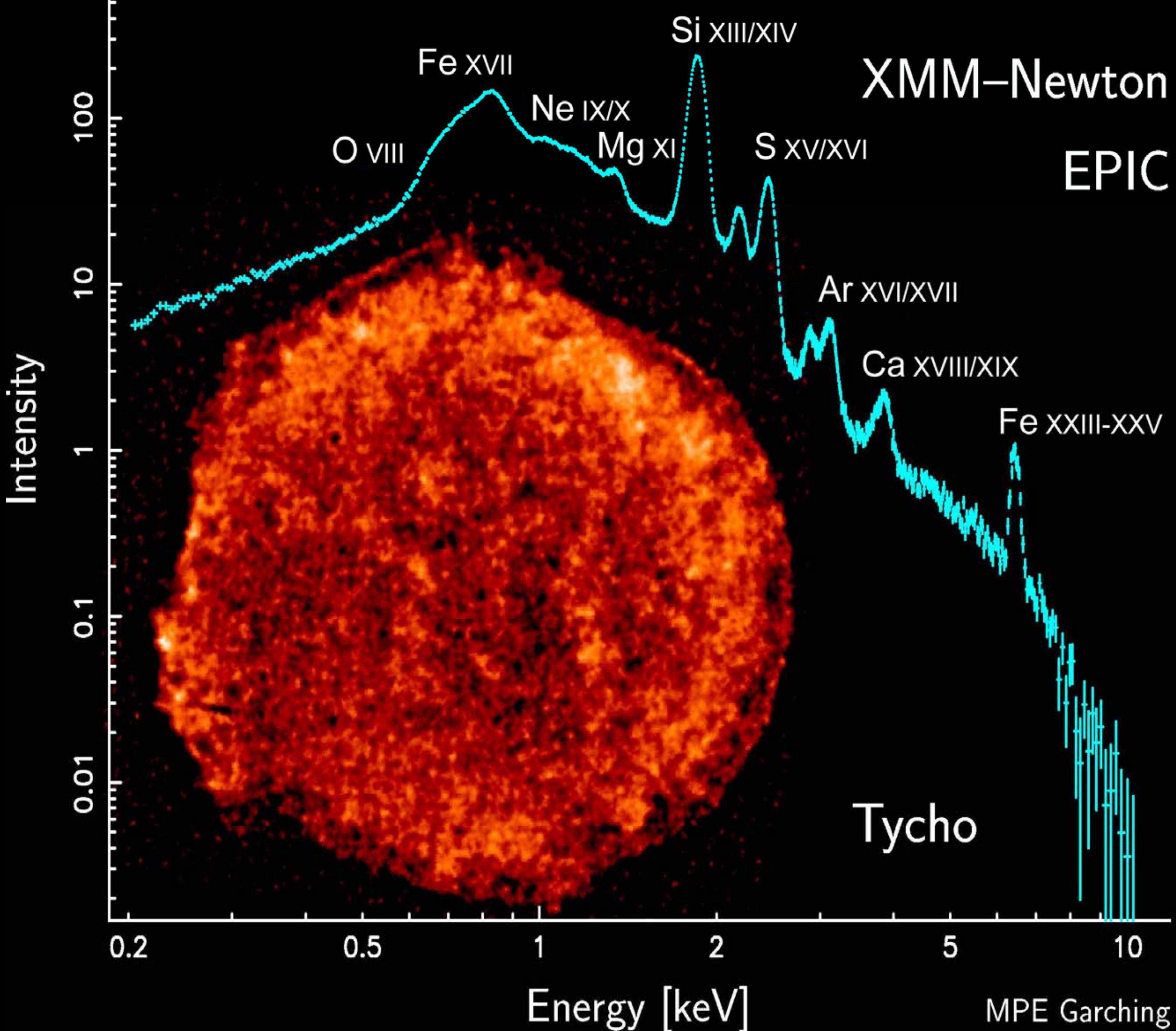


r, Munich, germany

Q

Dicing,

Device tests and operation


XMM–Newton
EPIC
Tycho
O VIII
Fe XVII
Ne IX/X
Mg XI
Si XIII/XIV
S XV/XVI
Ar XVI/XVII
Ca XVIII/XIX
Fe XXIII-XXV
Intensity
100
10
1
0.1
0.01
Energy [keV]
0.2
0.5
1
2
5
10
MPE Garching