DSSC - an X-ray Imager with Mega-Frame Readout Capability for the European XFEL

Ladislav Andricek, MPI Halbleiterlabor, on behalf of the DSSC Consortium

DSSC consortium

M. Porro[1,2], L. Andricek[2,3], S. Aschauer[8], L. Bombelli[4,5], A. Castoldi[4,5] , I. Diehl[7], F. Erdinger[6], L. Strueder[1,2], G. De Vita[1,2], S. Herrmann[1,2], D. Muentefering[1,2], G. Weidenspointner[1,2], A. Wassatsch[2,3], P. Lechner[8], G. Lutz[8], C. Sandow[8], P. Fischer[6], A. Kugel[6], T. Gerlach[6], K. Hansen[7], C. Reckleben[7], P. Kalavakuru[7], H. Graafsma[7], C. Wunderer[7], H. Hirsemann[7], C. Fiorini[4,5], S. Facchinetti[4,5], C. Guazzoni[4,5], D. Mezza[4,5], V. Re[10], M. Manghisoni[10], U. Pietsch[9], T. Sant[9]

1) Max Planck Institut fuer Extraterrestrische Physik, Garching, Germany
2) MPI Halbleiterlabor, Muenchen, Germany
3) Max Planck Institut fuer Physik, Muenchen, Germany
4) Dipartimento di Elettronica e Informazione, Politecnico di Milano, Milano, Italy
5) Sezione di Milano, Italian National Institute of Nuclear Physics (INFN), Milano, Italy
6) Zentrales Institut für Technische Informatik, Universitaet Heidelberg, Heidelberg, Germany
7) Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
8) PNSensor GmbH, Muenchen, Germany
9) Fachbereich Physik, Universitaet Siegen, Siegen, Germany
10) Dipartimento di ingegneria industriale, Università di Bergamo, Bergamo, Italy

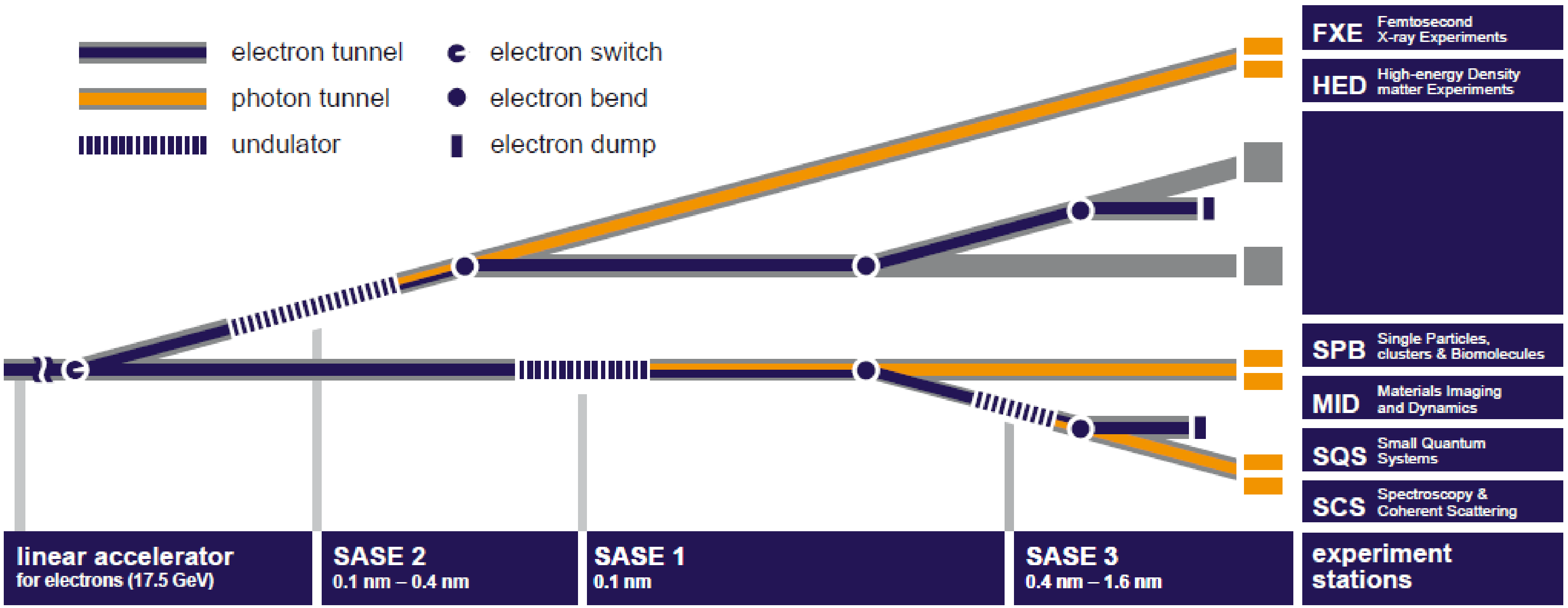
outline

- The European XFEL
- Detector System Overview
- Non-Linear DEPFET Detector working principle
- Detector expected performance:
  - Speed and Noise
- Summary

The European XFEL – DESY, Hamburg

- XFEL facility – overall 3.4 km
  - ▷ electron LINAC
    - Length: 1.6 km
    - Energy: 17.5 GeV (nominal)
  - ▷ beam distribution stations
    - → undulators (100 … 200 m)
  - ▷ 5 beam lines to the experiment stations

experiment end stations



Beamline	X-ray features	Proposed instruments
SASE 1	~12 keV High coherence High flux 3rd harmonic	PCS 1 – X-ray Photon Correlation Spectroscopy FDE 1 – Femtosecond Diffraction Experiments SPB 1 – Single Particles and Biomolecules
SASE 2	3.1 – 12.4 keV High coherence High flux	CXI 1 – Coherent X-ray Imaging HED 2 – High Energy Density XAS 2 – X-ray Absorption Spectroscopy
SASE 3	0.25 – 3.1 keV High coherence High flux 3rd harmonic	HED 1 – High Energy Density SQS 1 – Small Quantum Systems XAS 1 – X-ray Absorption Spectroscopy SQS 2 – Small Quantum Systems PCS 2 – X-ray Photon Correlation Spectroscopy CXI 2 – Coherent X-ray Imaging
U 1, U 2	15* – 90 keV	FDE 2 – Femtosecond Diffraction Experiments CXI 3 – Coherent X-ray Imaging RAD 1 – Research And Development

3 Detector systems at the end stations

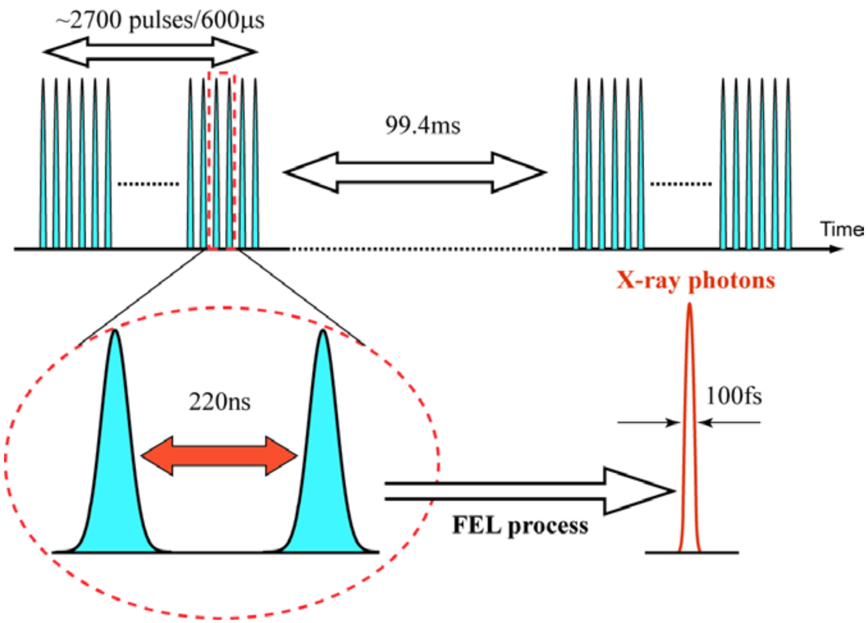
-: All are 1 Mpix 2D X-Ray cameras

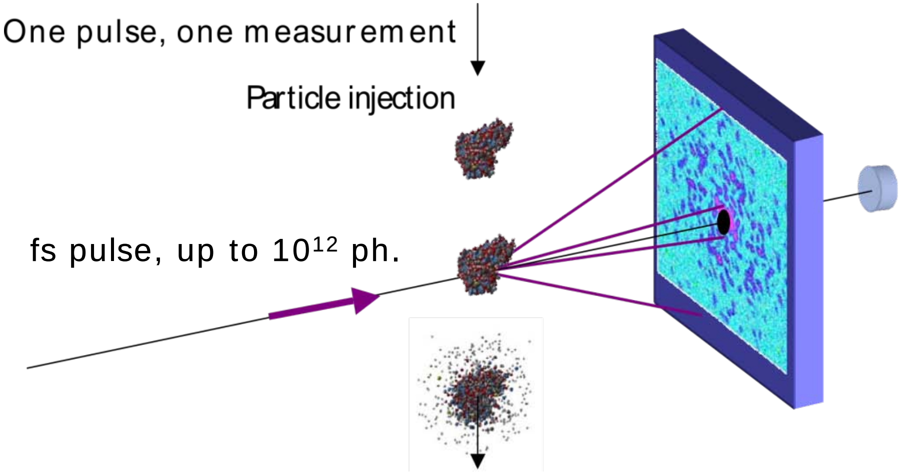
-: LPD – **L**arge **P**ixel **D**etector

-: AGIPD - **A**daptive **G**ain **I**ntegrating **P**ixel **D**etector

-: DSSC - **DE**PFET **S**ensor with **S**ignal **C**ompression

bunch structure (Tesla, ILC → XFEL)





- e^- come in "trains", ~2700 bunches/train, 600 µs long, 10 Hz train rate
- bunch spacing 220ns (4.5 MHz)
- each bunch gives an intense x-ray flash of ~100 fs duration

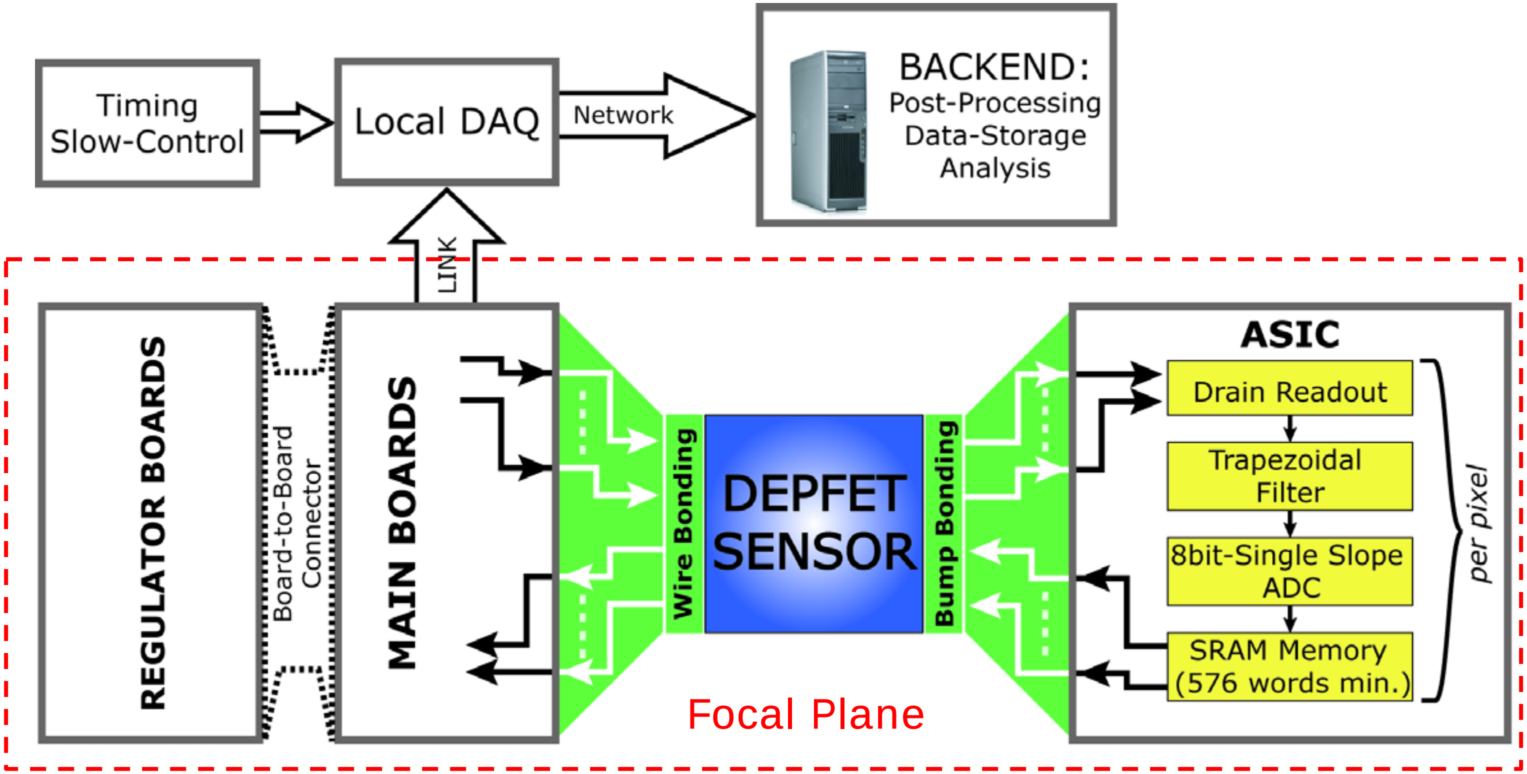
Key Requirements for the camera:

- Take "snap shot" with a 1Mpix camera with every flash
- Detect single low energy X-rays (≥0.5 keV → 140 e-h+ pairs in Si)
- Detect up to 10^4 X-rays with resolution better than Poisson limit
- Possibility to process ≥500 pulses in each burst

DSSC – design parameters

Parameter	Specification
Energy range	0.5 … 25 keV (optimized for 0.5 … 6 keV)
Number of pixels	1024 x 1024
Sensor Pixel Shape	Hexagonal
Sensor Pixel pitch	~ 204 x 236 μm^2
Dynamic range / pixel / pulse	> 6000 photons @1 keV
Resolution (S/N >5:1)	Single photon @ 1 keV (5 MHz)
Electronics noise	< 50 electrons r.m.s.
Frame rate	Variable, up to 5 MHz
Stored frames per Macro bunch	≥ 576
Operating temperature	-20˚C optimum, RT possible
Ambient	Vacuum, ~10^{-6} mbar

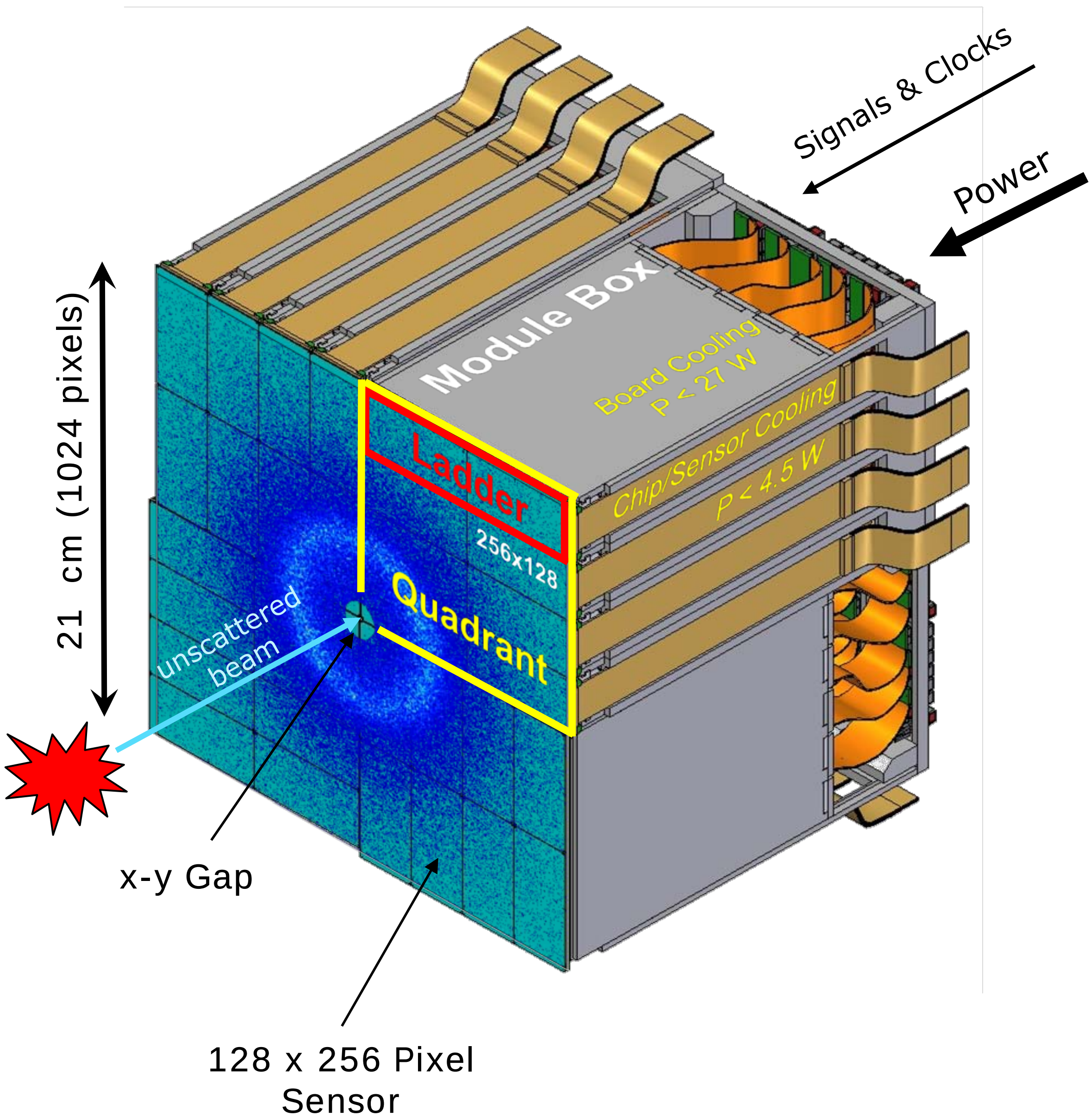
system block diagram



- System Overview

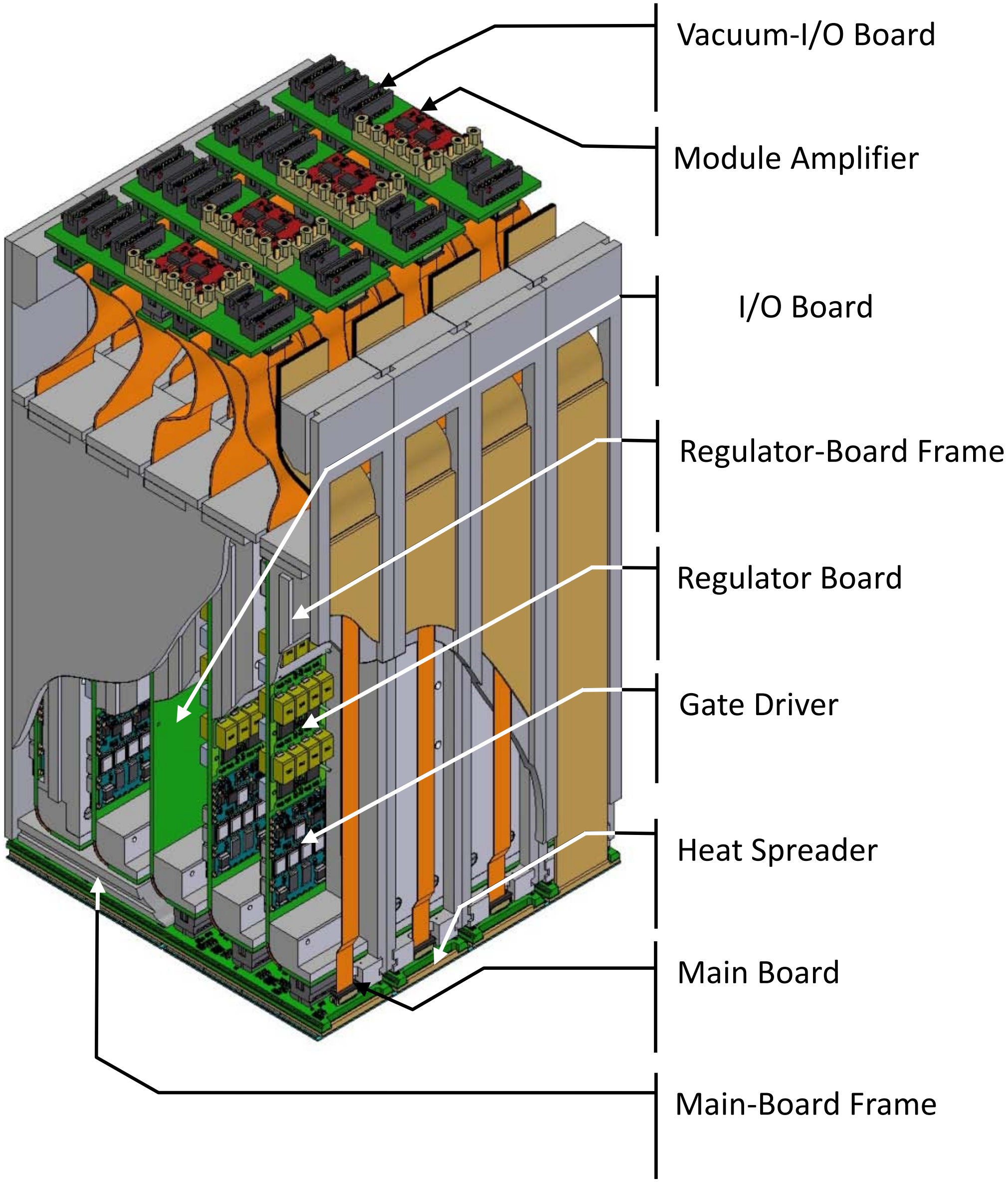
  - ▷ Hybrid pixel detector with DEPFET active pixels
  - ▷ r/o ASICs bump bonded, one bump per pixel
  - ▷ Front- end amplifier, ADC, and SRAM per pixel
  - ▷ Digital data are sent of the focal plane during the train gap (~100ms)
  - ▷ Power cycling: sensors and analog f/e in stand-by during train gap

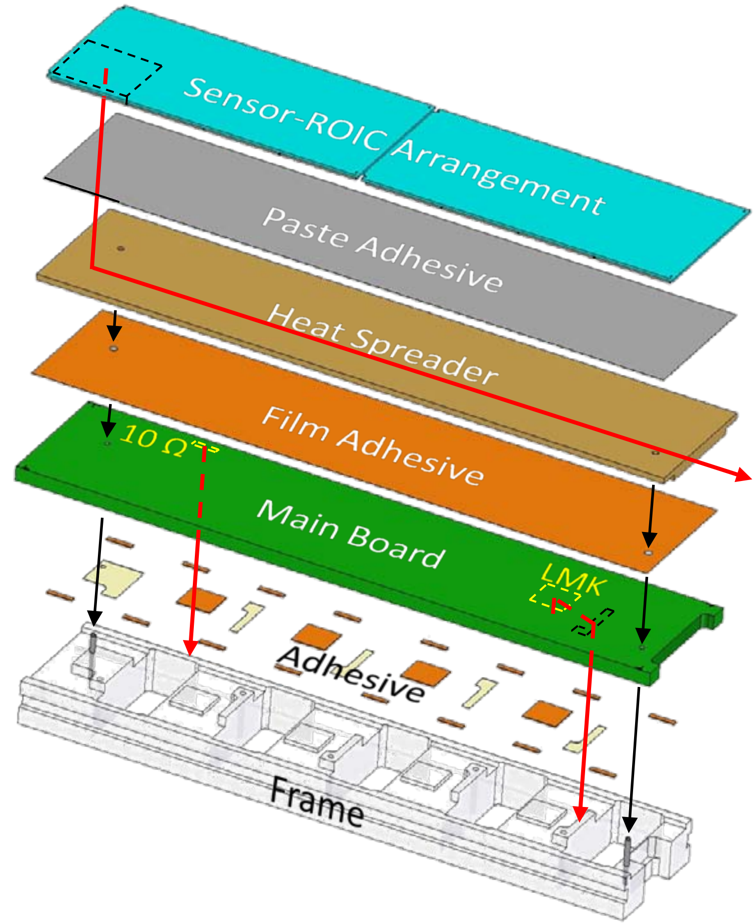
focal plane overview, power budget



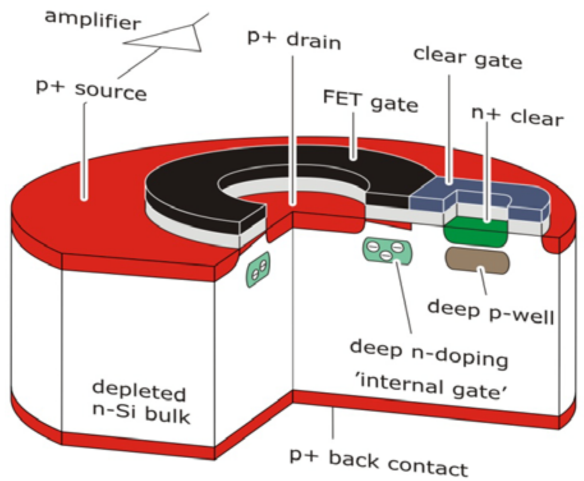
- focal plane
  - ▷ Sensitve area 21x21 cm^2
  - ▷ 4 quadrants
  - ▷ 4 ladders / quadrant
  - ▷ 2 pixel sensors / ladder
  - ▷ sensor format 128 x 256 pixels
  - ▷ 8 r/o asics / sensor
  - ▷ dead area: 14.5 %
  - ▷ central hole for beam dump
- Power budget
  - ▷ 1-2 mW/pixel, 1-2kW peak power
  - ▷ Power cycling 1/100 → ~20W mean
  - ▷ Thermal design under way
  - ▷ Voltage regulators for power delivery

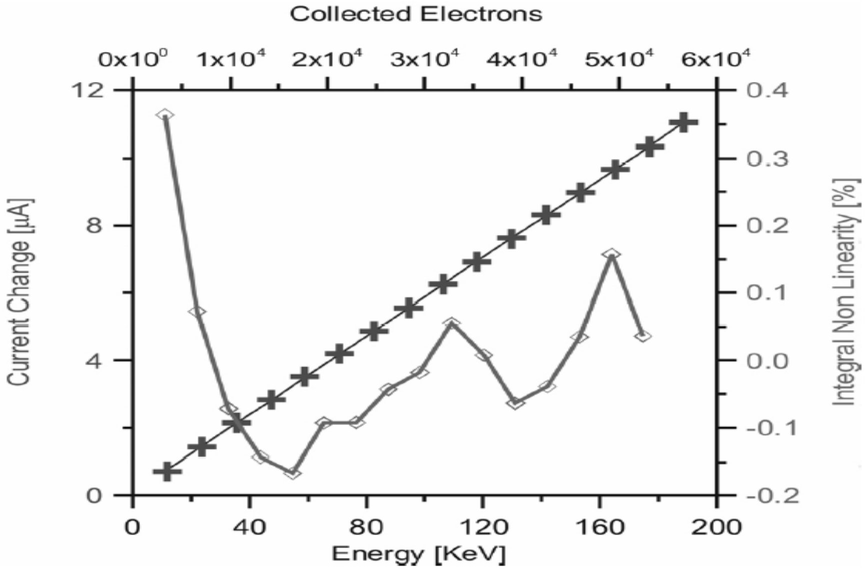
A quadrant and the ladder components

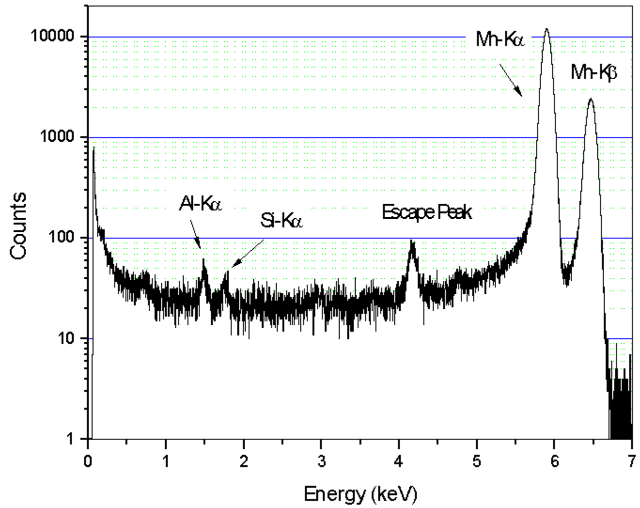




DEPFET Active Pixel Sensor

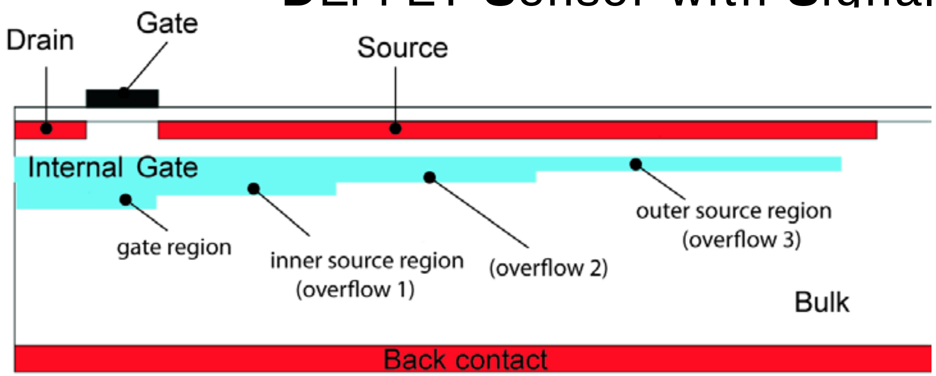




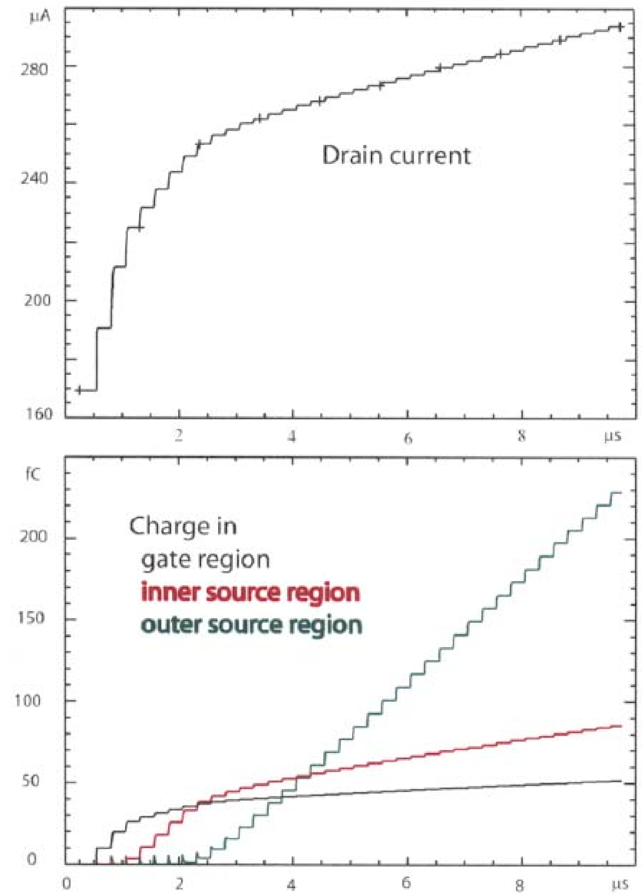


- Depleted P-channel FET
  - ▷ Charge to current conversion, amplification → low noise
  - ▷ Fully depleted, back side illuminated → low energy
  - ▷ Pixel size ~100µm
    - ↳ **Add drift rings for larger pixel**
  - ▷ Linear response up to 10^5 electrons tested
    - ↳ **Up to ~10^6 e^- at XFEL, large signal saturates FE**
  - ▷ Usually column parallel matrix read-out ("rolling shutter")
    - ↳ **Fully parallel read-out for highest frame rates**
- DEPFET Matrix
  - ▷ 300 Hz frame rate, 25 µs row time
    - ↳ FWHM 126 eV, ENC 4.9 e^- @Mn Kα

DEPFET Sensor with Signal Compression - DSSC

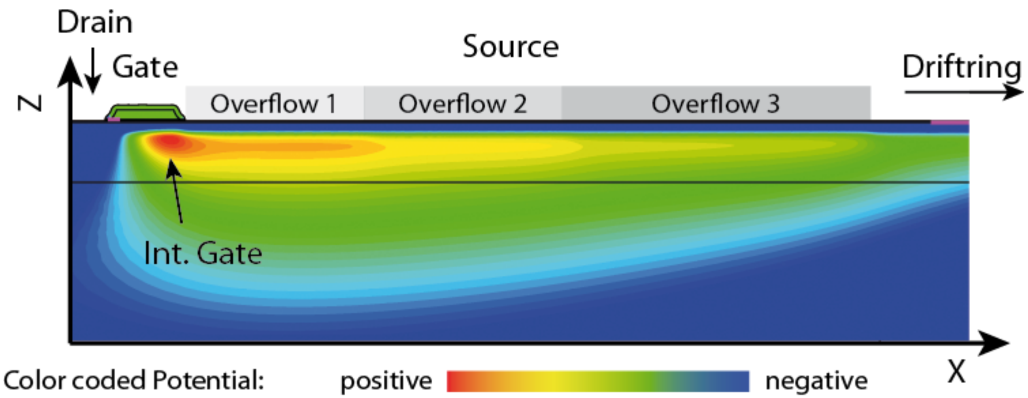


Device Simulation

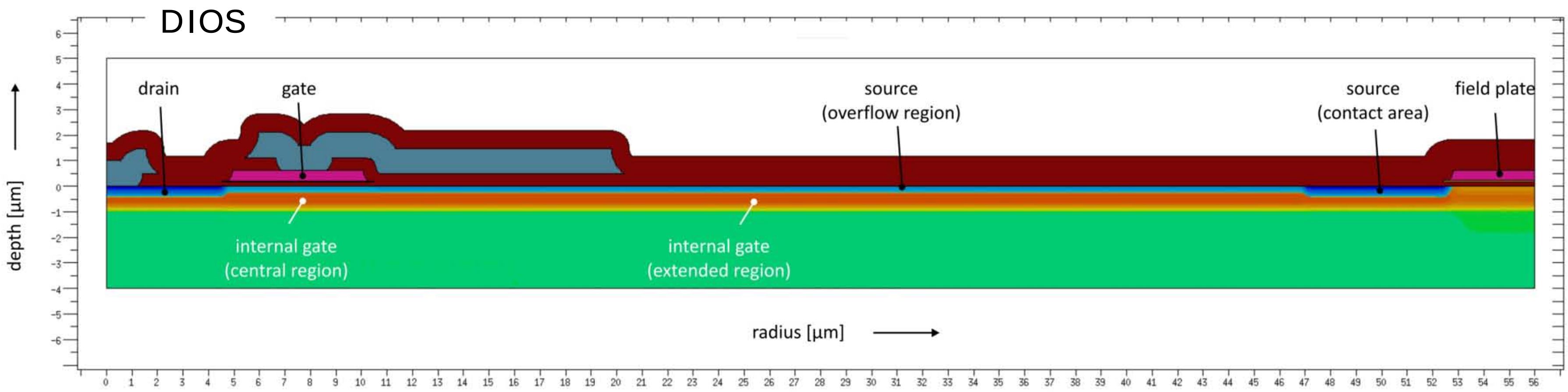


Inject 10fC, 37 steps, every 250ns

- The internal gate extends into the region below the source
- Small signals collected directly below the channel
  - ↳ Most effective, large signal
- Large signals spill over into the region below the source
  - ↳ Less effective, smaller signal
- staggered potential inside internal gate by varying impl. doses

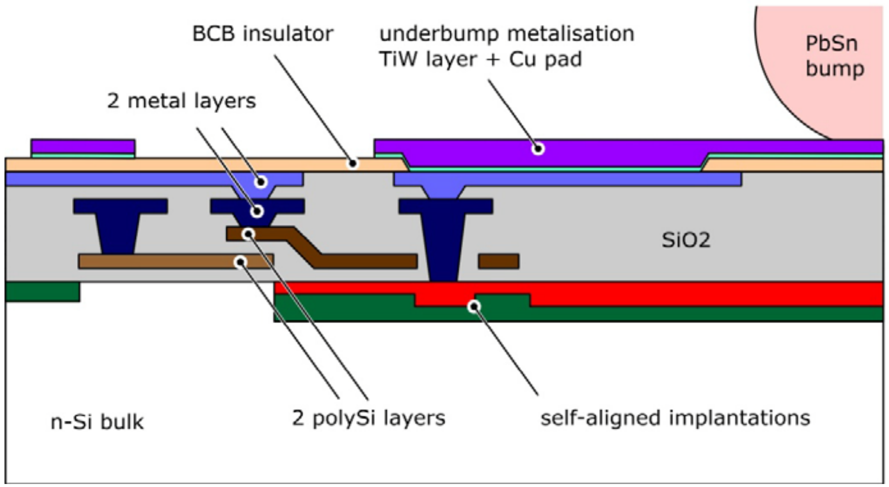


Technology



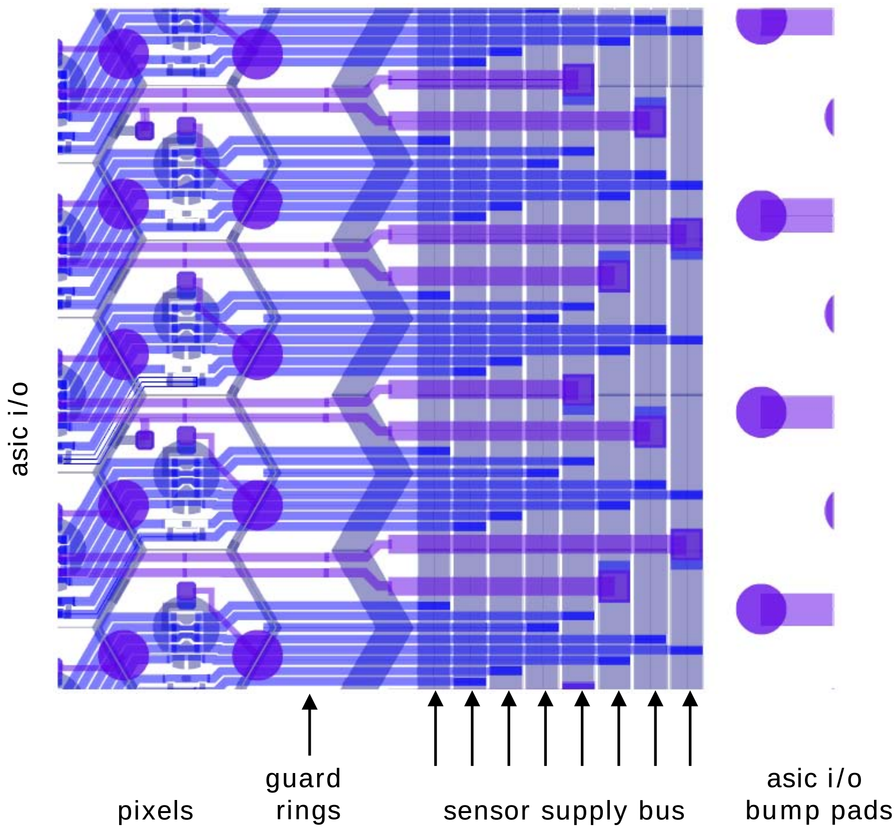
- complex technology, verified by simulation
  - 12 implantations
  - ~30 masks
  - 2 poly-silicon layers
  - 2 aluminium layers
  - 3rd metal layer in Cu as UBM and re-distribution layer

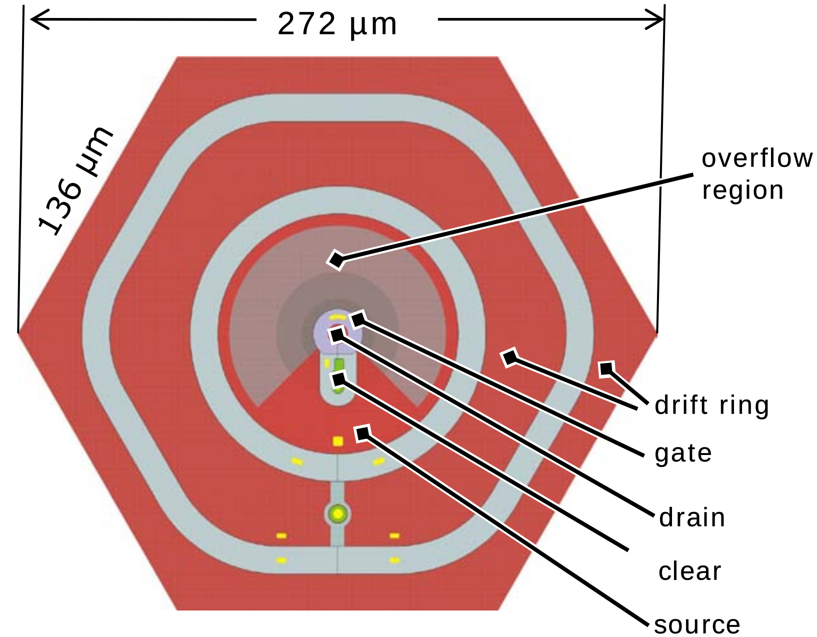
- Thin radiation entrance window at the back
  - Fully customized double sided processing



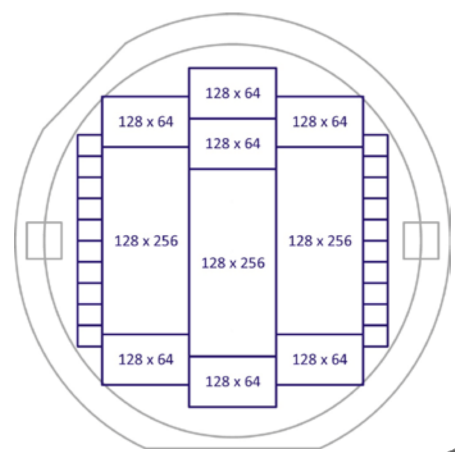
Sensor - Pixel Layout

- hexagonal pixel shape
  - side 136 µm, A=48144 µm^2
  - pitch x: 204µm, pitch y: 236µm (C4 bumping)



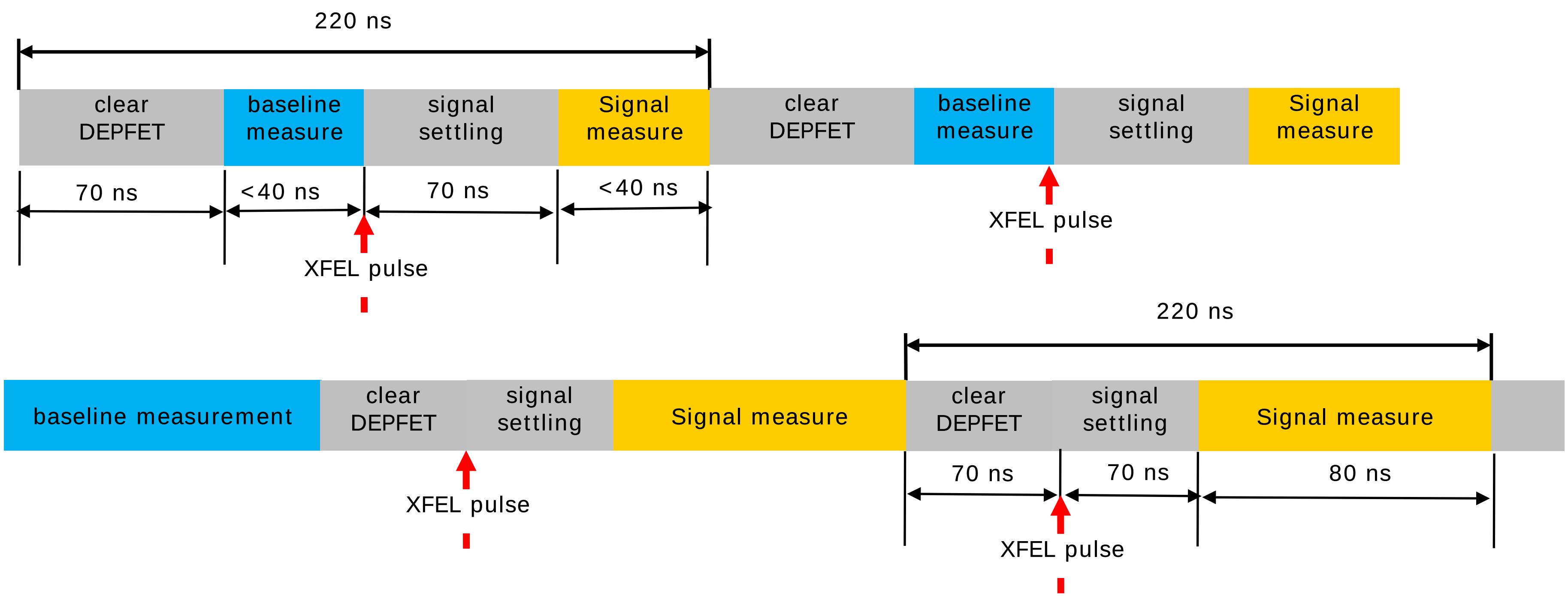


- wafer (150 mm Ø) floor plan
  - DSSC sensor matrix: 62x30 mm^2



why hexagonal? answ.: speed!!

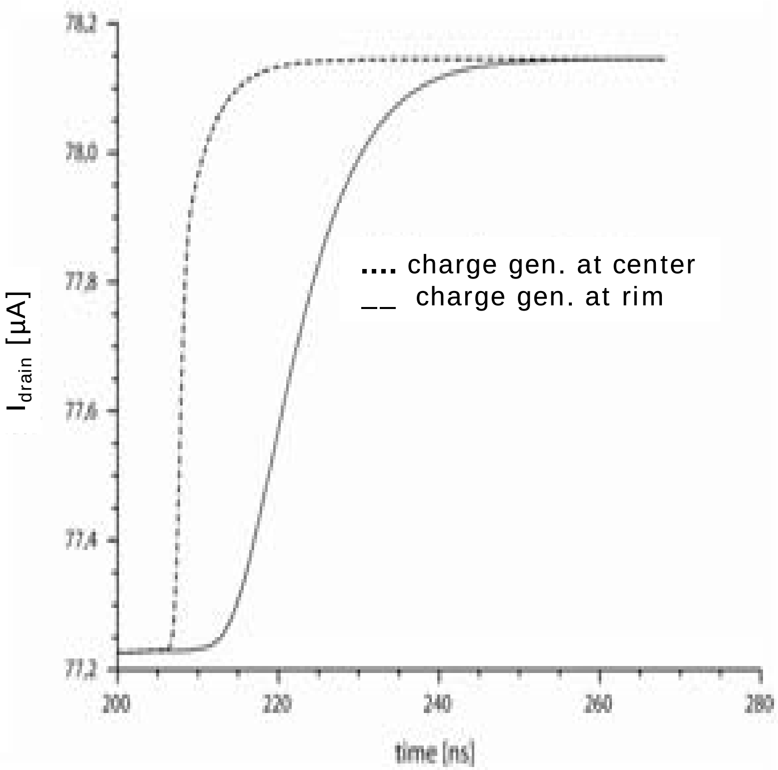
- two read-out modes possible: double and single sampling, both make use of beam trigger

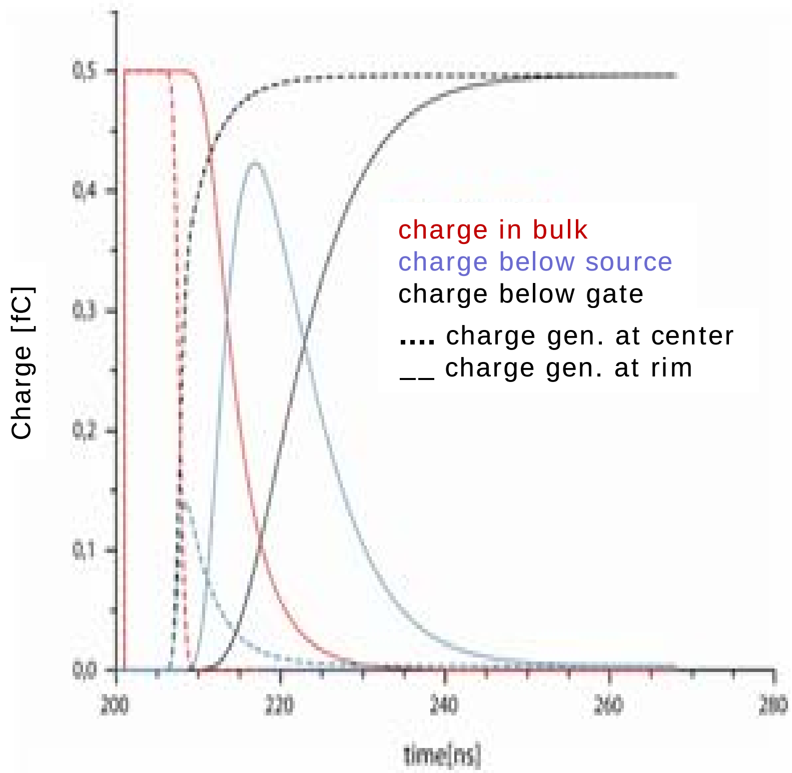


- very little time for signal collection in the DEPFET and signal processing
- how fast is the DEPFET?
- and how noisy is the fast signal processing?

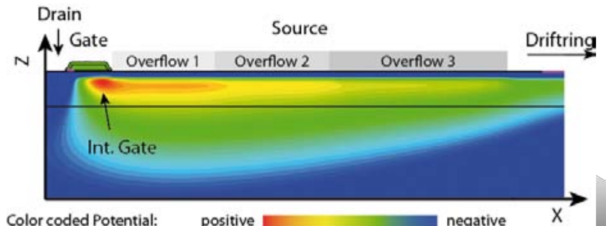
charge collection

- simulated time response of the DEPFET in cylindrical approximation

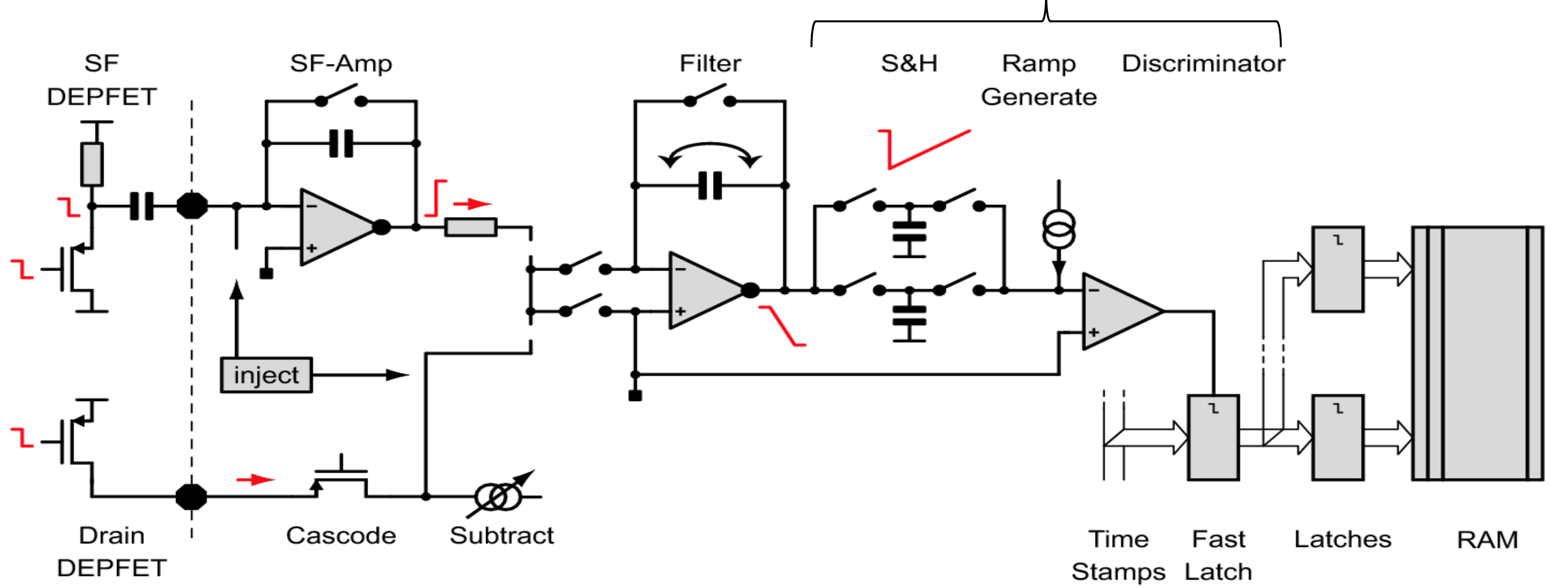




- inject 0.5 fC (~3000 e-) close to the back side at 202 ns
  - charge arrives at the internal gate after ~25 ns (if central)
  - and after ~65 ns (at the edge)
- charge collection takes more time in rectangular pixels

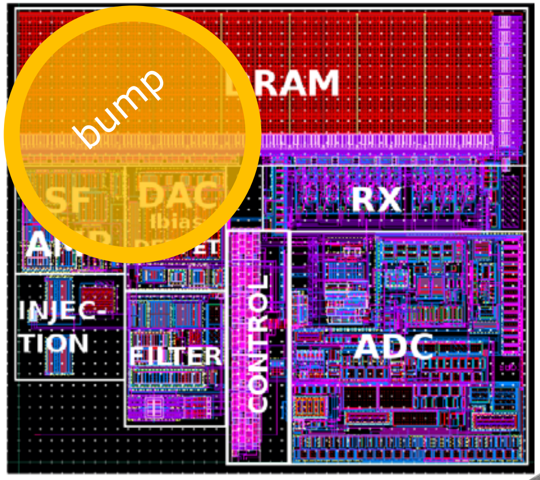


read-out electronics



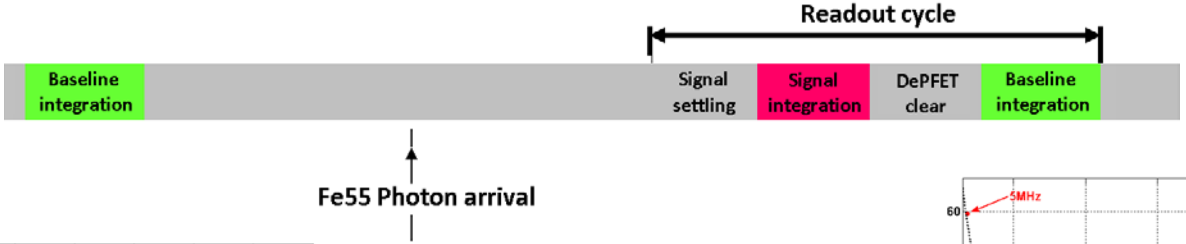
- ASIC with 4096 readout channels, IBM 130nm, C4
- two front-end options
  - current read-out (baseline)
  - source follower read-out
- filter, single slope 8 bit ADC, in-pixel memory (SRAM)
- all blocks designed, test chips submitted and tested

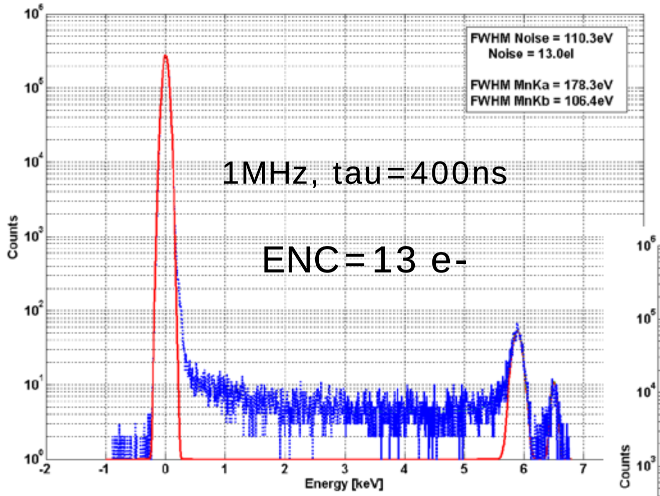
pixel with 236×204 μm²

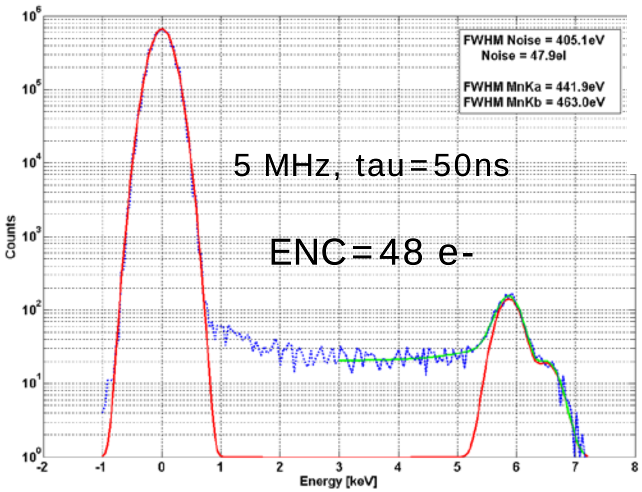


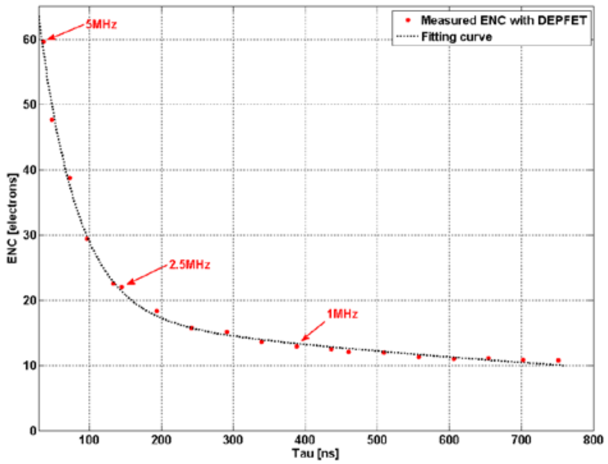
front-end noise

- test chips (drain read-out, filter, no ADC yet) connected to conventional DEPFETs close to expected DSSC values
- noise measurements with Fe55 source and various integration times
  - Slightly modified readout sequences due to asynchronous photon arrival times









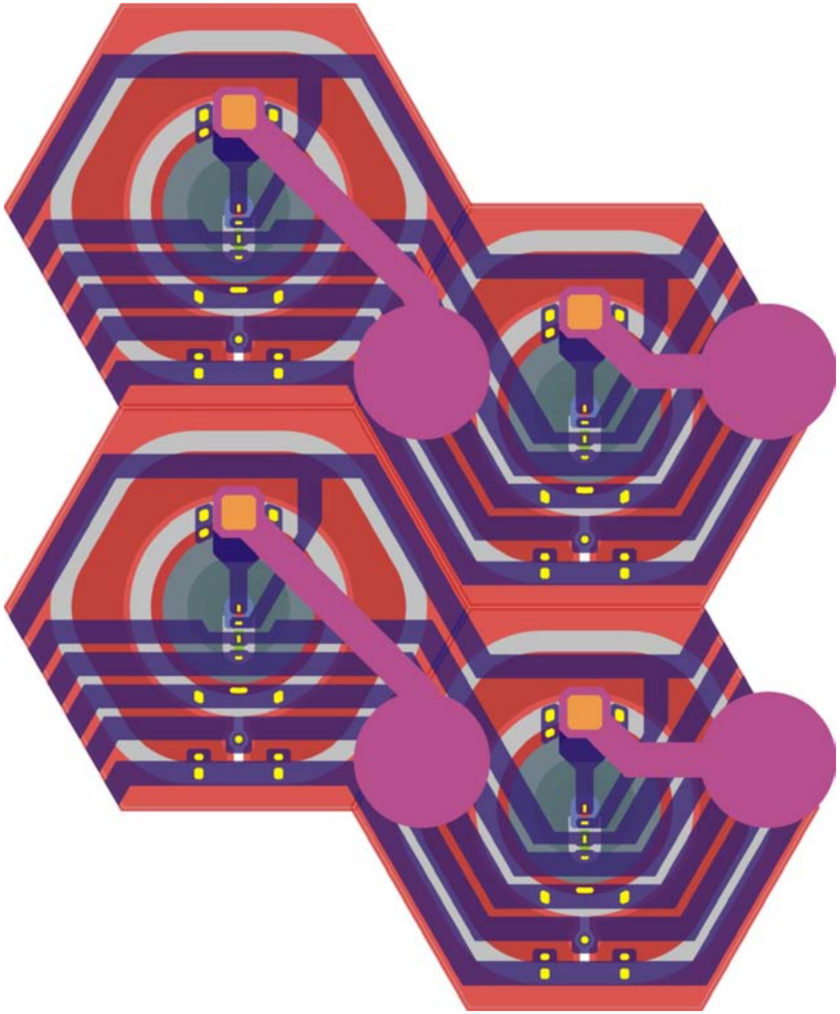
Summary

- We are developing a Pixel Detector system for the European XFEL based on innovative non-linear DEPFETs as the first elements of the front-end electronics
- In our fully parallel readout scheme, the signals coming from the pixels are filtered, digitized and stored in the focal plane
- Device and circuit simulations have shown that:
    - It is possible to achieve 5MHz frame readout
    - A dynamic range of at least 6000 Photons at 1keV per pixel can be achieved
    - A single 1keV photon resolution (S/N>5) is reachable @ 5MHz preserving the high dynamic range
- Measurements on first ASIC blocks show performance in good agreement with simulations and a noise below 50 el. r.m.s. at the maximum operating speed
- First DEPFET with signal compression to be finished these days
- The first DSSC sensor production comprising full-size sensors started in May 2011

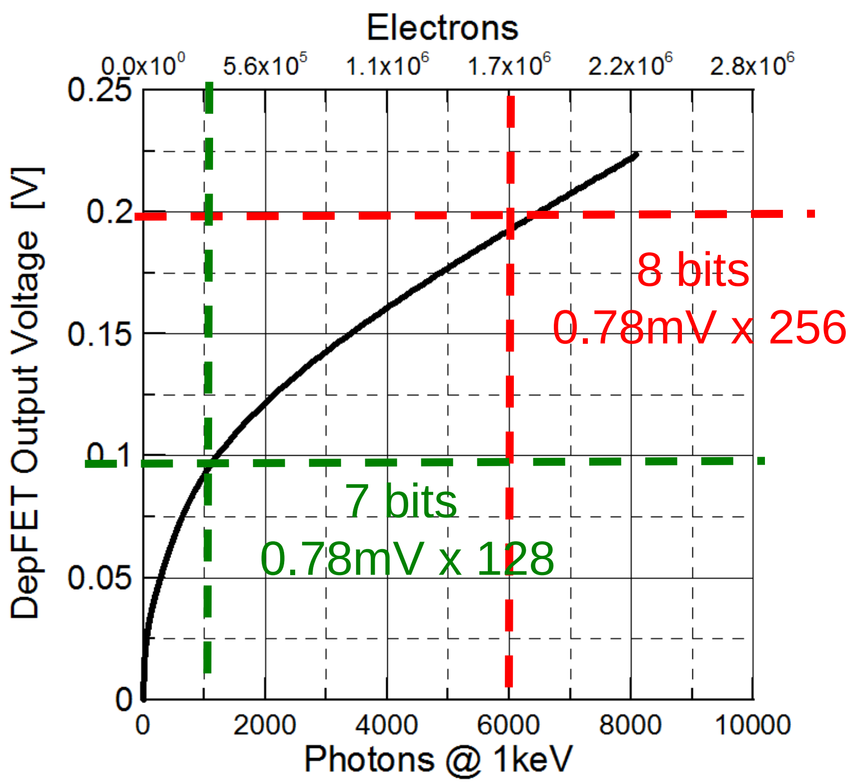
Backup slides follow

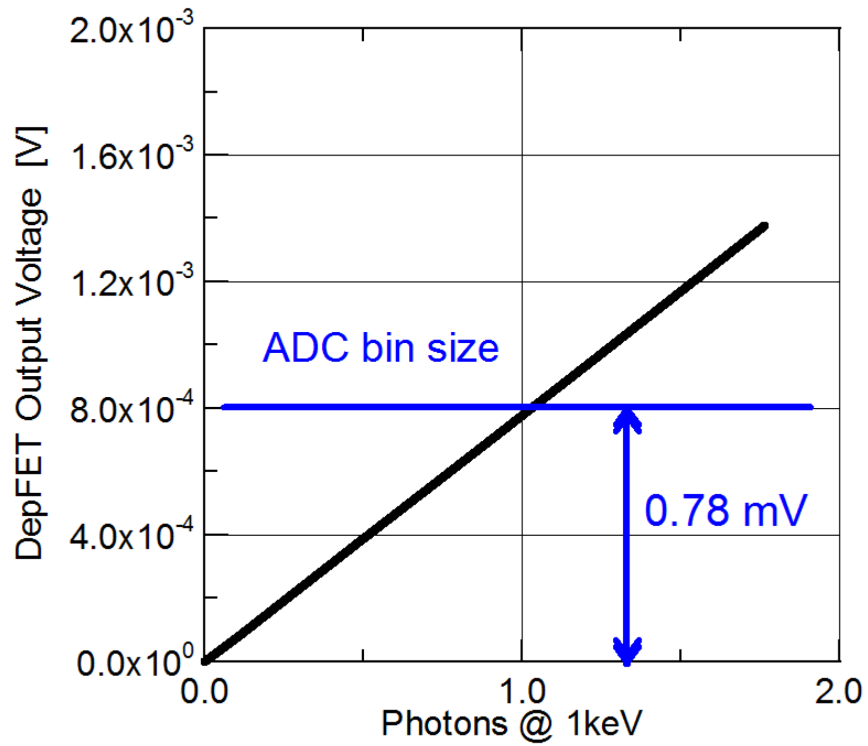
pixel layout

- 2 SDD-like drift rings
- zig-zag row-wise connections
- irregular routing from hexagonal sensor pixels to rectangular asic cells in copper ubm layer
- optional use of ubm layer as 3rd conductive layer



Achievable dynamic range





- The dynamic range depends on:

  The shape of DEPFET curve

  The number of ADC bits

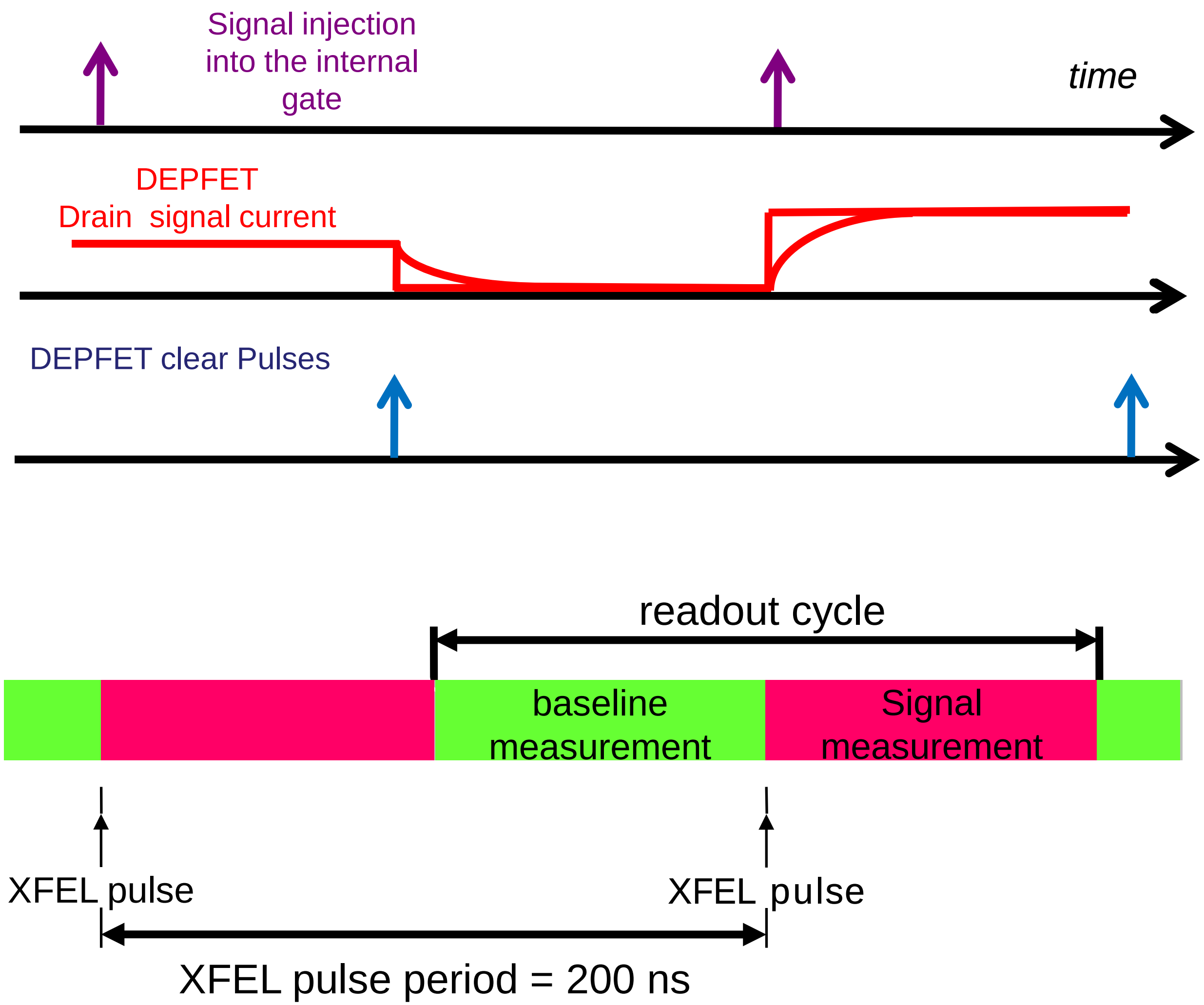
- The gain of the first region defines the bin size

1 ph @1keV → 1 bin = 0.78 mV

7 bits → 0.78mV x 2^7 = 100 mV
→ 1245 photons

8 bits → 0.78mV x 2^8 = 200 mV
→ 5850 photons

DEPFET readout scheme



- The signal arrival time is known
- One measurement is composed of the difference of two evaluations:

  Baseline

  Baseline + signal
- A time variant filter is used
- In the real case some time must be reserved for the settling time of the DEPFET output both for :

  Signal Build up

  Signal clear
- Less than100ns out of 200ns are used to process the signal

System noise and resolution

- The noise sources of the system are:

  (a) Electronics Noise: DEPFET, Analog Front-End

  (b) Quantization noise introduced by the ADC

  (c) Noise of the Poisson distributed Photon Generation Process

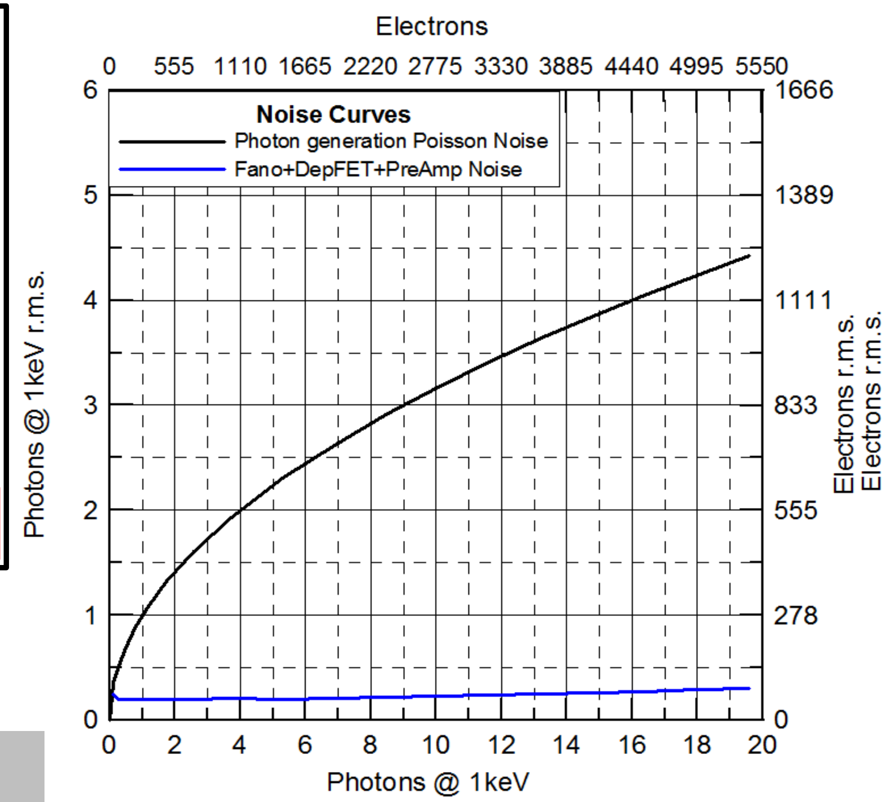
- The non-linear characteristic of the DEPFET makes (a) and (b) *Signal Dependent*

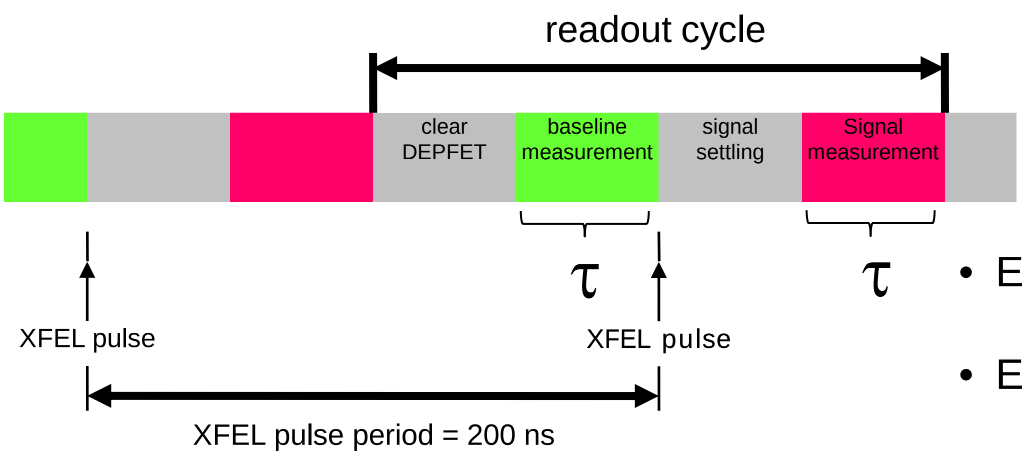
- The quadratic sum of (a) and (b) must be negligible with respect to (c): the Photon Generation Noise must be dominant

Electronics noise

$$ENC^2 = \frac{a}{\tau} C_{EQ}^2 A_1 + 2\pi a_f C_{EQ}^2 A_2 + b\,\tau A_3$$

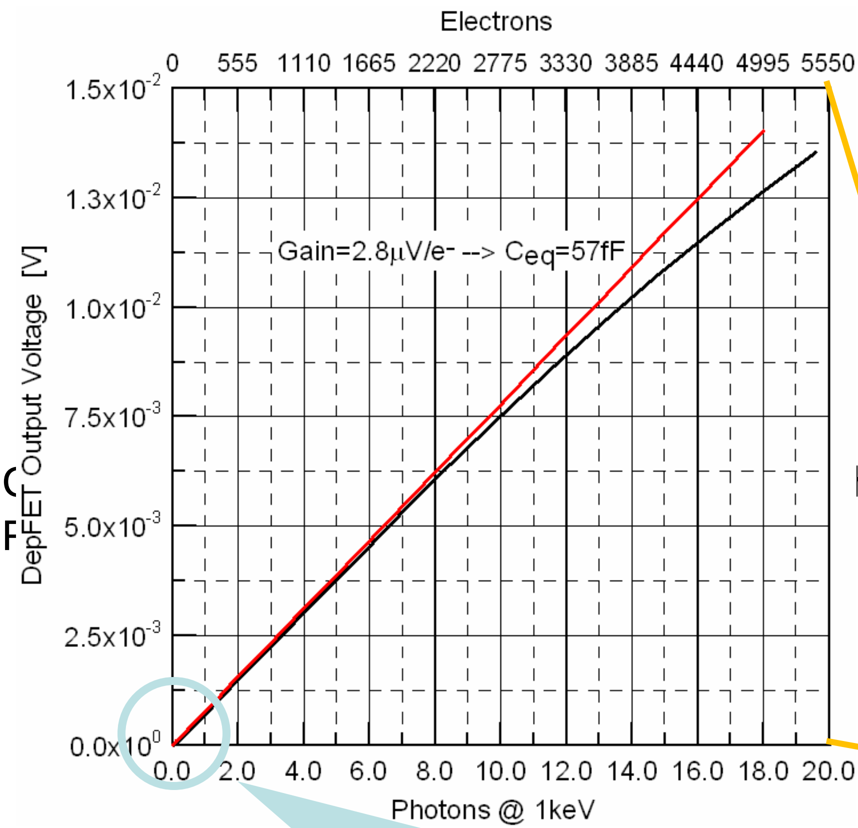
- C_{EQ} DEPFET equivalent input capacitance (decreases as the input signal increases)
- a, a_f, b physical noise sources
- $A_1\, A_2\, A_3$ filter parameters (better for current readout)
- τ filter shaping time (200ns processing time)

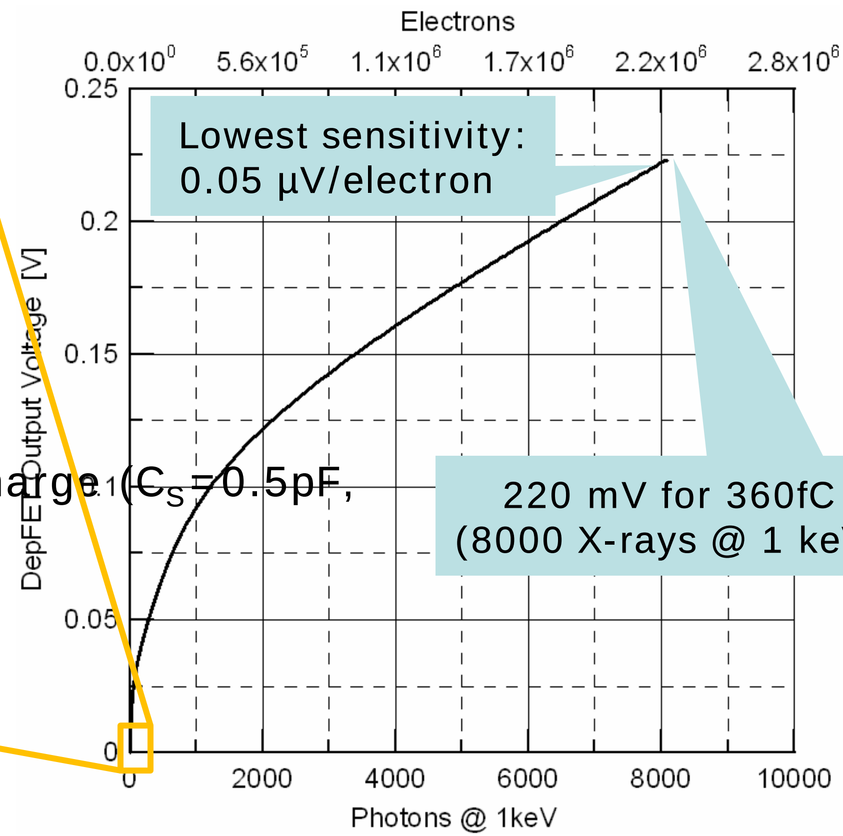




- ENC for small signals: 45 electrons r.m.s.
- ENC for large signals: 2300 electrons r.m.s.

Non-Linear DEPFET Characteristic



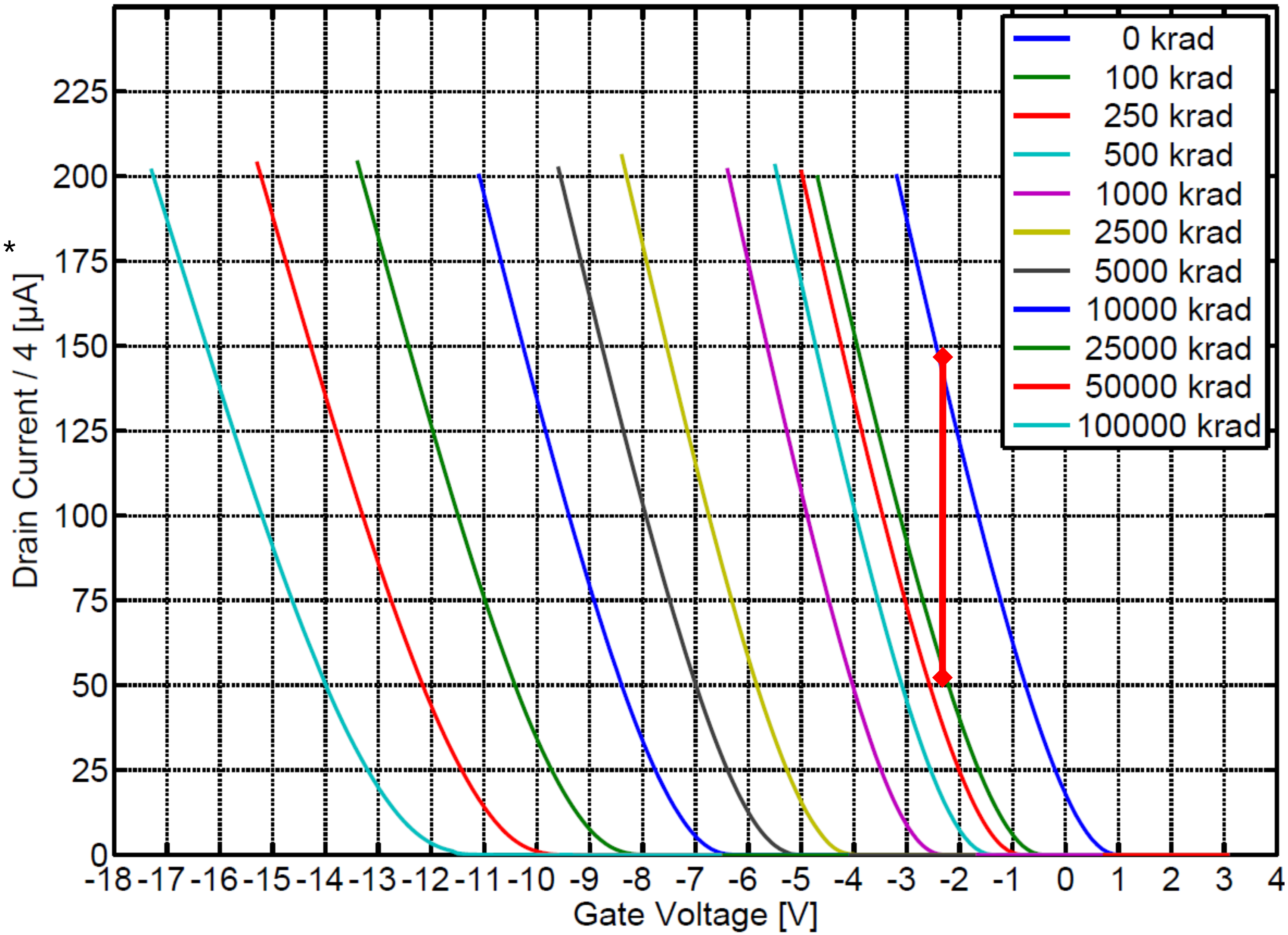


harge (C_S = 0.5pF,

Lowest sensitivity:
0.05 µV/electron

220 mV for 360fC
(8000 X-rays @ 1 keV)

Highest sensitivity: 2.8 µV/electron
(→ 6.2V output swing without compression!)


Drain Current / 4 [µA] *
Gate Voltage [V]
0
25
50
75
100
125
150
175
200
225
-18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4
0 krad
100 krad
250 krad
500 krad
1000 krad
2500 krad
5000 krad
10000 krad
25000 krad
50000 krad
100000 krad