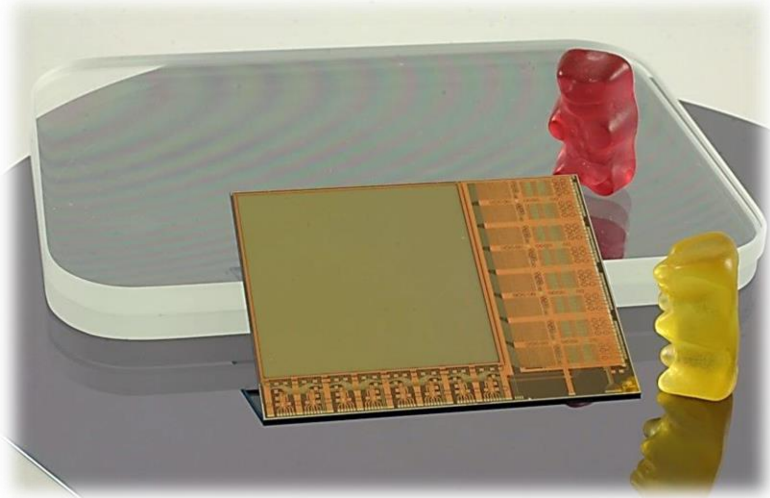
Sensor ideas for photon science detectors developed at the MPG Semiconductor Lab

Rainer Richter on behalf of the MPG Semiconductor Lab

Outline:

- About the Semiconductor Lab.
- Sensor ideas with potential usability in photon science
- Proposals to overcome limitations of (pn)CCDs



MPG Semiconductor Laboratory (German: MPG Halbleiterlabor - HLL)

Located in the south-east of Munich on the Siemens Campus in Neuperlach

25 employees: scientists, engineers and technicians

+ guest scientists, engineers and students

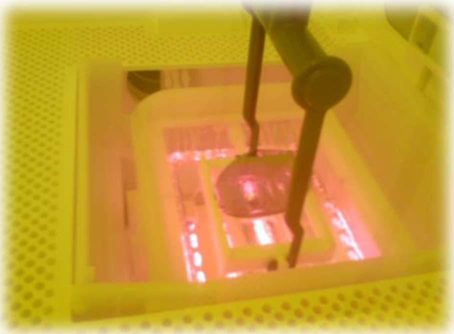
MPG HLL is a central institution (ZE) of the Max-Planck Society

doing fully depleted silicon radiation sensors

with integrated electronics optimized for different scientific projects

Inside HLL – Sensor Fabrication

cleaning

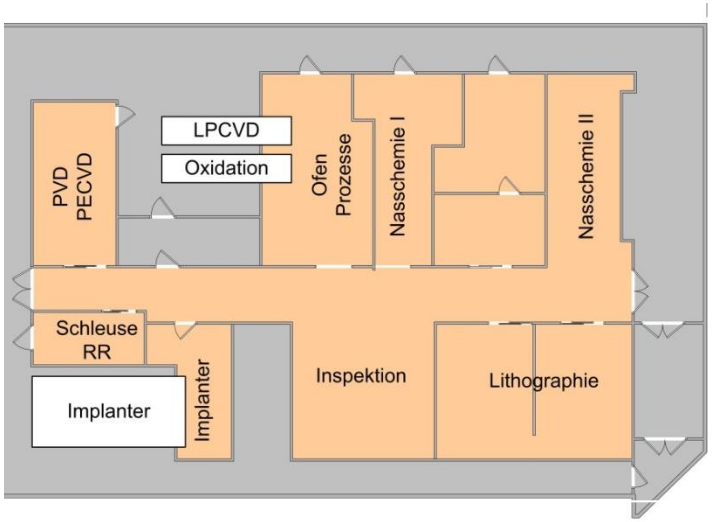


lithography

thermal

inspection

implantation

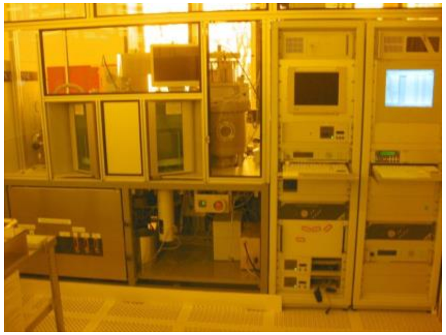


6" Si full processing line

class 1000 to class 1 in certain areas

Inside HLL – Backend processes

plasma and sputter



Cu line

flip chip

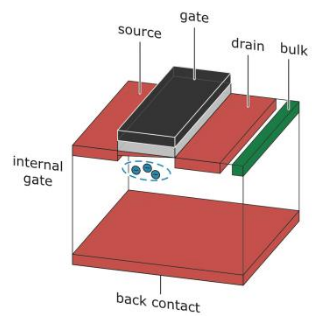
wire bonding, hybrid assembly

@ HLL:

- sensor design and fabrication
- interconnection
- system/camera design and test

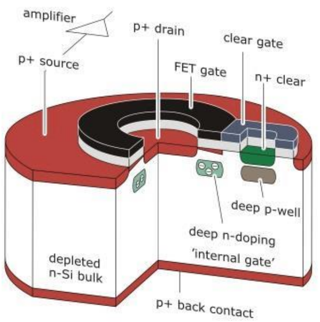
System test facilities

Detector portfolio



Standard DEPFET

- Sidewards depleted
- Internal gate

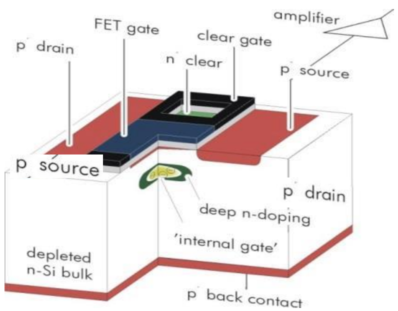


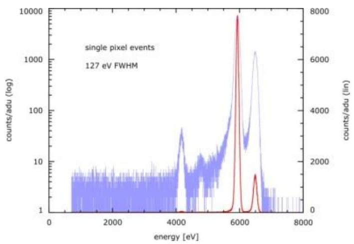
Circular DEPFET

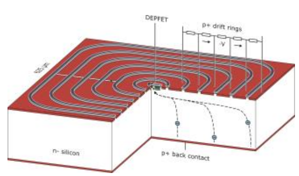
- Large pixels > 75 µm^2
- Noise ~ 4 e- ENC
- Efficient filling of area
- Macropixel compatible

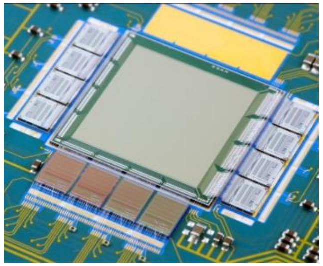
Linear DEPFET

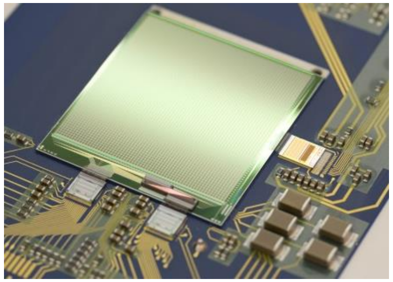
- Small pixels > 25 µm^2
- Noise ~2 e- ENC
- High packing density
- Array compatible

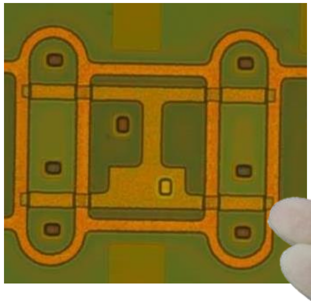


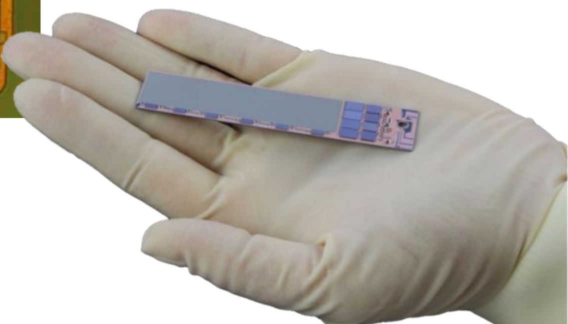




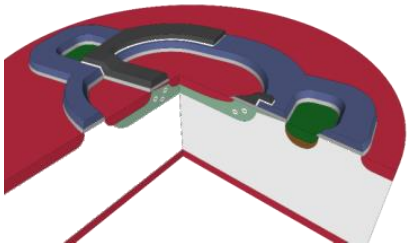






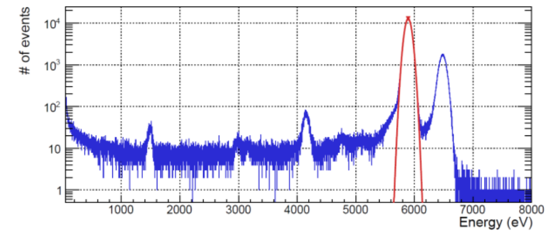


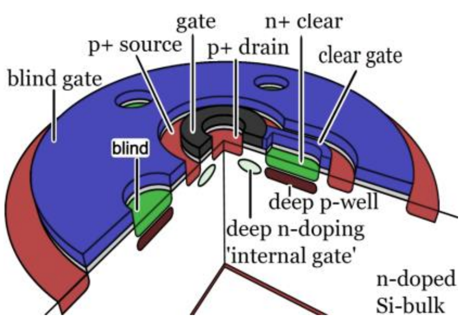
Detector portfolio



Semicircular DEPFET

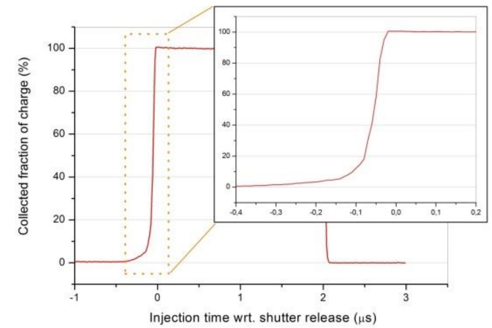
- Combine advantage from linear and circular device
- Large pixels > 150 μm^2
- Noise ~ 1.5 e- ENC
- Macropixel compatible

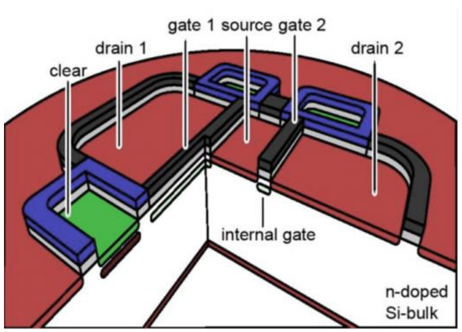




GPIX DEPFET

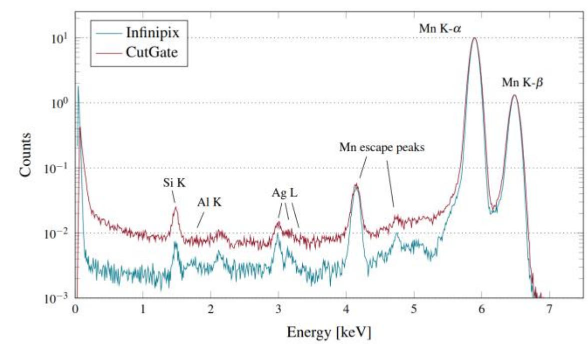
- Add electronic shutter capability
- Overcome rolling-shutter effects
- Precision gating & timing < 100 ns



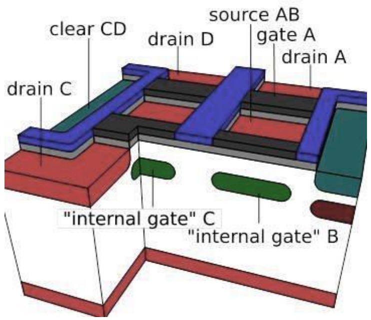


Infinipix

- Two storage nodes
- Overcome rolling-shutter effects
- Fast timing @ optimal spectral performance
- Array compatible
- Macropixel compatible

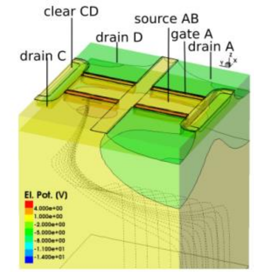


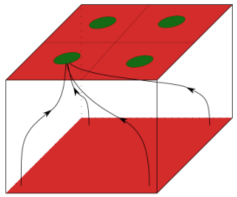
Detector portfolio

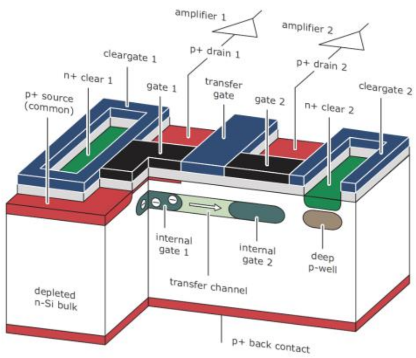


Quadropix

- 4 storage nodes
- Periodic time slicing
- MicroMovies
- Suppression > 1 ‰
- Time resolution < 100 ns
- Upgrade to Octopix under investigation

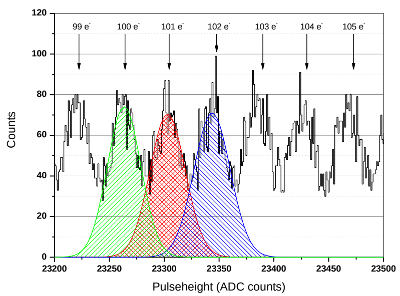


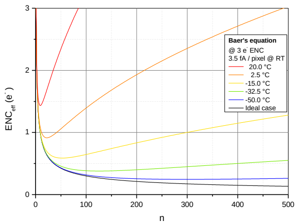


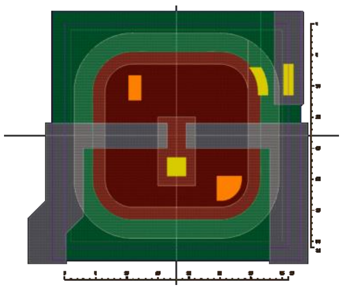


RNDRpix

- Repetitive non-destructive readout
- Self-Calibrating
- Ultra-low noise
- Incremental / differential imaging

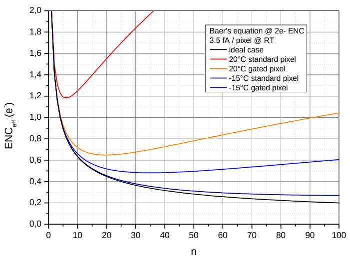




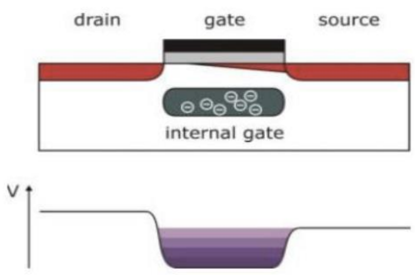


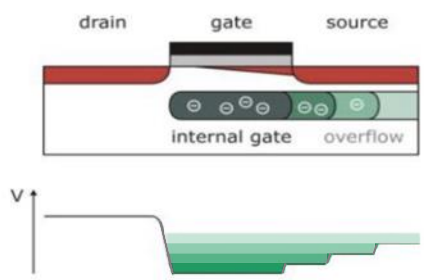
RNDRpix

- Repetitive non-destructive readout
- Included electronic shutter
- Suppress shaping artifacts
- Incremental / differential imaging



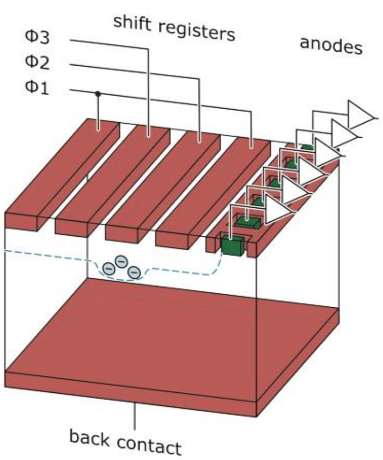
Detector portfolio





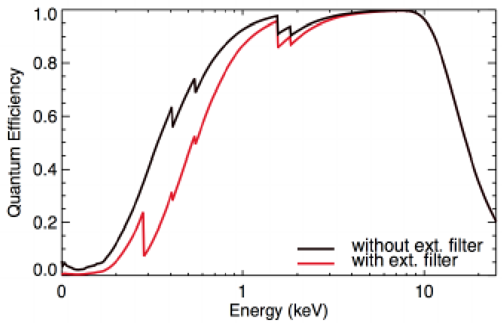
Extended dynamic range:

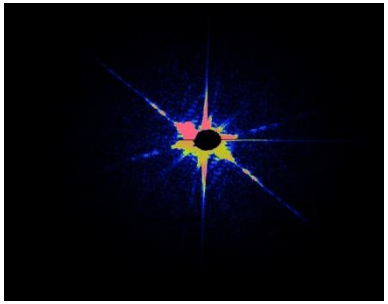
- Tailor pixel response to experimental requirements
- Use "overflow" regios for internal gate
- Create in-sensor analog signal compression
- Implantatnions and topologic variations



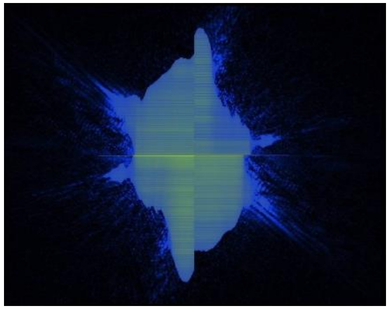
Large CHC modes (pnCCD):

- Enlarged pixel CHC / full well capacity
- Improved imaging capability at high intensities
- Special operation mode



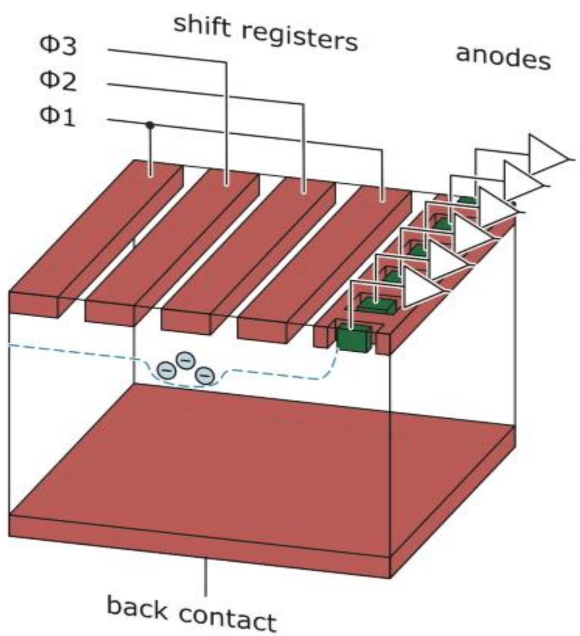


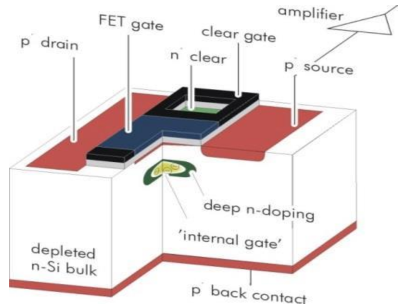
800 ke- dynamic range



200 ke- dynamic range

Detector portfolio





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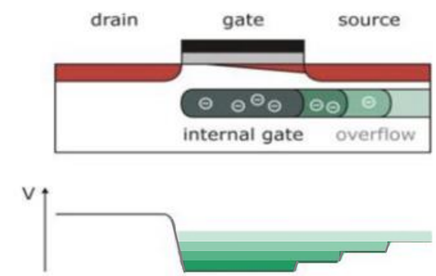
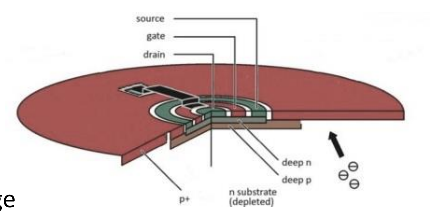




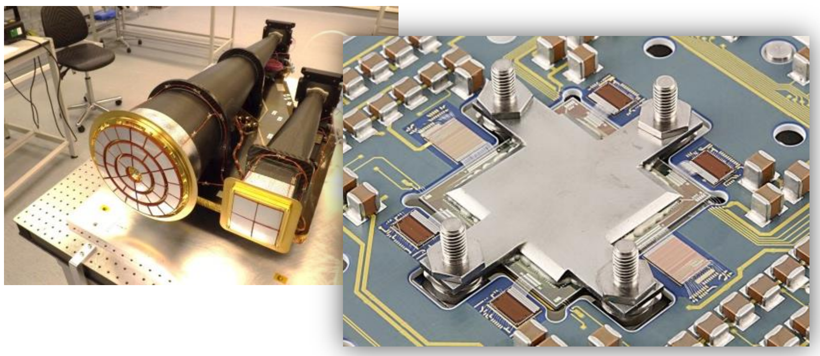
Combination of different conceptual features creates devices with multiple capabilities

CCD2020 devices:

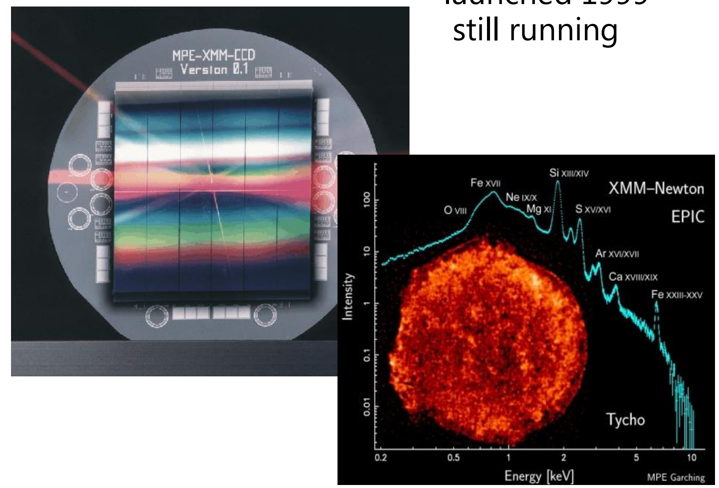
- DEPFET readout w/ all benefits (speed, compression…)
- Narrow guard ring topology for minimized inactive edge
- Virtual pitchadapter / smart binning
- Near room temperature operation

Some finished and running projects

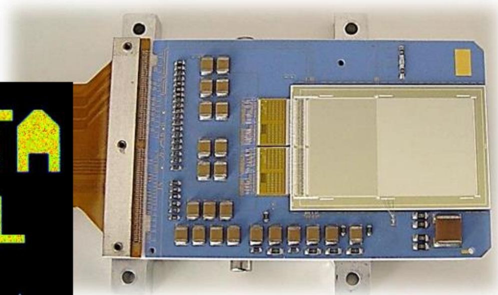
Bepi Colombo MIXS FPA (DEPFET)
to be launched this year

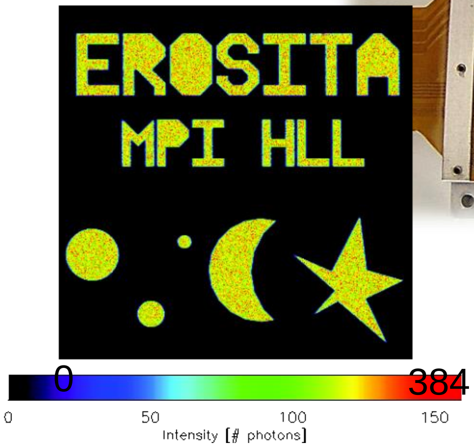


XMM-Newton (pnCCD)
launched 1999
still running

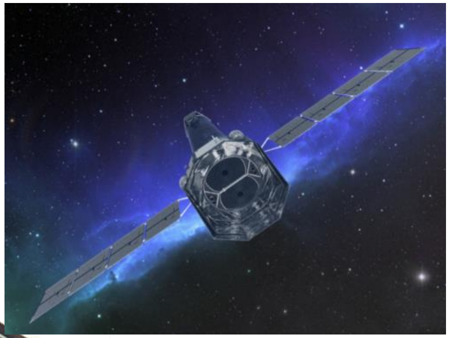


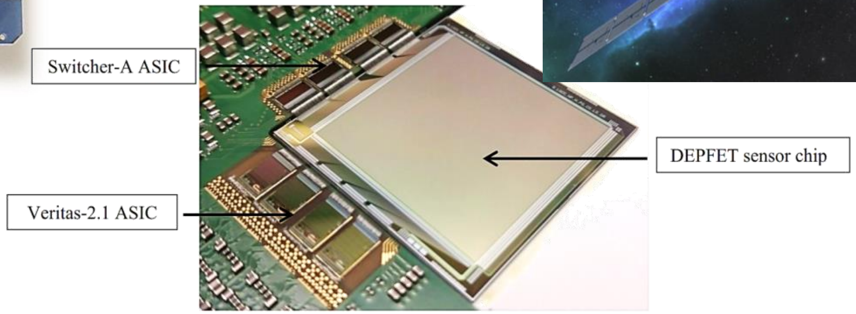
EROSITA
to be launched
this year (pnCCD)





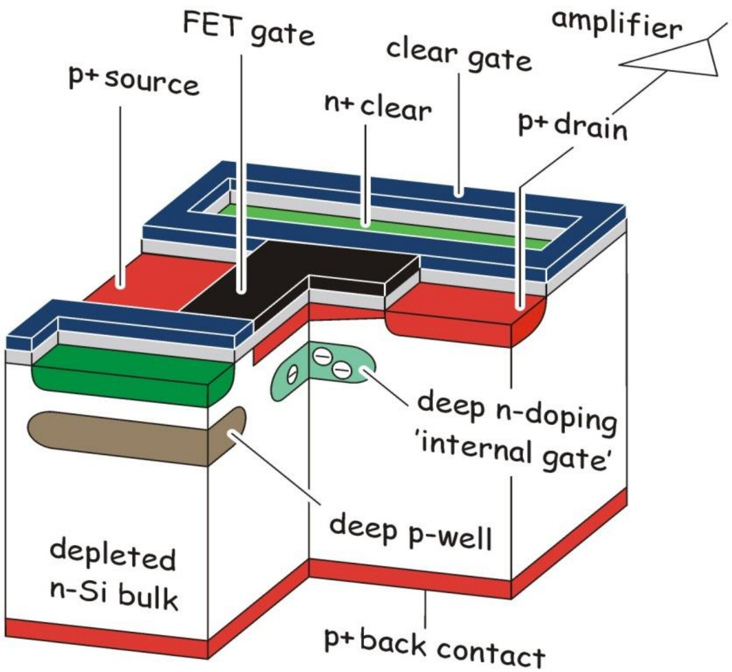
ATHENA WFI (DEPFET)
to be launched this 2028

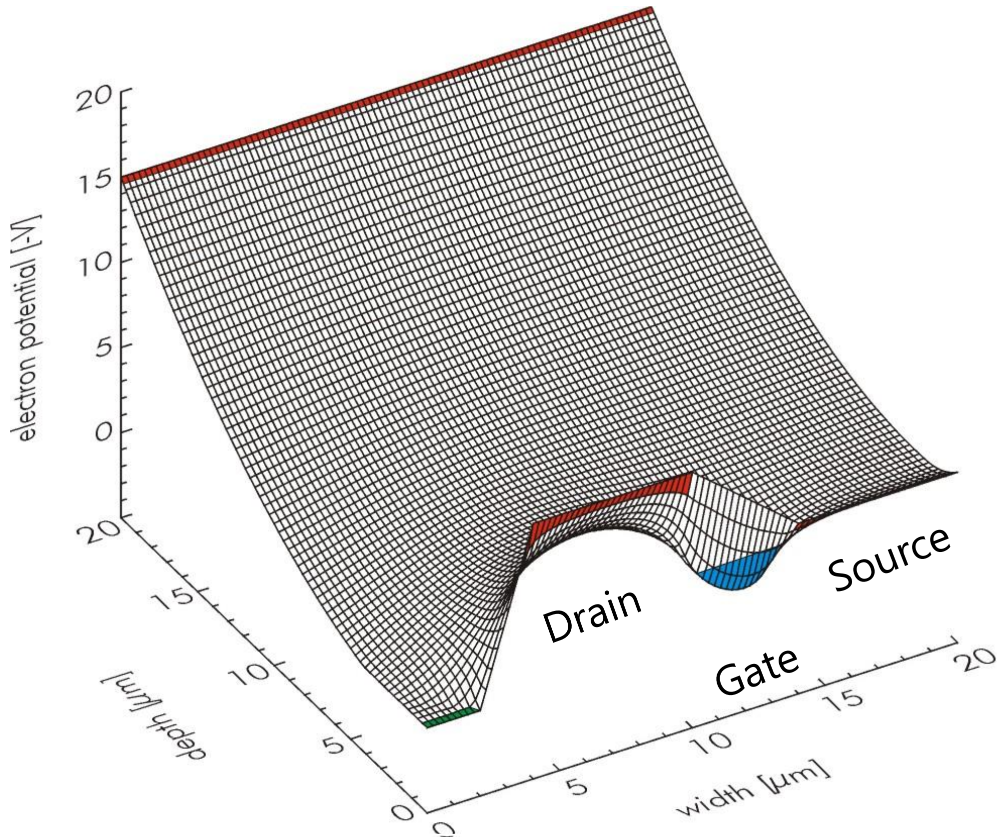




DEPFET Active Pixels

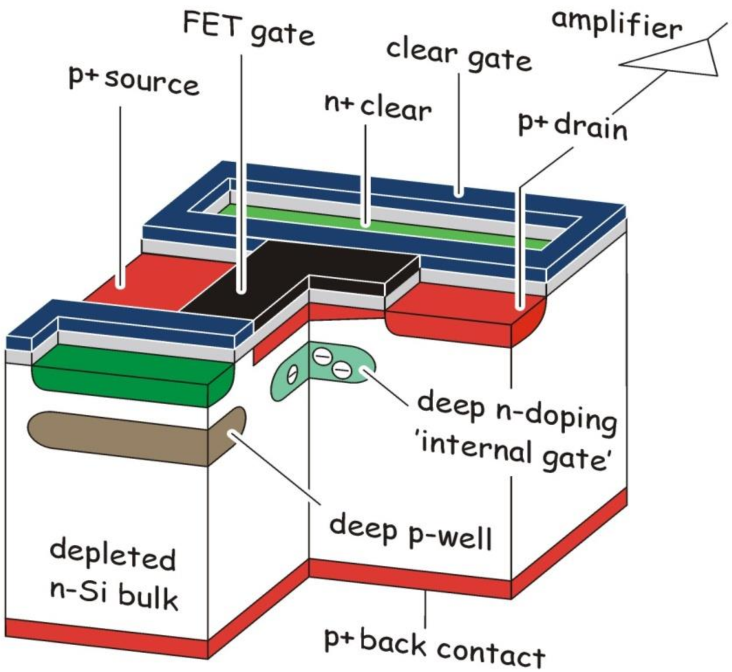
(J. Kemmer, G. Lutz, 1987)

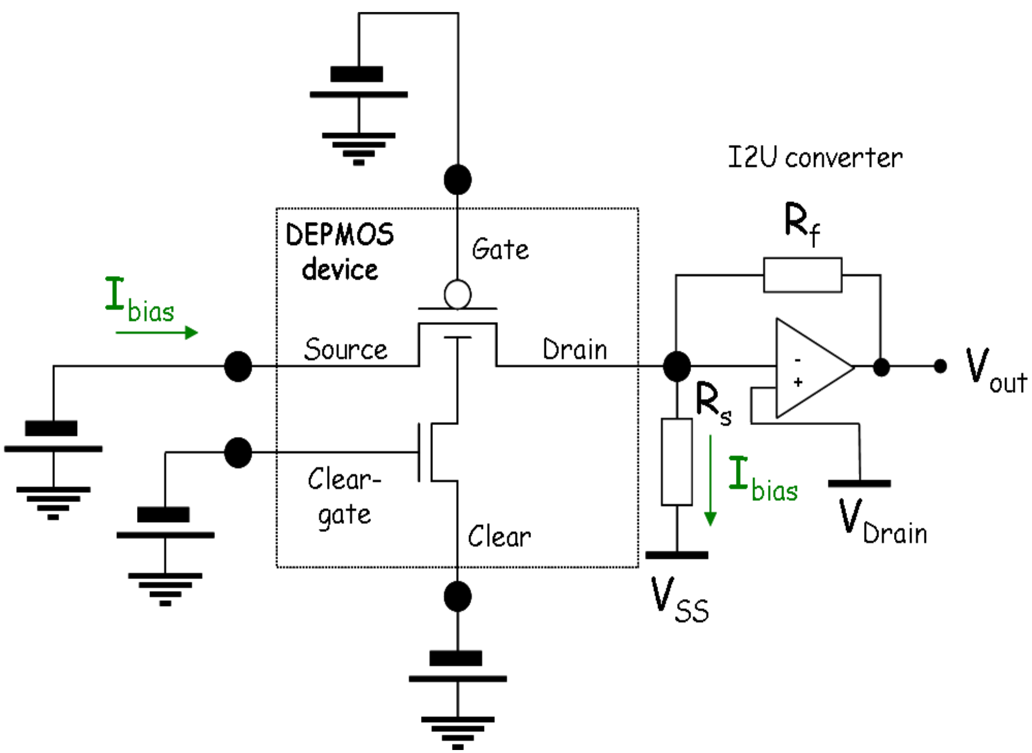




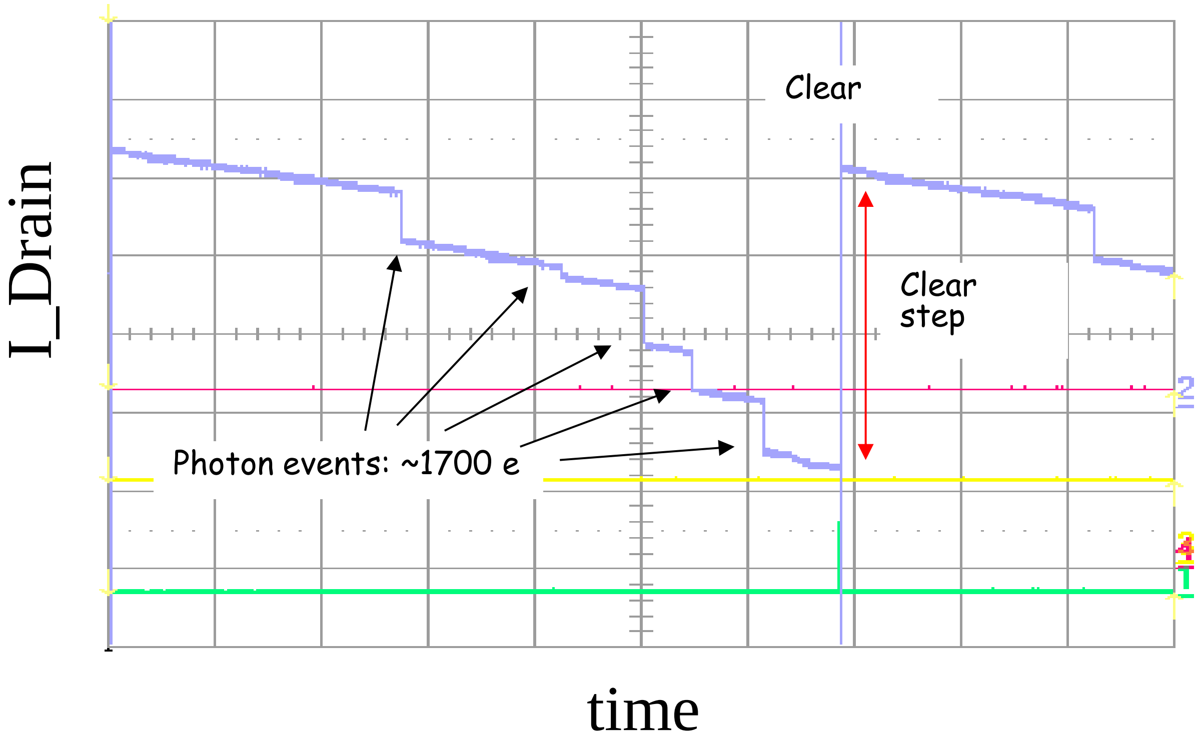
- fully depleted sensitive volume
- internal amplification low input capacitance
- Charge collection in "off" state, non-destructive read out on demand

DEPFET Active Pixels





Internal Amplification

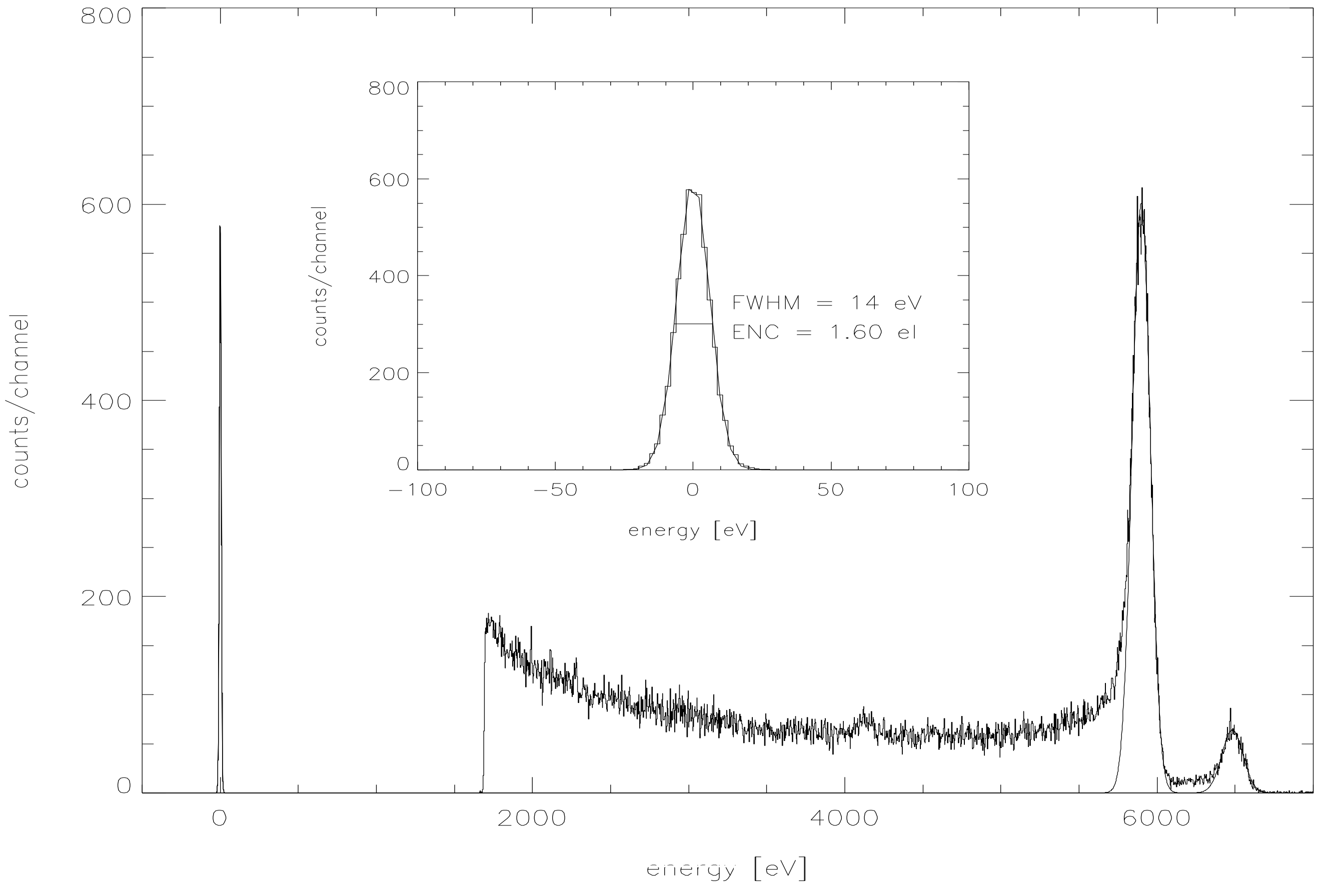


$$g_q = \frac{dI_D}{dQ} = \frac{g_m}{C_{ox}} \Rightarrow \quad g_q \sim \frac{1}{L^{3/2}} \qquad g_q \sim I_D^{1/2} \qquad g_q \sim \frac{1}{W^{1/2}} \qquad g_q \sim t_{ox}^{1/2}$$

g_q for of the recent DEPFET generation (large Belle II sensors): ~0.5 nA/e-

not fully exploited at all (2-3 nA) !

Single pixel performance – Fe55 Source



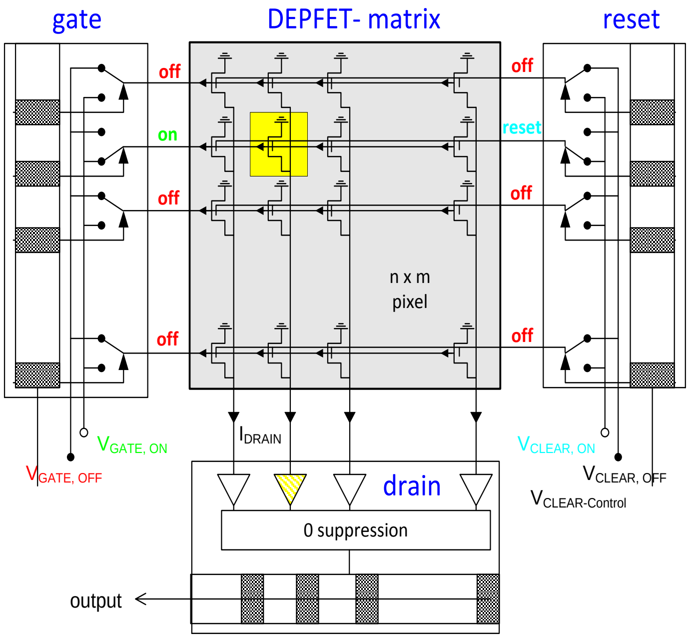
$V_{thresh} \approx -0.2V$, $V_{gate} = -2V$

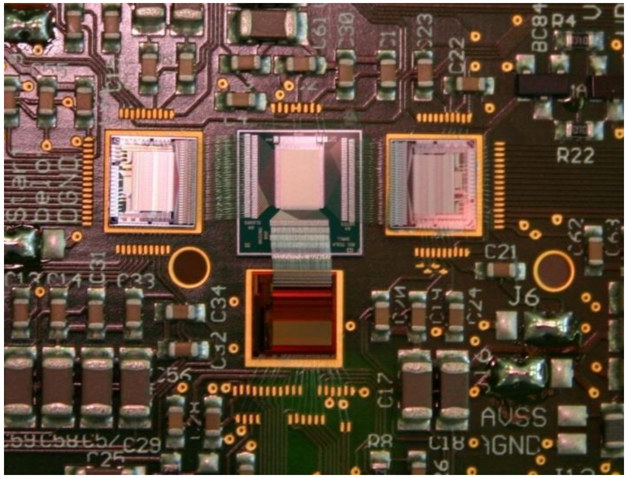
$I_{drain} = 41\ \mu A$

time cont. shaping $\tau = 10\ \mu s$

Noise ENC=1.6 e^- (rms)

An array of DEPFETs - two different read out schemes



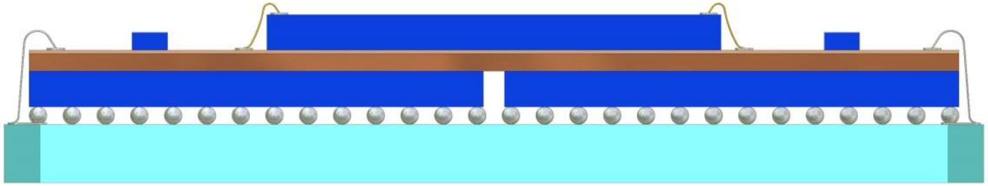


Row wise read-out ("rolling shutter")

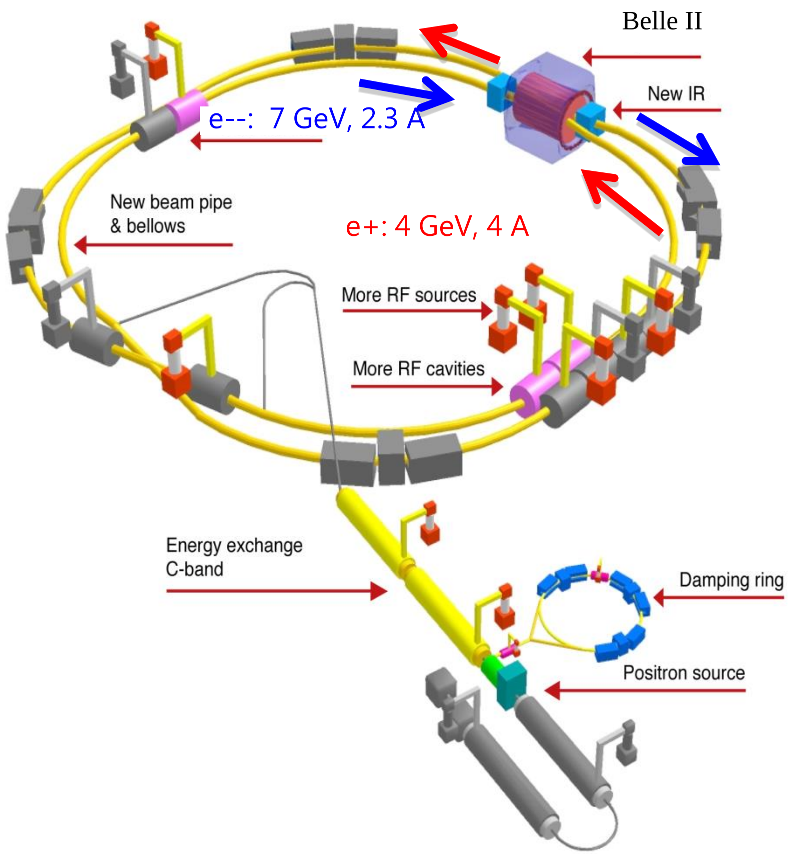
- select row with external gate, read current, clear DEPFET, read current again
- two different auxiliary ASICs needed
- r/o needs time.....
- only one(?) row active → low power consumption

One read-out node per pixel ("hybrid pixel")

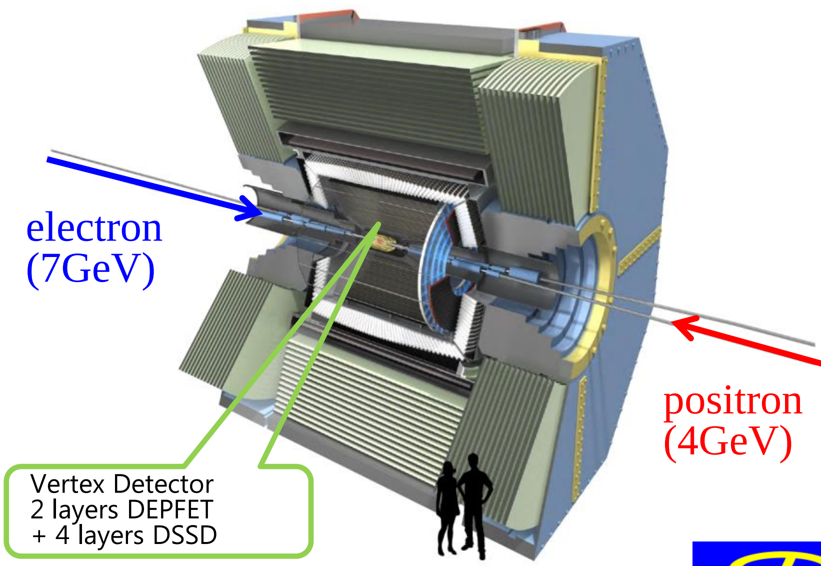
- fully parallel read-out, high frame rate
- more power hungry
- need active cooling or power pulsing (XFEL)



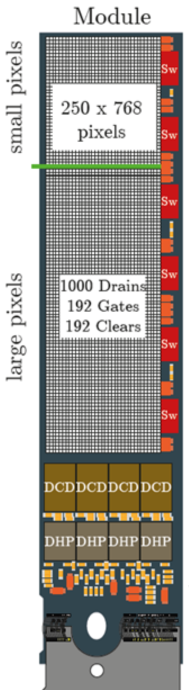
BELLE II @ SuperKEKB (Tsukuba)



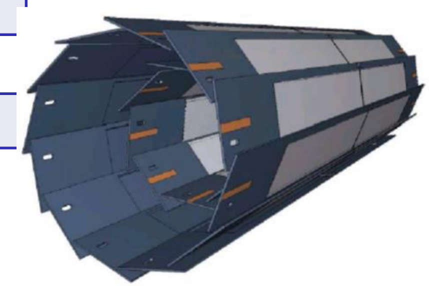
- Vertex Detector upgrade
- DEPFETs are chosen for the inner layers
- Developed by the DEPFET collaboration
- Phase 2 (part of the detector) starts this summer
- Phase 3 (full detector) next year

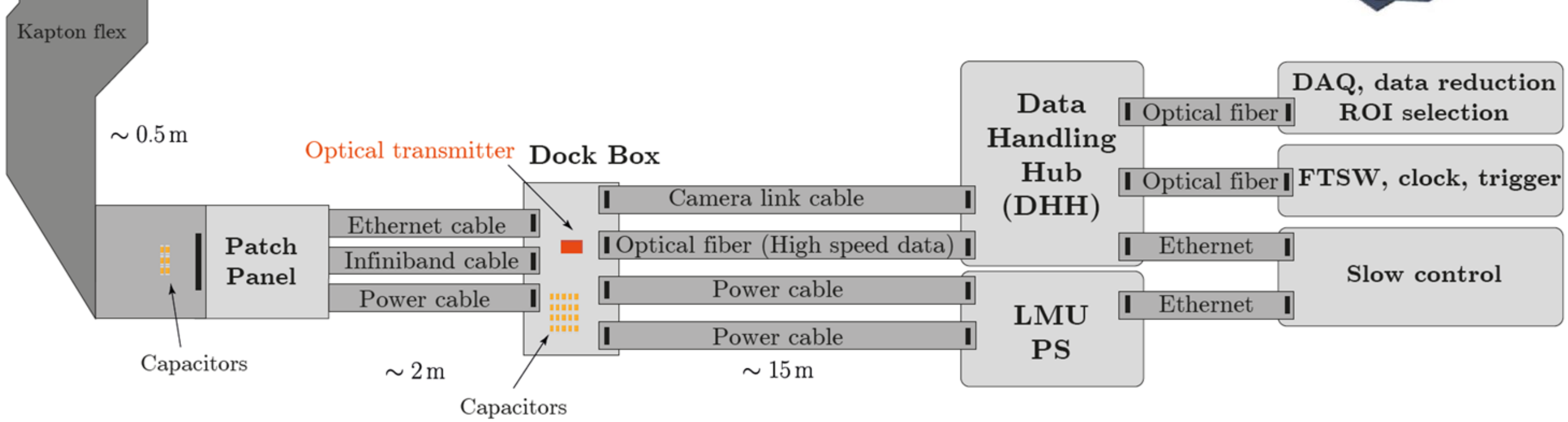


Thin DEPFETs: Belle II PXD



	L1	L2
# modules	8	12
Distance from IP (cm)	1.4	2.2
Thickness (µm)	75	75
#pixels/module	768x250	768x250
#of address and r/o lines	192x1000	192x1000
Total no. of pixels	3.072×10^6	4.608×10^6
Pixel size (µm^2)	55x50 60x50	70x50 85x50
Frame/row rate	50kHz/10MHz	50kHz/10MHz
Sensitive Area (mm^2)	44.8x12.5	61.44x12.5



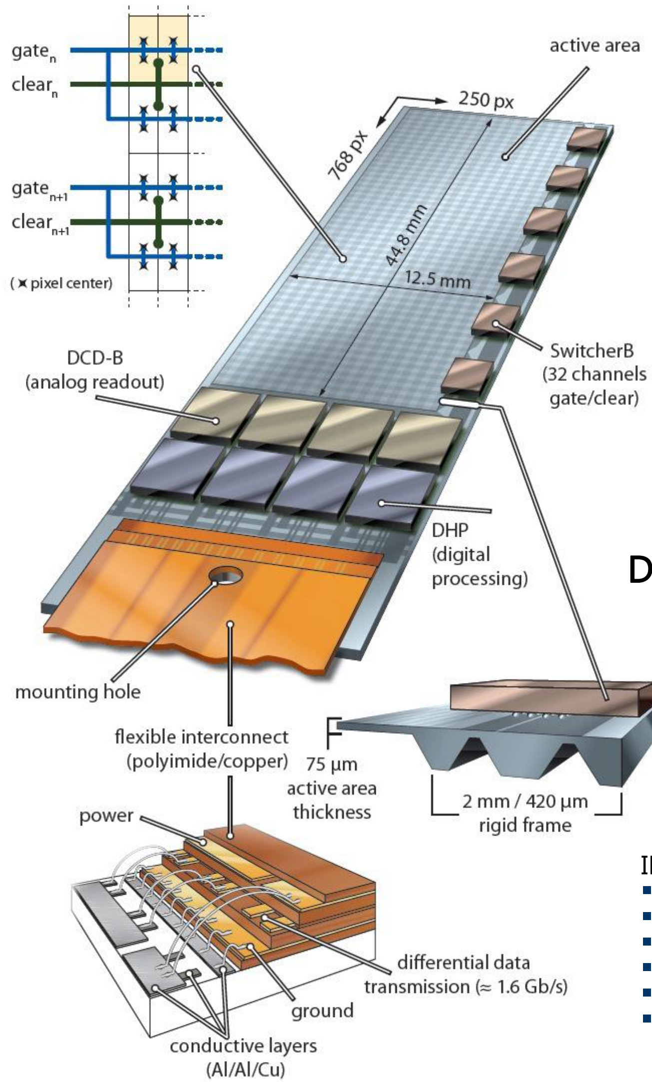


the PXD all-silicon module

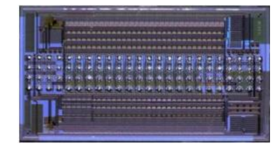
DCDB (Drain Current Digitizer)
Analog front-end

Amplification and digitization of DEPFET signals.

- 256 input channels
- 8-bit ADC per channel
- 92 ns sampling time
- new version w/ 50ns sampling time under test
- UMC 180 nm

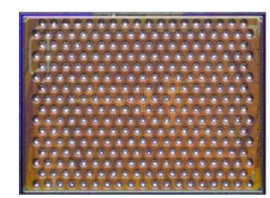


SwitcherB - Row Control



AMS/IBM HVCMOS 180 nm
- Size 3.6 × 1.5 mm^2
- Gate and Clear signal
- 32x2 channels
- Fast HV ramp for Clear

DHP (Data Handling Processor)
First data compression



IBM CMOS 90 nm (TSMC 65 nm)
- Size 4.0 × 3.2 mm^2
- Stores raw data and pedestals
- CM and pedestal correction
- Data reduction (zero suppression)
- Timing and trigger control
- Drives data link

Key to low mass vertex detectors:

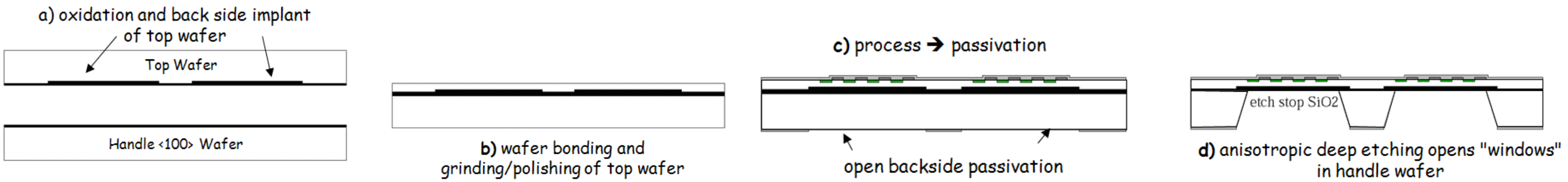
→ **highest integration!**

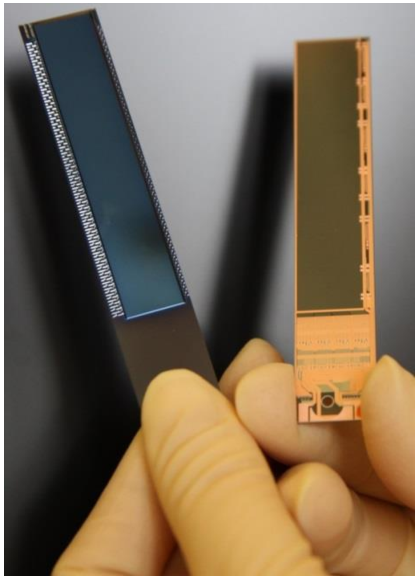
↳ Thin sensor area

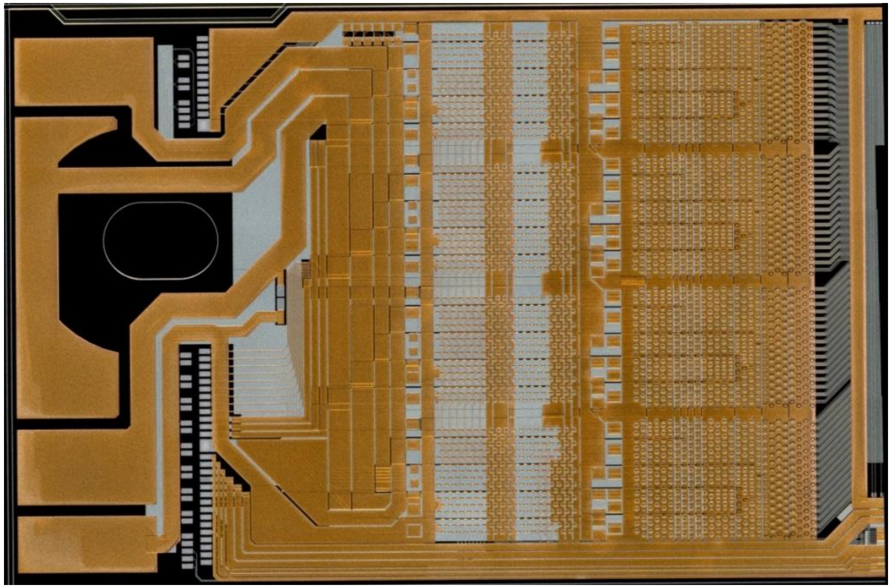
↳ EOS for r/o ASICs

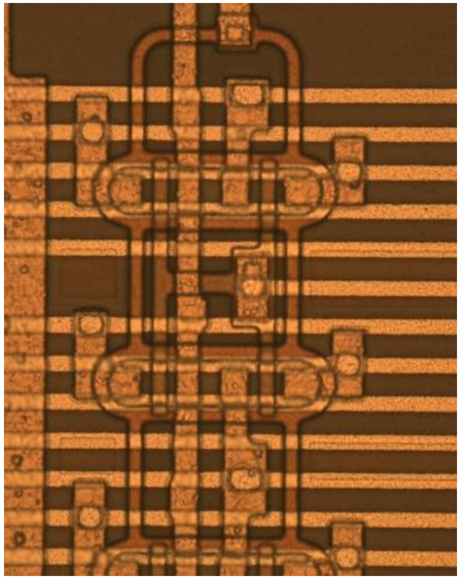
↳ Thin (perforated) frame w/ steering ASICs

Thinning technology and metal system



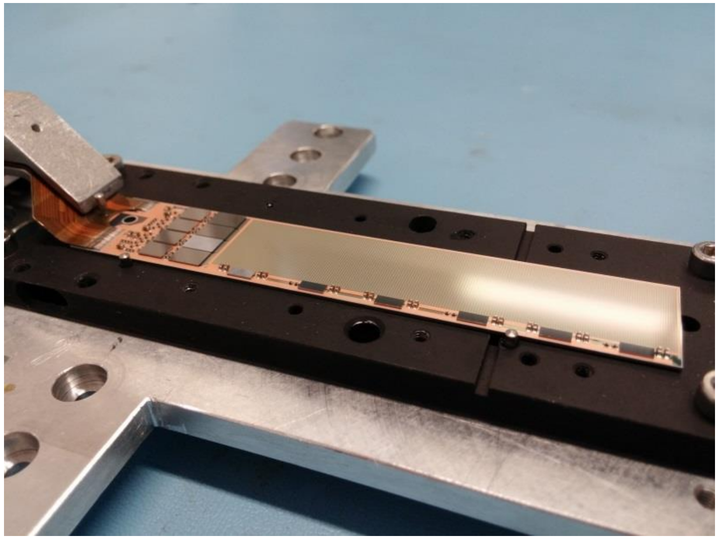






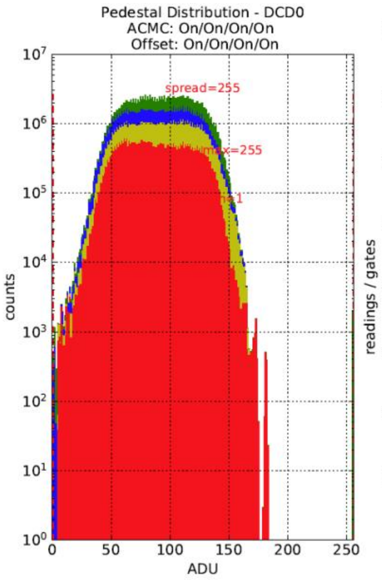
- thickness of the sensitive area is an almost free parameter
- full DEPFET technology in thin area
- thin area supported by a monolithically integrated silicon frame
- three metal layers at periphery as substrate for passives, ASICs and off-module interconnect

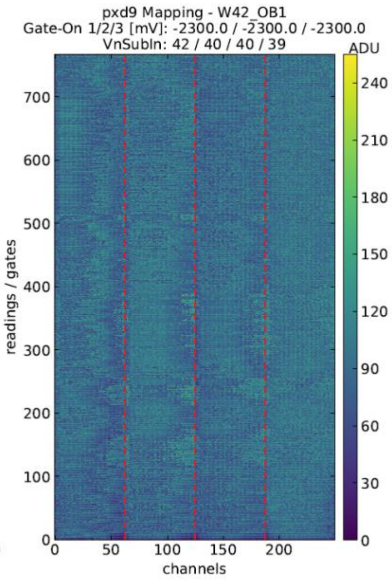
results on the test bench – Cd109 source scan

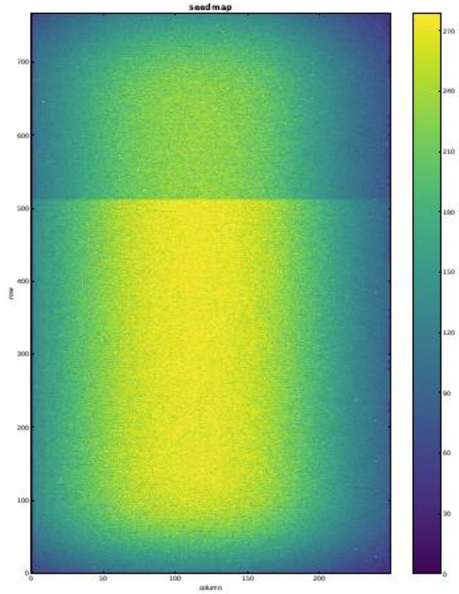


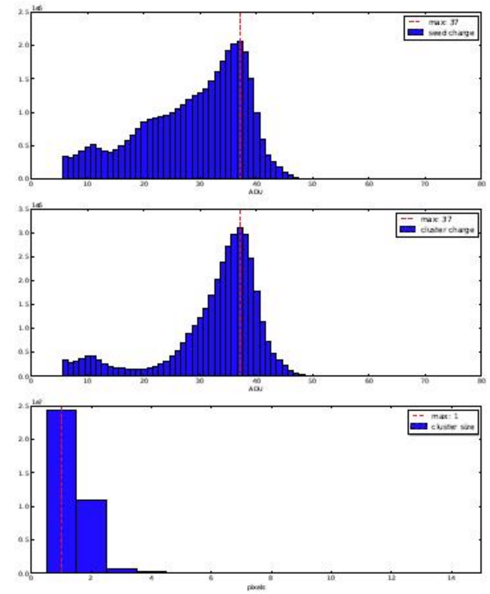
- full speed read-out (~100ns/row, 20µs/frame)
- 191983/192000 pixels alive – **99.99%**
- S/N for mip ~40

- **module is ready for Belle2 Pixel Detector**



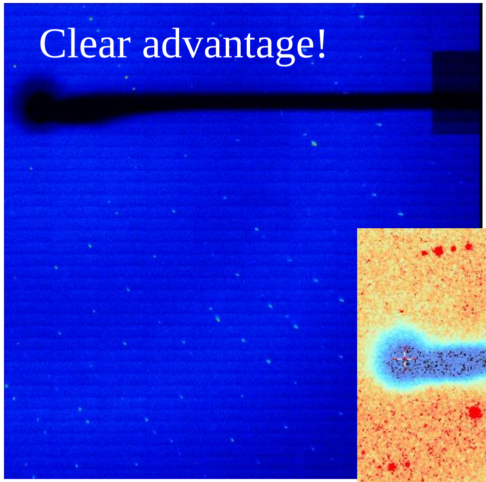




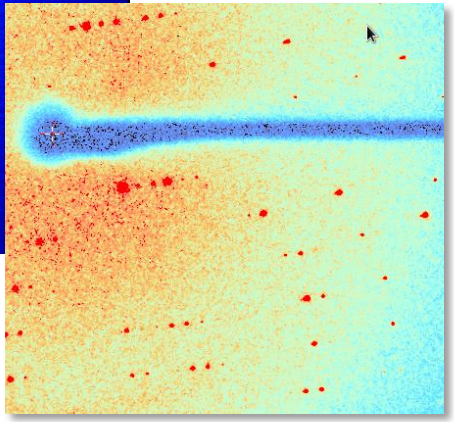


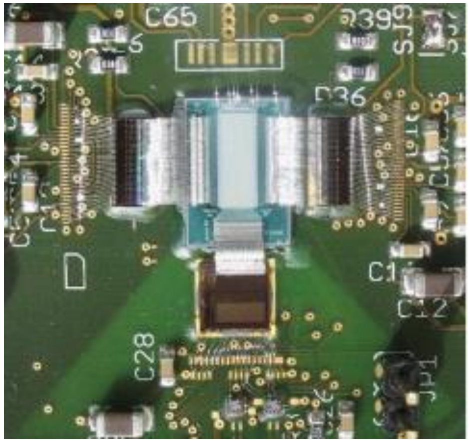
Belle2 and Photon factory are neighbors at KEK … ☺

- Combination of high speed, low noise and high resolution
- Tests with a small PXD test array

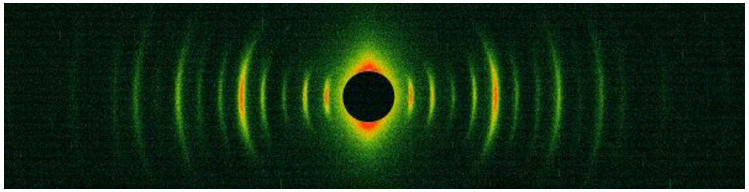


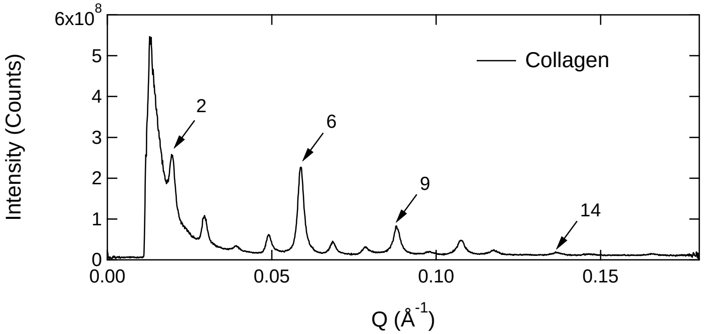
CCD
(different sample)





Small DEPFET test sensor
256 × 64 pixels

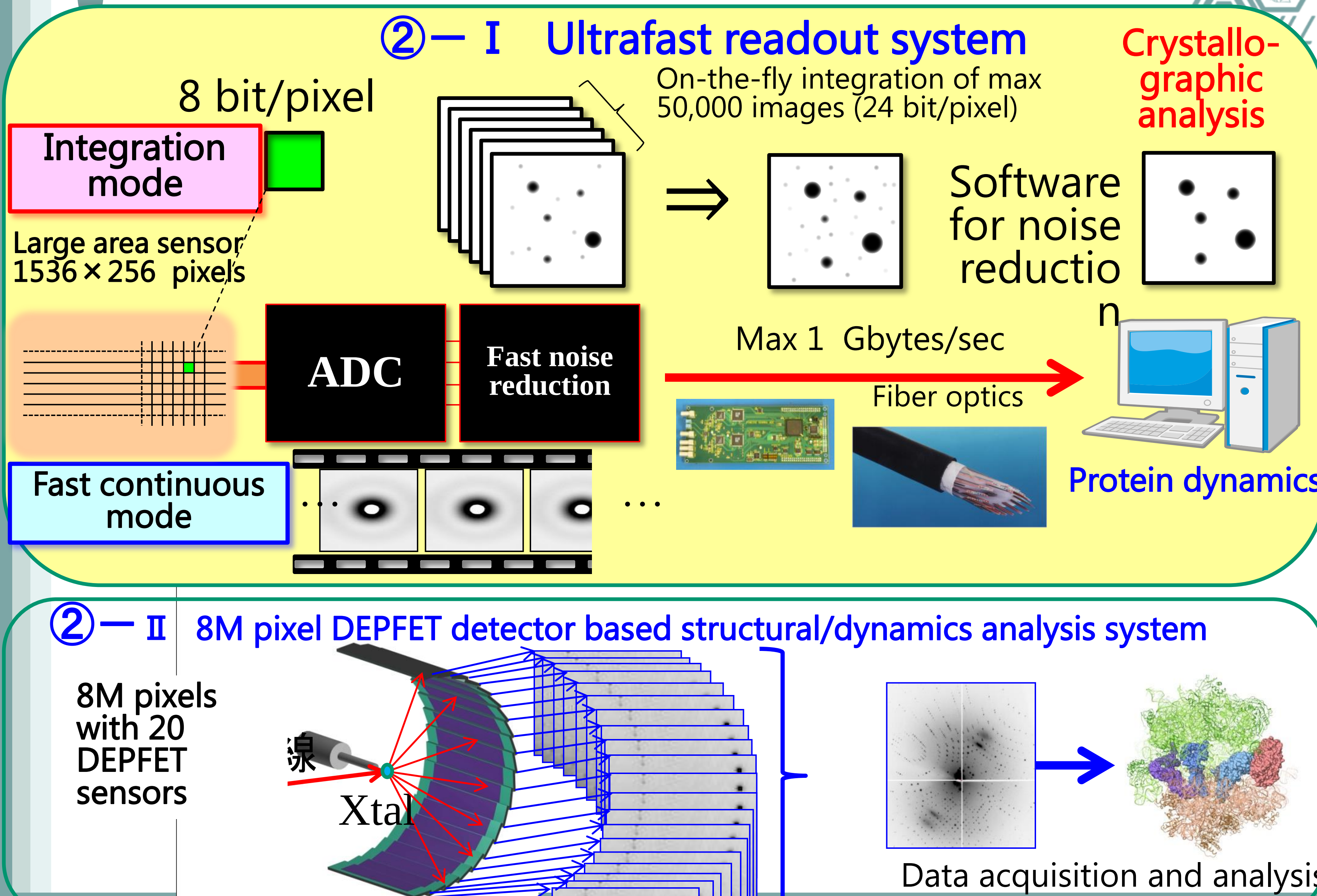




Small-Angle X-ray scattering image,
collagen from chicken Achilles tendon at 8.33 keV

Joint effort of IMSS KEK, MPI for Physics and HLL

DEPFET @ Photon Factory (KEK) (slide from Soichi Wakatsuki IMSS, KEK)



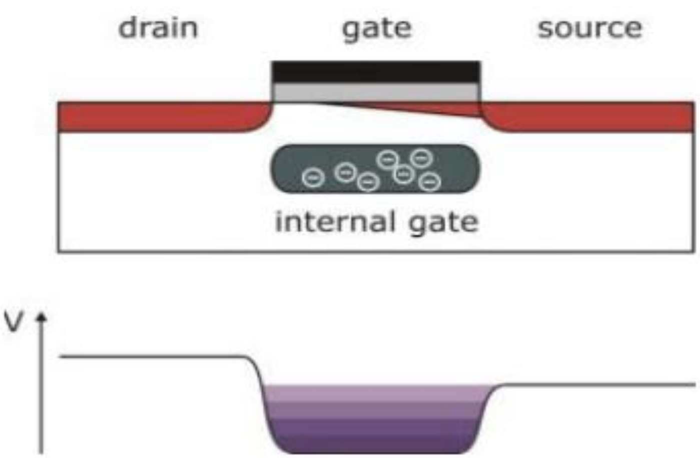
Can we do better?

- The small Internal Gate capacitance of the Belle Pixel limits the dynamic range to about 60000 electrons
  -> drastic restriction for the counting capability in photon science

- **The DSSC project at XFEL uses a DEPFET with enhanced charge storage capability and inherent signal compression.**

What happens if the Internal Gate is full?

DEPFET technology offers a simple natural solution



Internal amplification

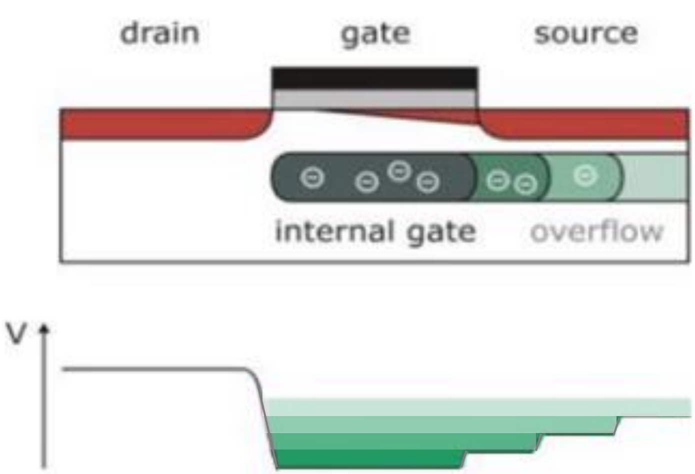
gq = dI/dQsig

for a given transistor :

gq ~ channel carrier velocity

gq ~ fraction of mirror charge

influenced in the channel by Qsig < 1



Multiple n-implants to create

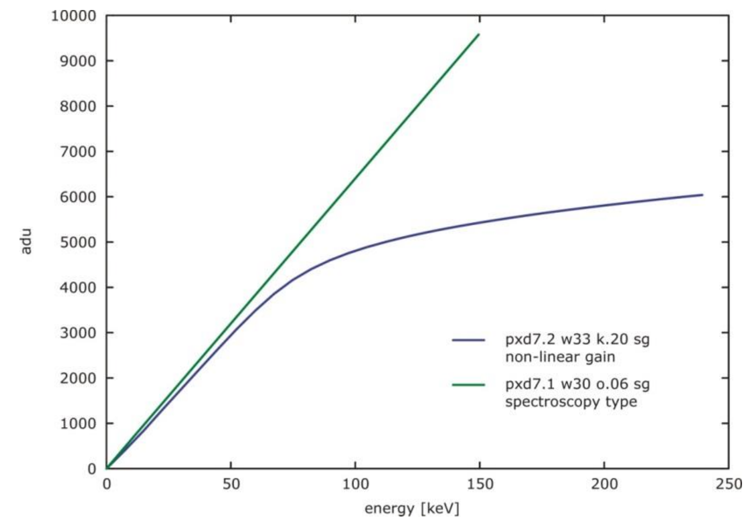
an electric field towards the Internal Gate

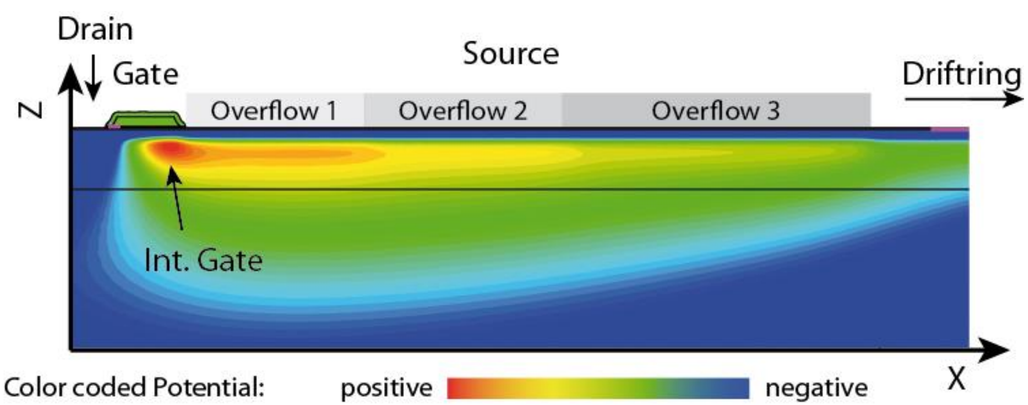
and to tailor the response

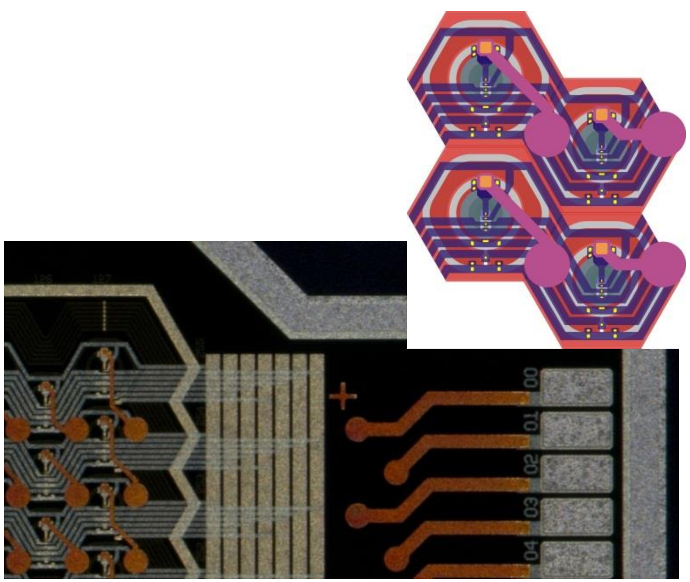
With courtesy:
P. Lechner et al
DEPFET Active Pixel Sensor
with Non-Linear Amplification
IEEE NSS, Valencia 2011

DEPFET Sensor with Signal Compression

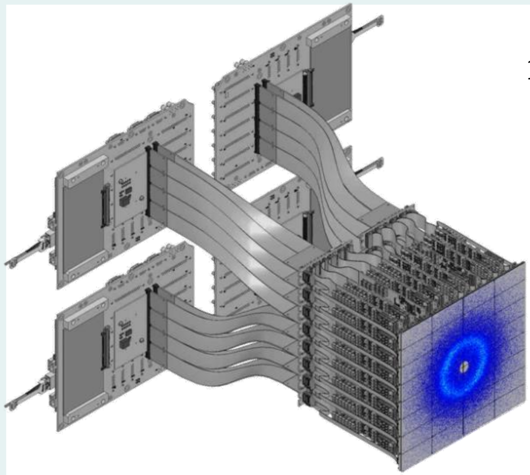
- The internal gate extends into the region below the source
- Small signals collected directly below the channel
  - ↳ Most effective, large signal
- Large signals spill over into the region below the source
  - ↳ Less effective, smaller signal
- staggered potential inside internal gate by varying impl.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



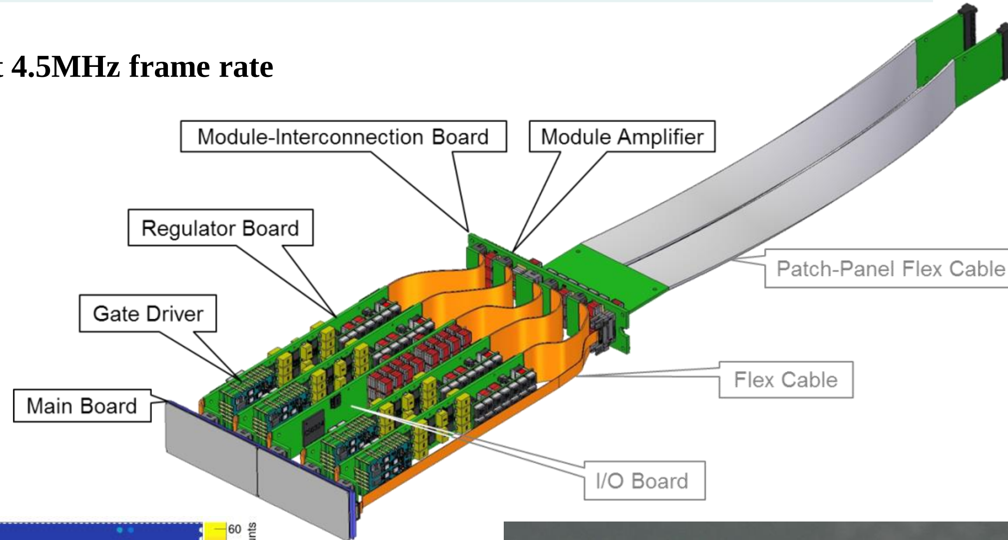


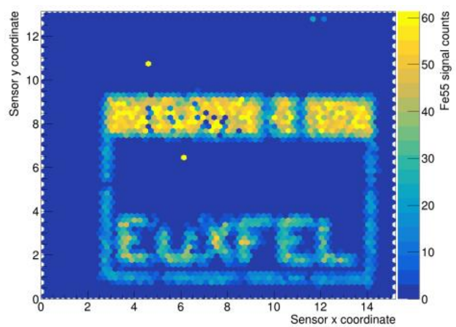


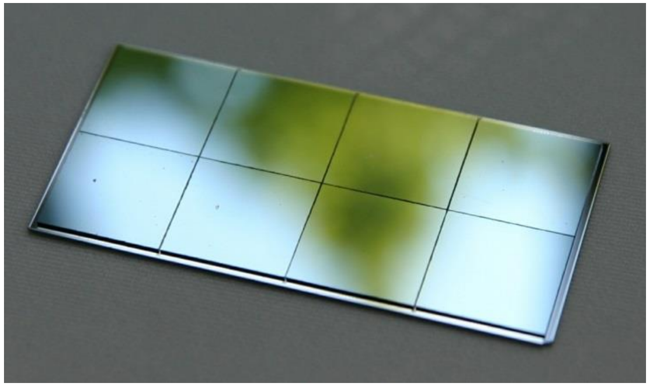
Hybrid pixel detector with non-linear DEPFET active pixels full parallel read-out



1Mpix at 4.5MHz frame rate





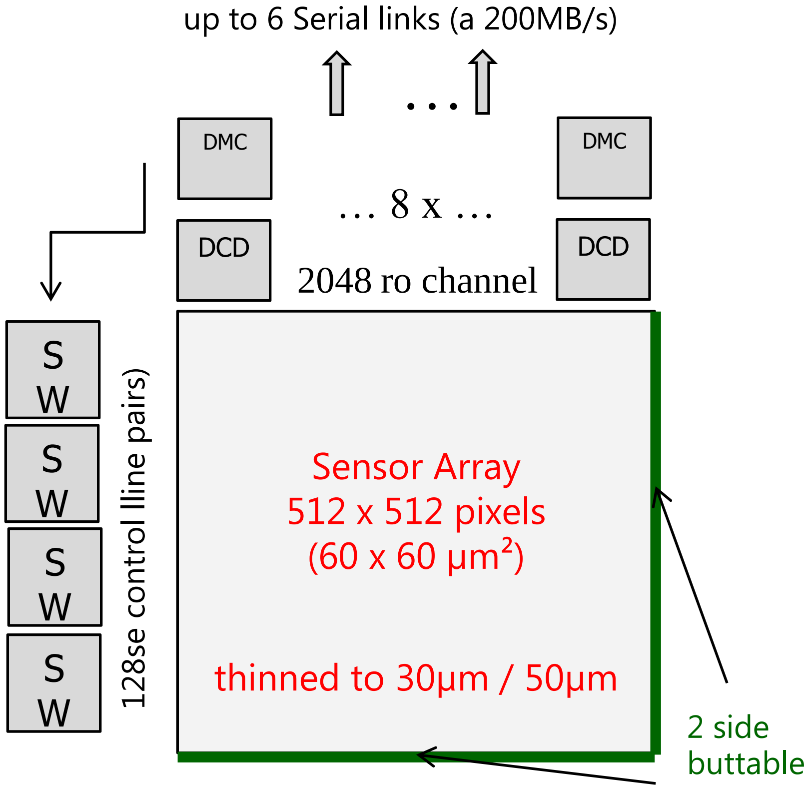


1st light image

- 64 x 64 section of a DSSC chip
- bump-bonded to readout ASIC
- irradiation by ^{55}Fe source
- baffle shadow image
- bright pixels by ASIC threshold settings

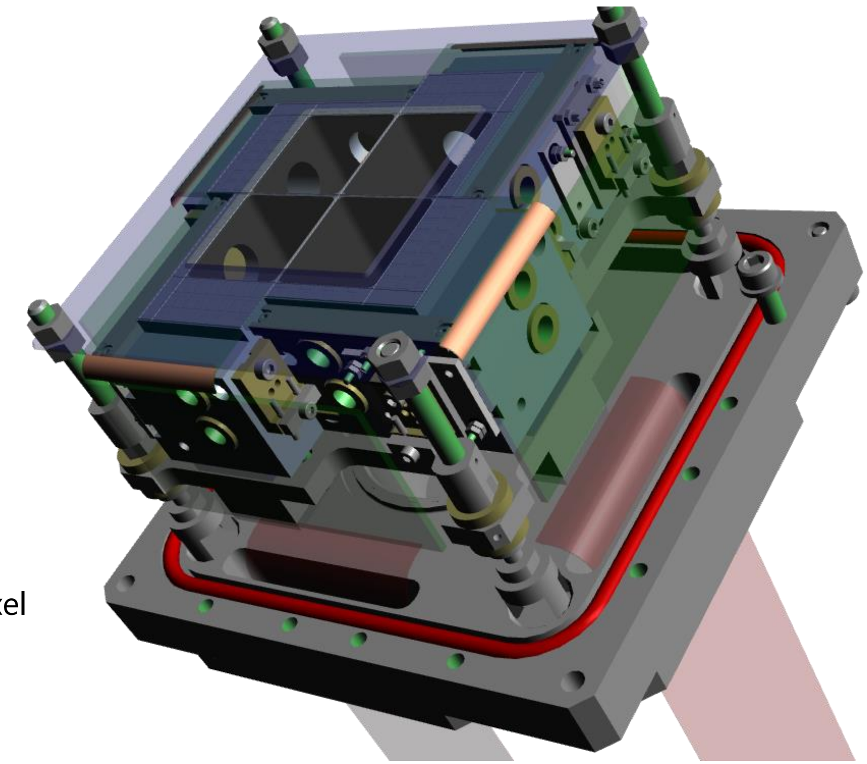
- 8 chips, 1.5x1.4 cm^2, 33000 bumps in total per half-ladder
- **Hybrid pixel sensor with active pixels, 4.5 MHz frame rate**

DEPFET based Direct Electron detector used for TEM



- 4 modules closely placed (gap 2mm)
- 1M pixel
- Sensor area: 36 cm²

- 4-fold rolling shutter readout
- (4 lines are adressed simultaneously)



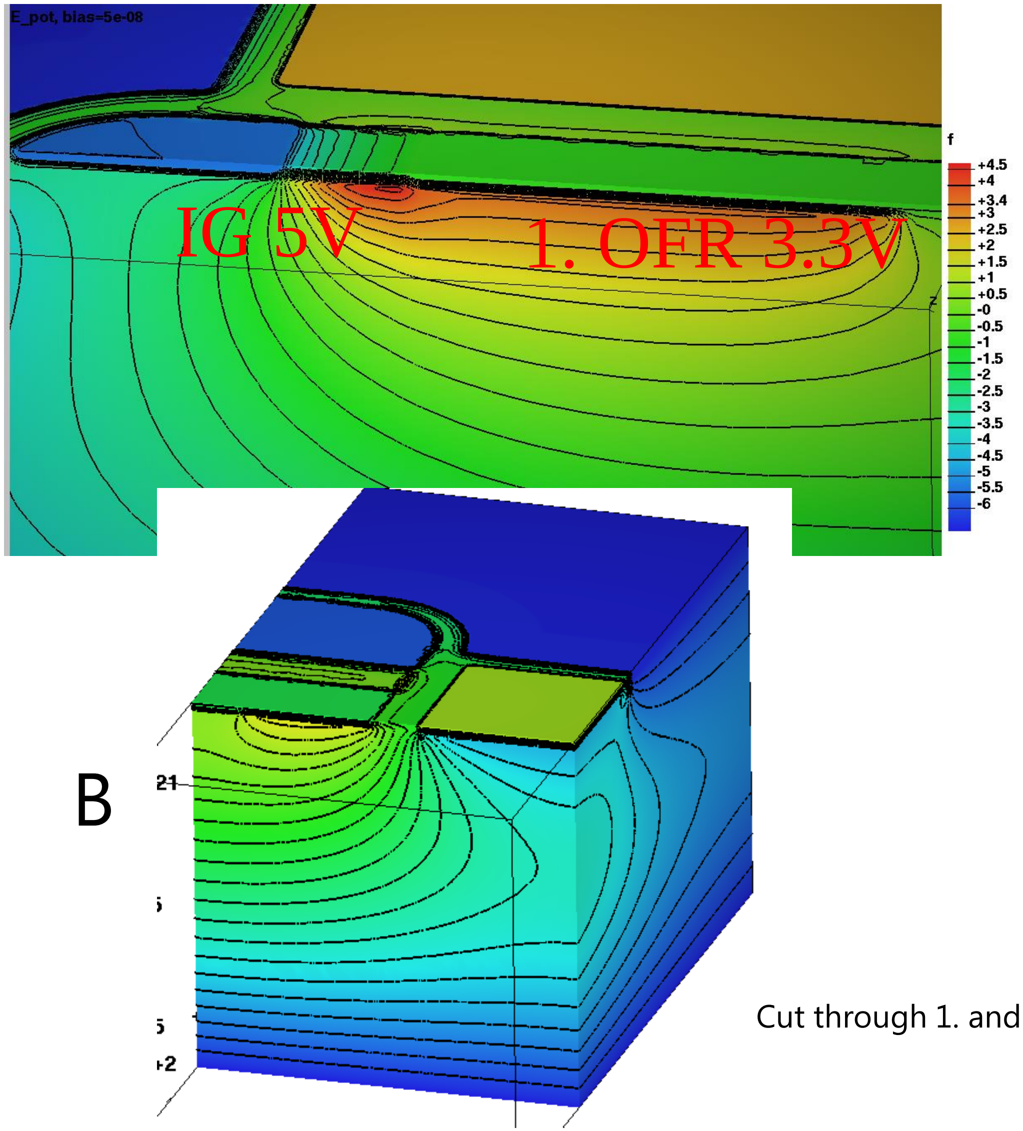
From Belle2-PXD: 100ns/row x 128 ->   80kHz frame rate

For good contrast about: 100 primary electrons (300keV) per pixel

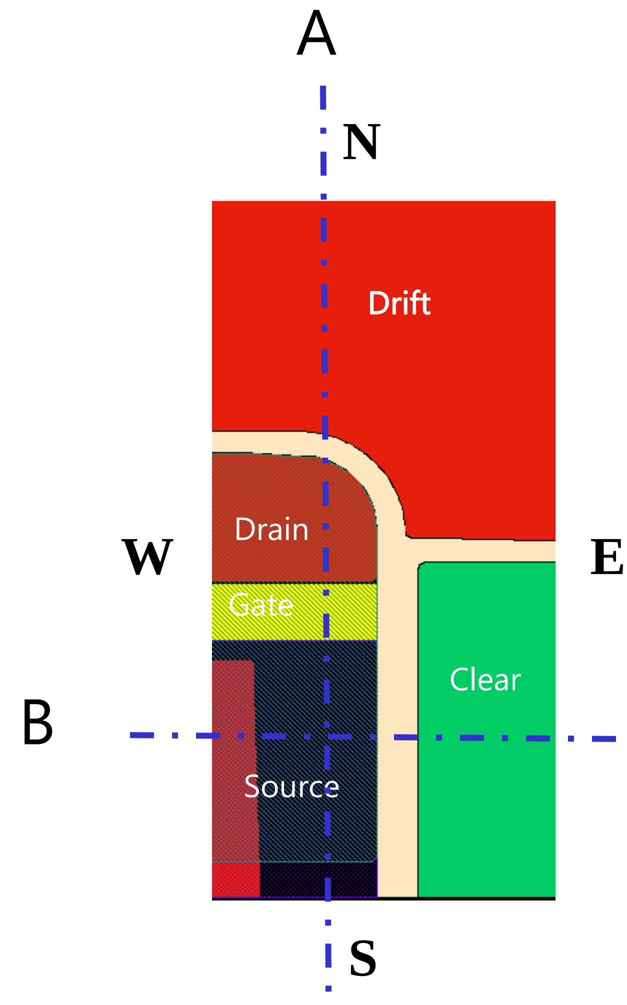
-> 800 k signal electrons

Signal compression in a linear DEPFET

A

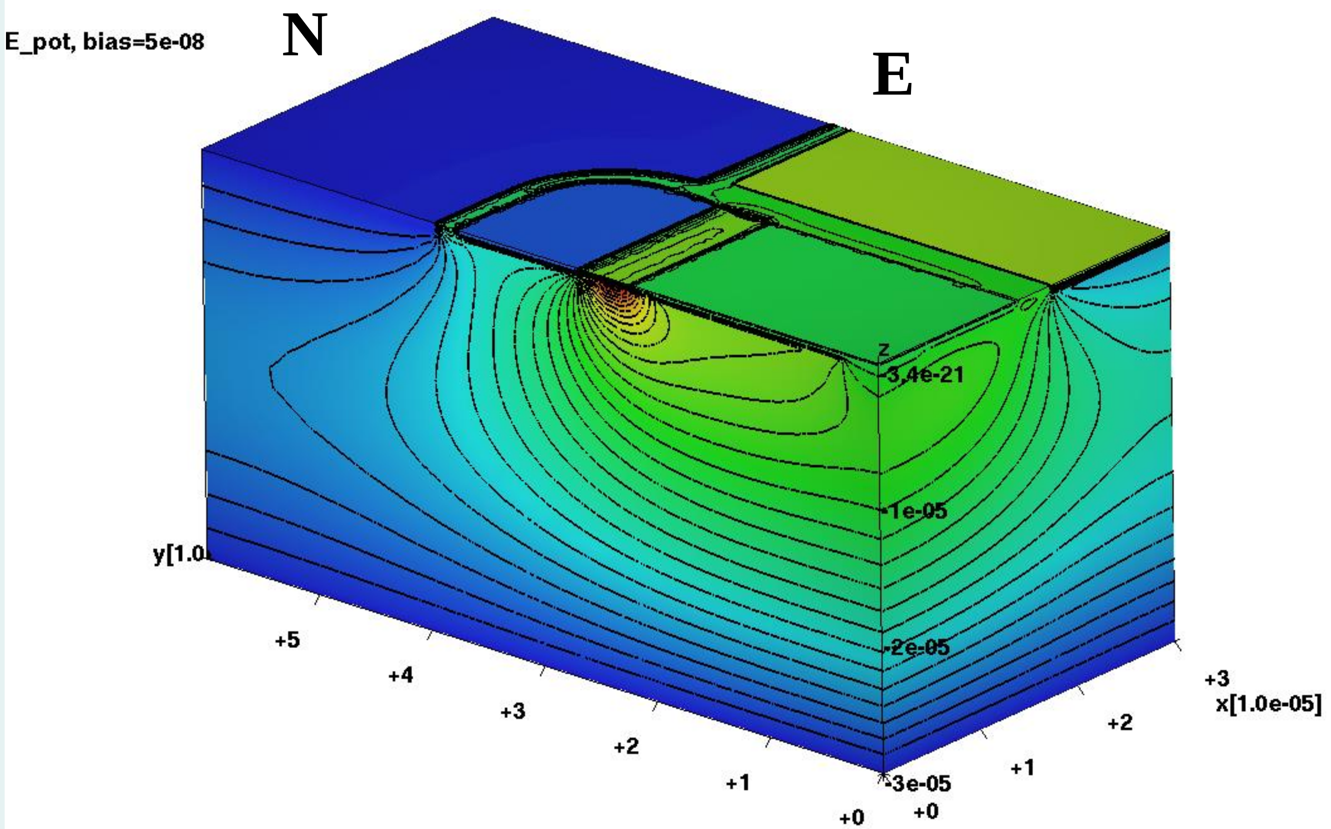


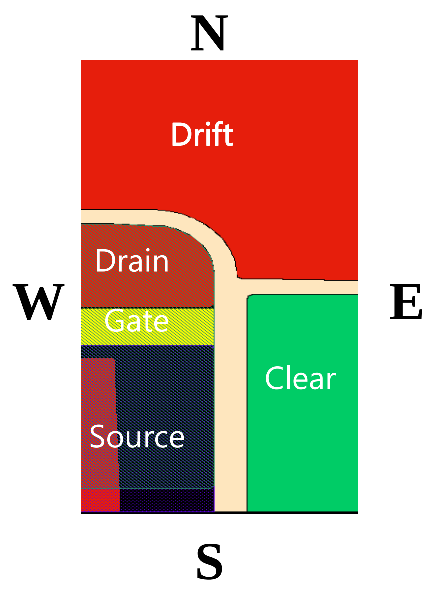
B



Cut through 1. and 2. OFR region

Potential distribution during charge collection

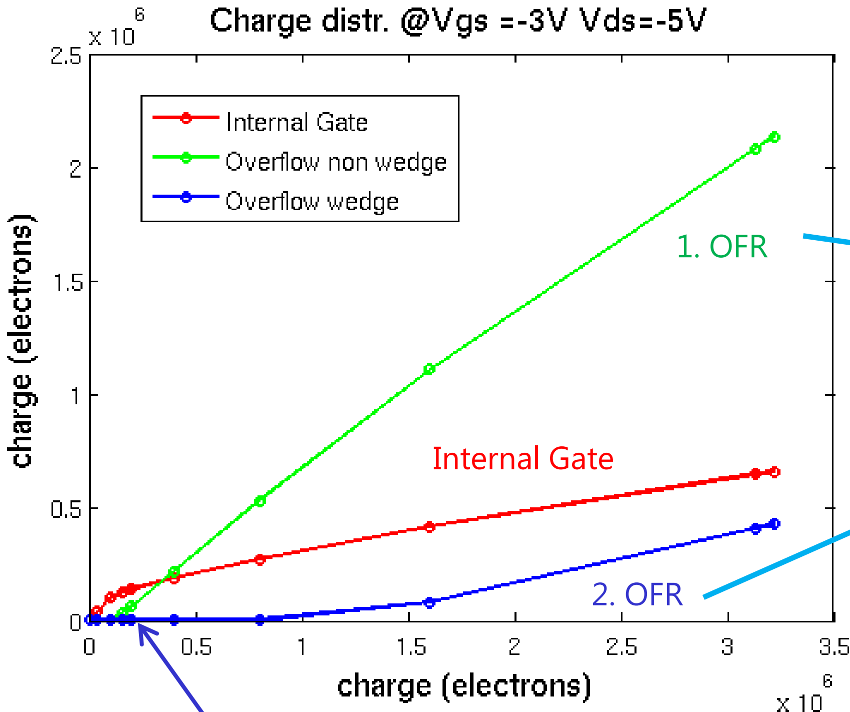


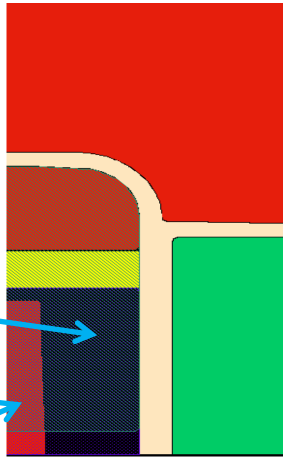


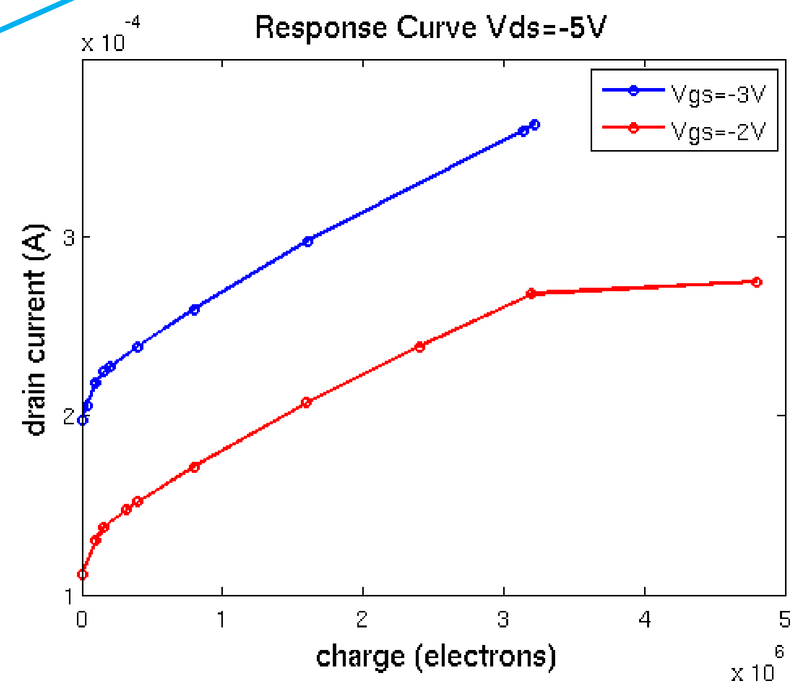
30µm/50µm detector thickness

Simulated with Oskar3 (K. Gärtner)

Charge distribution in storage regions and current response



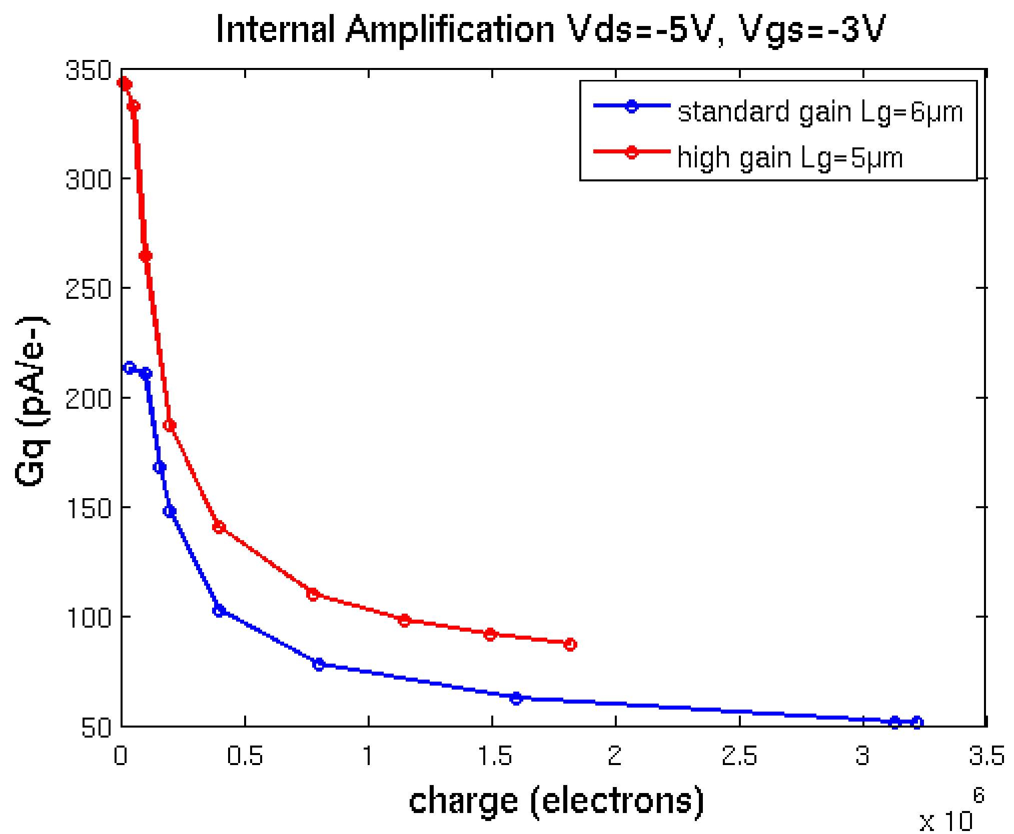




Onset of overflow

= onset of signal compression

Tailoring the amplification by design and implantation parameters

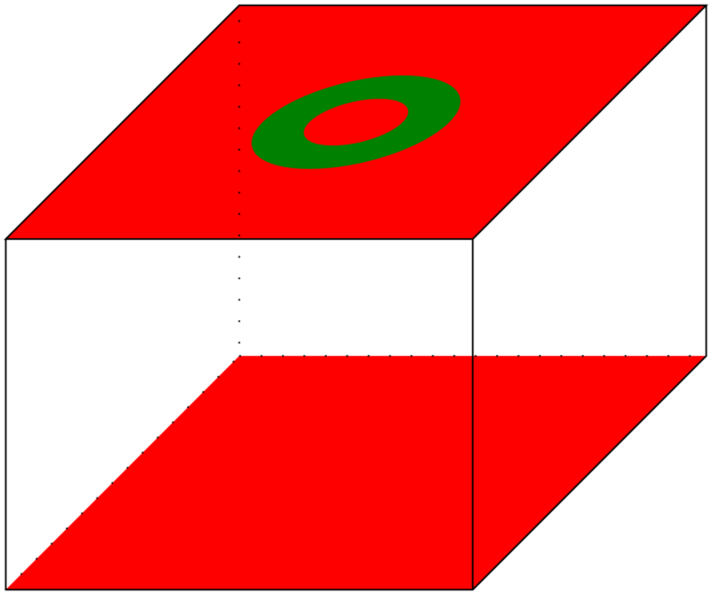


Using signal compression we get single electron resolution as well as a high dynamic range

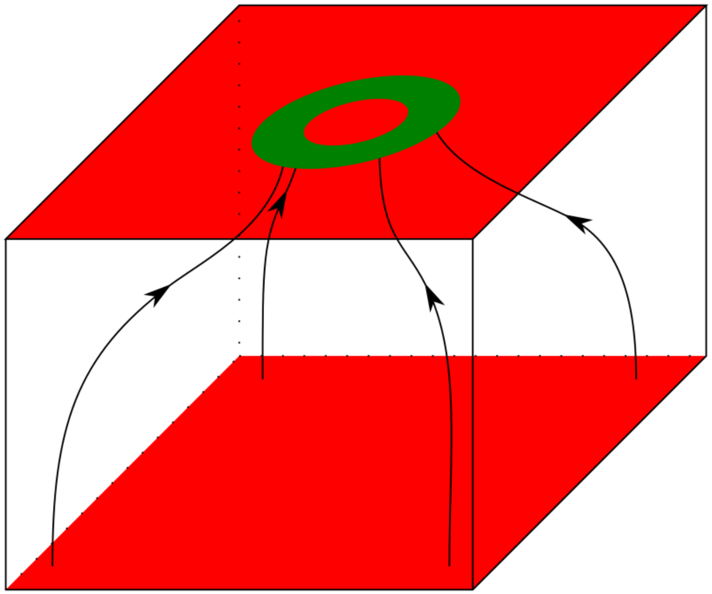
Modified DCD (Belle) ro chip has 4 different gain settings to cope with various design options (I.Peric, KIT)

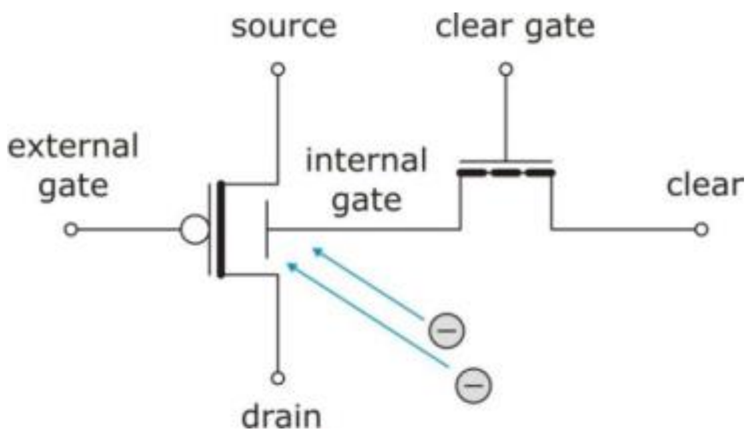
The Super pixel approach

Single pixel – one collection node

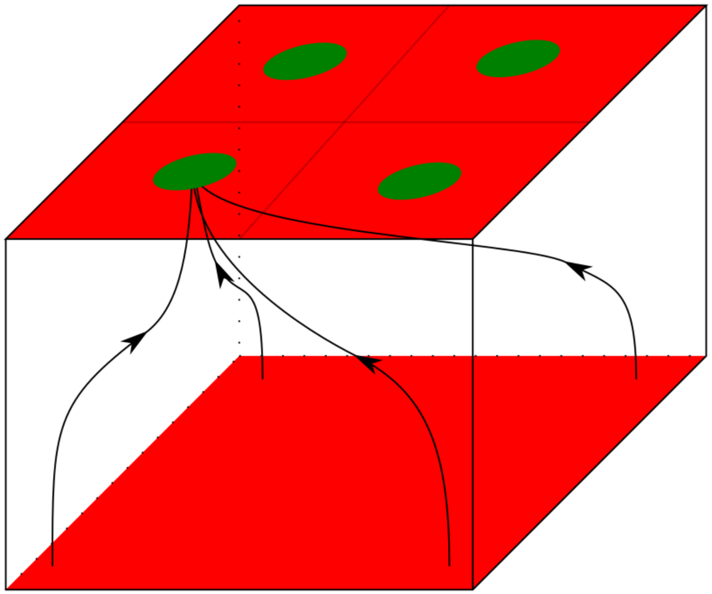


Single pixel – one storage node

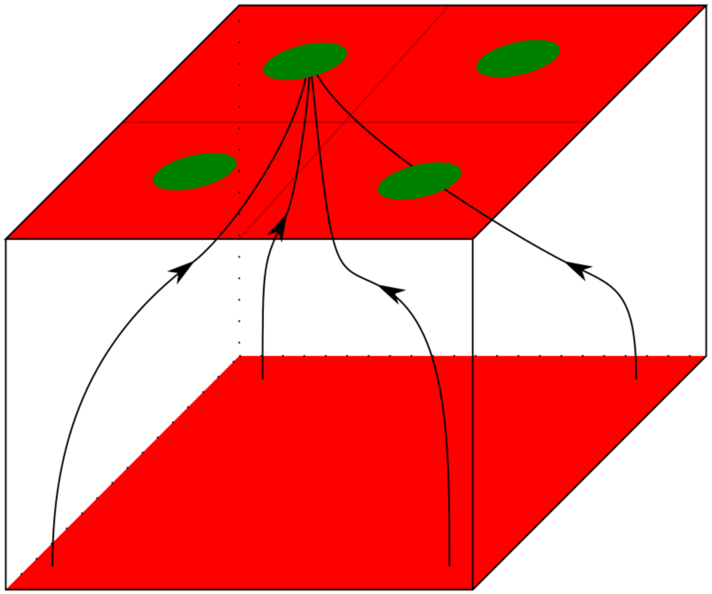




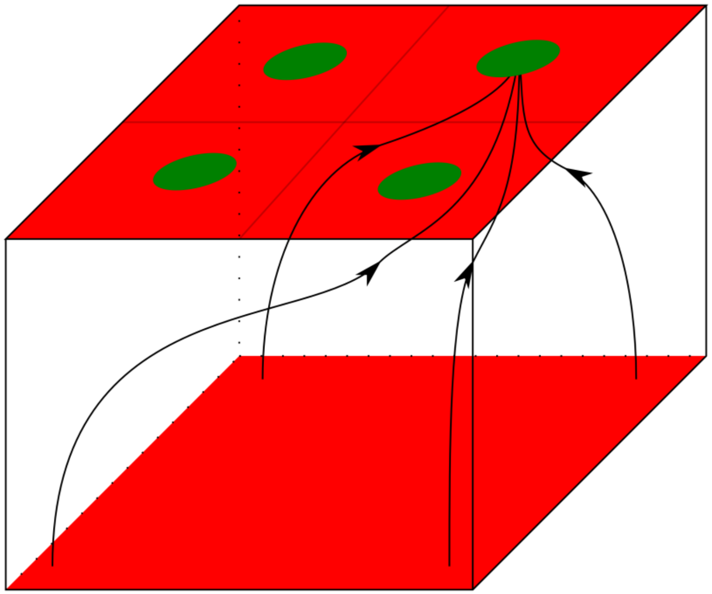
Single pixel – four storage nodes



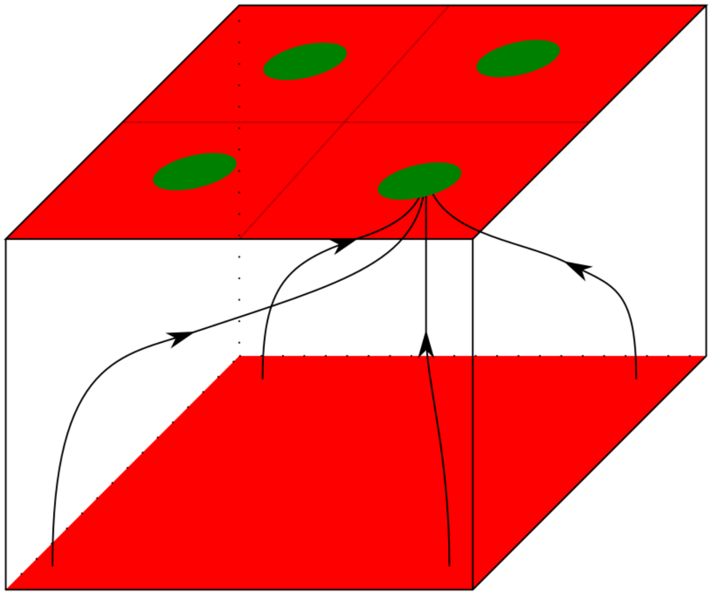
"Superpixel" with four "subpixels"

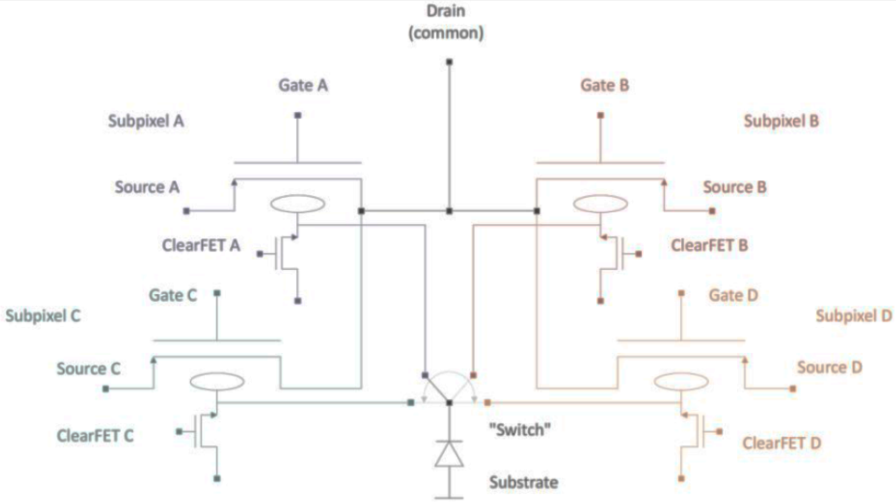


"Quadropix"



Each subpixel is a DEPFET -> Quadropix



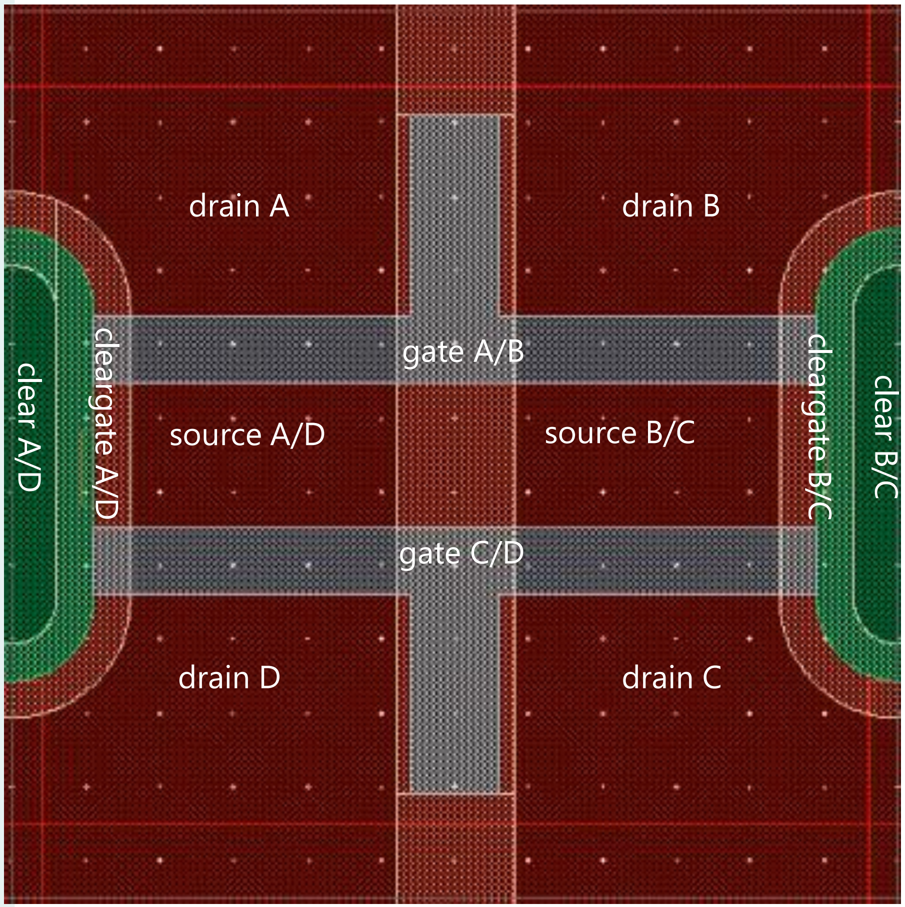


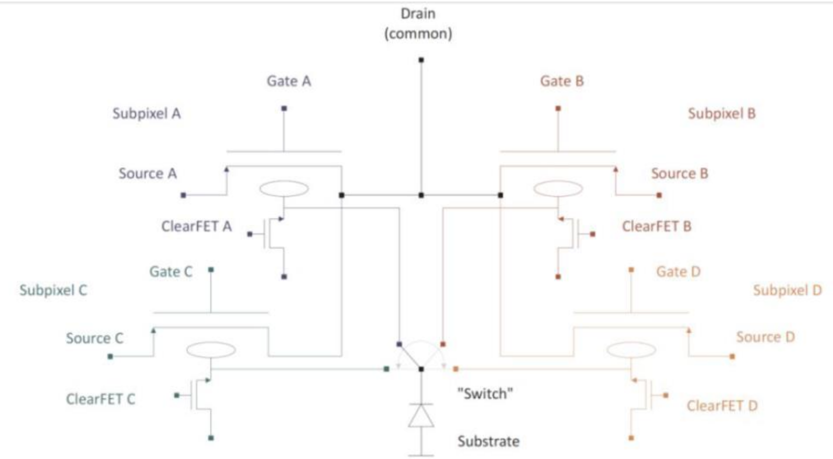
four storage nodes

much faster switching than the frame readout time

Quadropix layout with shared switchable drains (shield eletrodes)

four storage areas beneath (gate A,B,C,D)
four switching electrodes (drain A,B,C,D)





p+ regions have simulteneous functions

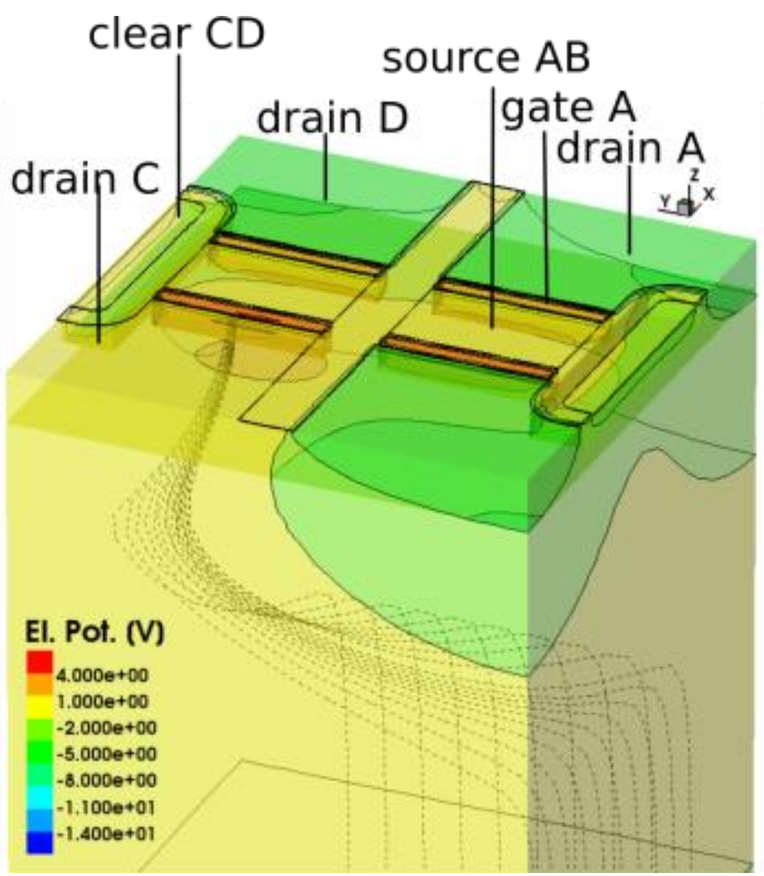
as drains and as switching electrodes

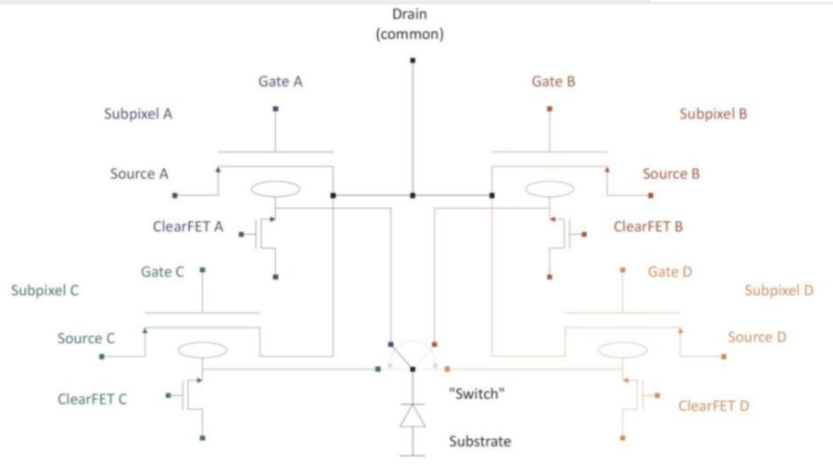
charge is stored in the internal gates

beneath external gates (grey)

TCAD simulations

four storage areas
fast modulation





A negative drain (-5V) blocks charge collection

of the neighboring internal Gate

when it switches to 0V charge collection is enabled

(lower left)

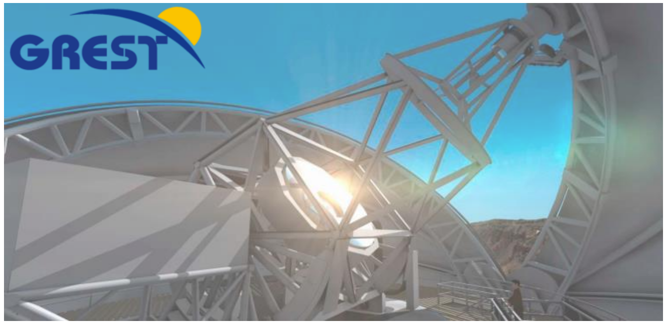
working principle was verified using 3d simulations (A. Bähr)

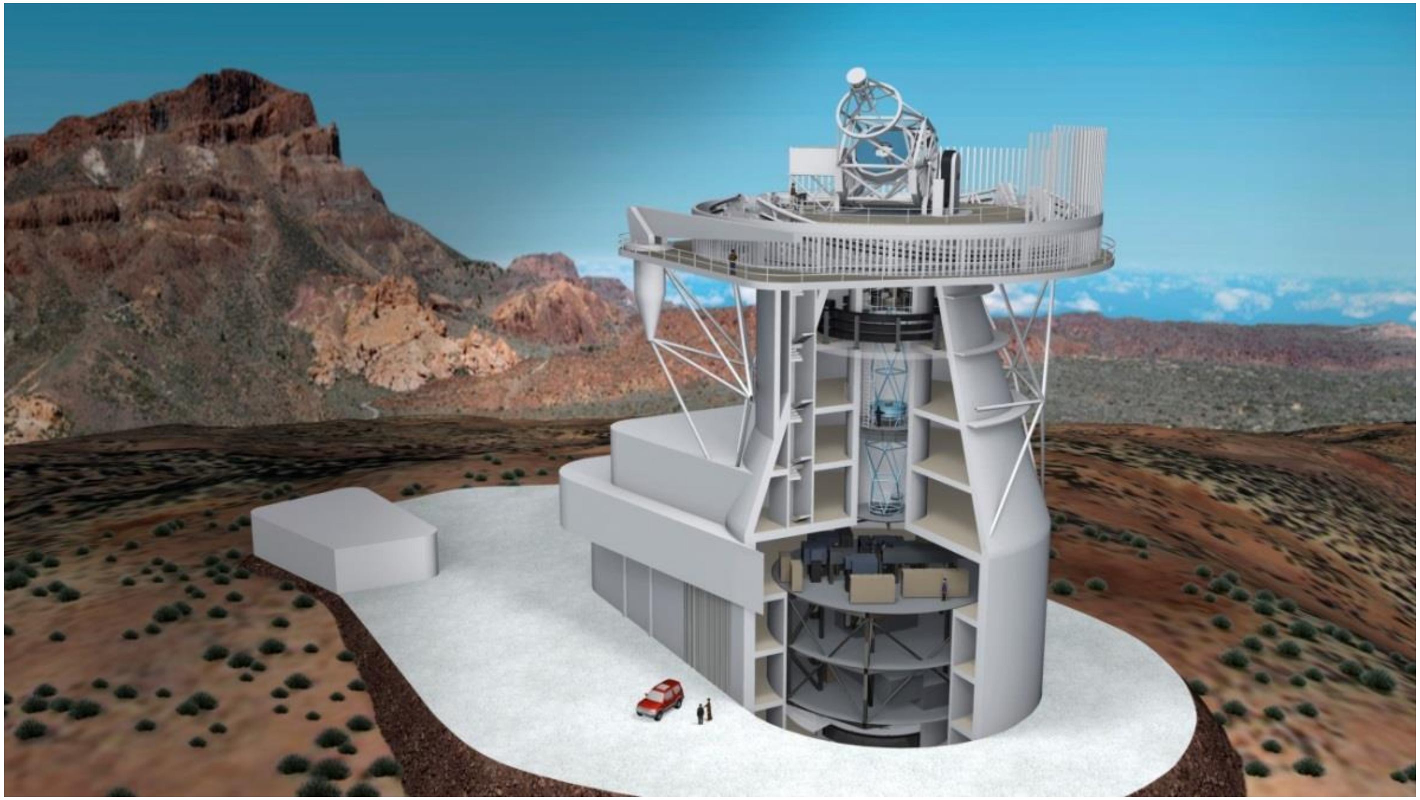
see trajectories

for details see: Bähr et al „Advanded DePFET concepts: Quadropix"
https://doi.org/10.1016/j.nima.2017.10.048

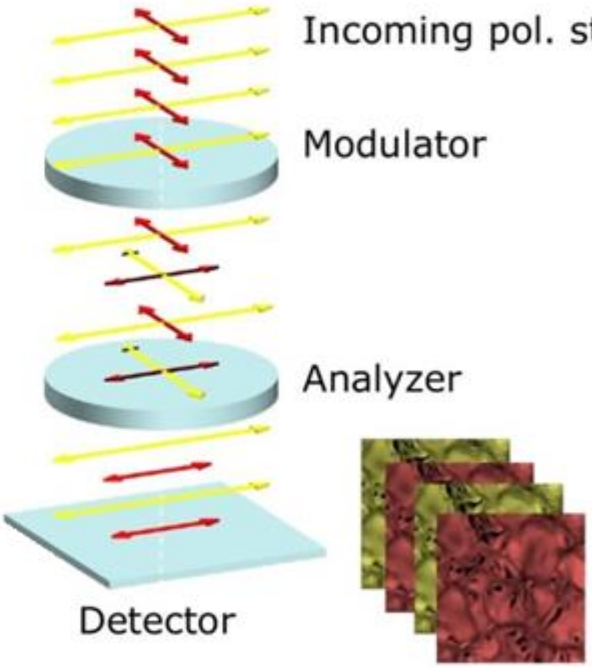
GREST

Getting Ready for the European Solar Telescope planned in 2028 at Canarian islands



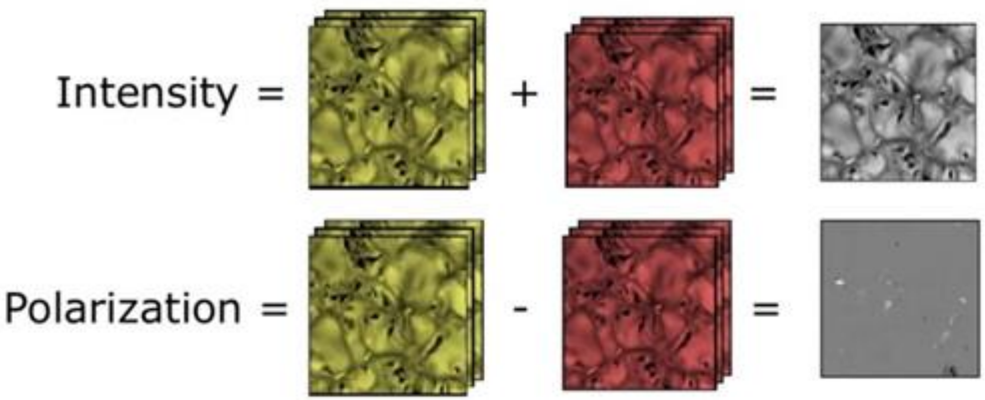


GREST – fast polarimetry detector



Modulation ~ 10 kHz

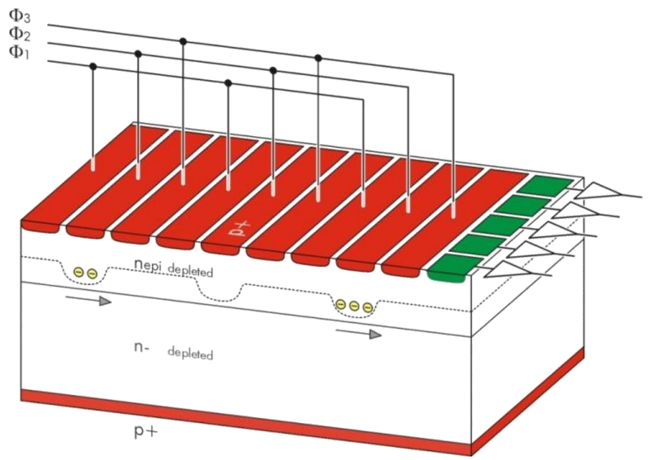
Frame-Rate ~ 400 Hz



Taking fast ‘snapshots‘ useful in photon science!?

- ▷ Switching speed of control electrodes (drains) < 100ns (matrix size)
  - ↳ experiences from CCDs registers
- ▷ Within frame read out time: possible to set take 3 fast intermediate samples
  - ↳ "Micro Movies"
  - ↳ The fourth for the rest of the frame time
- ▷ Combination with signal compression mode
  - ↳ To be studied
- ▷ Expansion to "Octopix"
  - ↳ Under investigation
- ▷ Stay tuned ☺

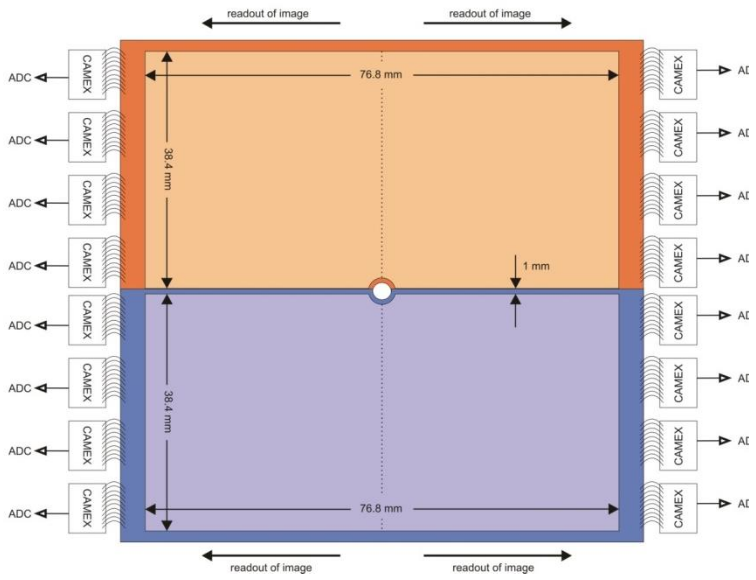
pn CCDs used at LCLS (Camp, Lamp), FLASH



- fast, robust, high quality

  entrance window and radiation hard

LCLS system



Large area pnCCDs

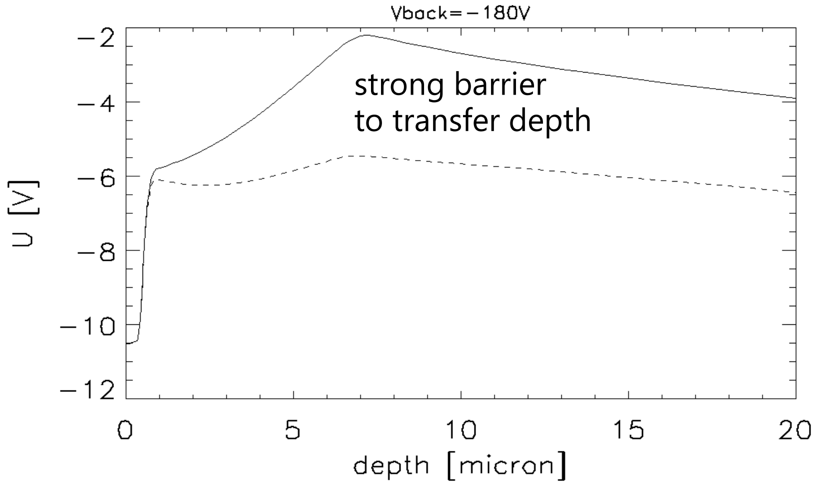
- use at synchrotron radiation facilities
- 2 x 1024 x 512 pixels
- area 7.8 x 3.7 cm^2 = 29.6 cm^2
- 60 cm^2 total sensitive area
- pixel size 75 x 75 μm^2
- 1024 parallel read nodes
- 6 e$^-$ @ 120 fps
- 4k x 4k resolution points

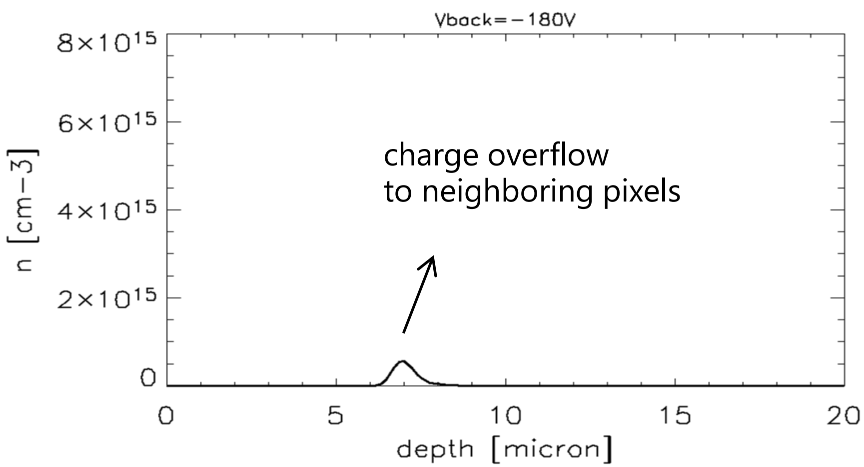
  (@ 6 keV, no pileup)

High dynamic range (HDR) mode – tuning of Vback

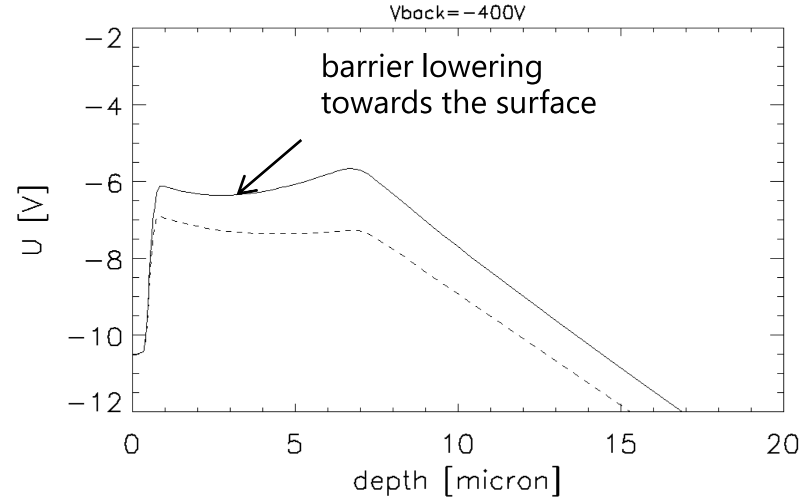
Perpendicular cross section through a register (top to back)

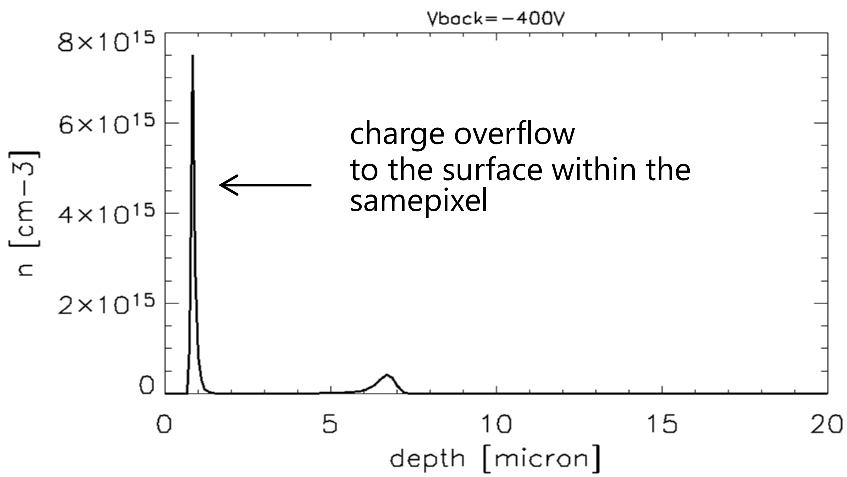
Normal operation





HDR operation



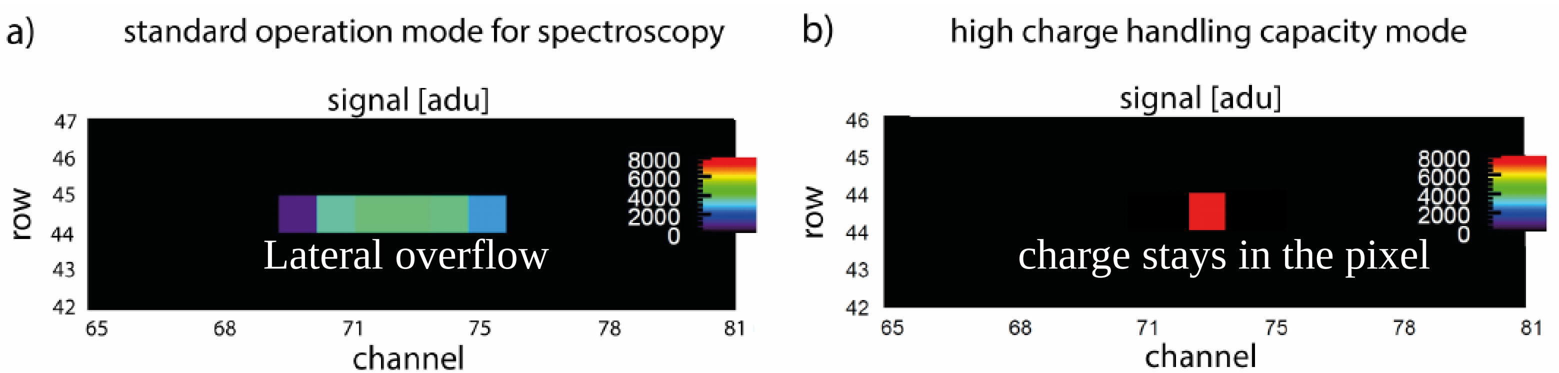


Example: pn CCD as electron detector

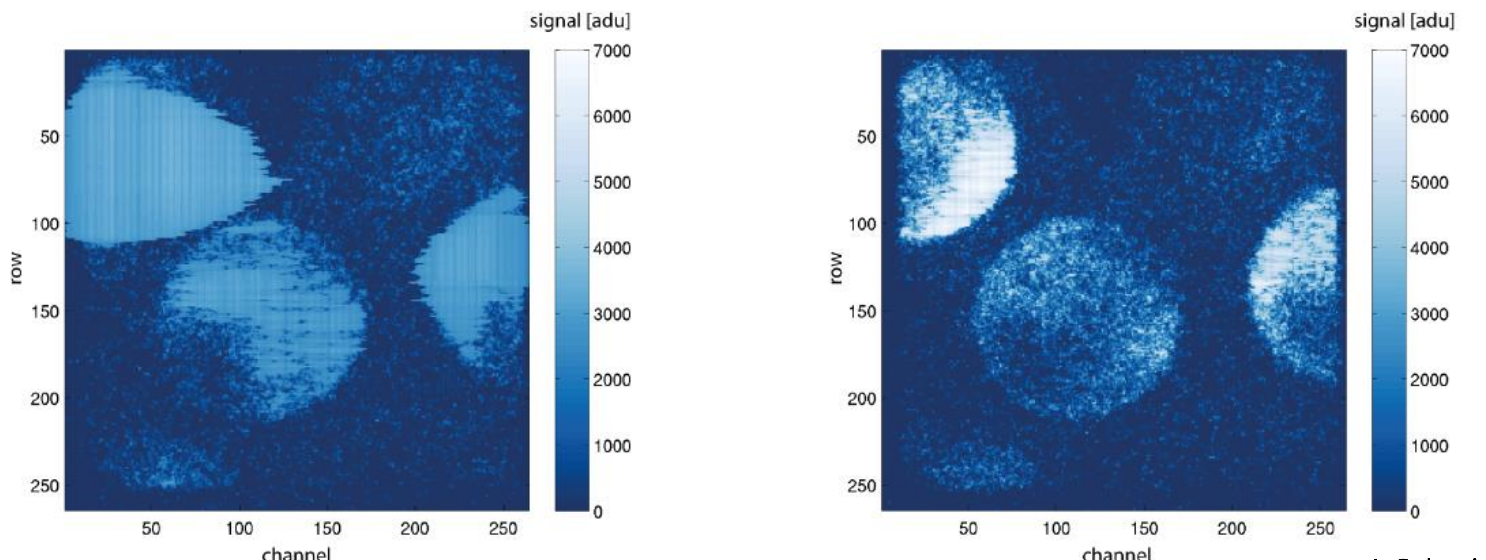
Laser focussed to 1pixel

300 000 e- /pixel

1 800 000 e-/pixel



TEM images (300keV electrons)



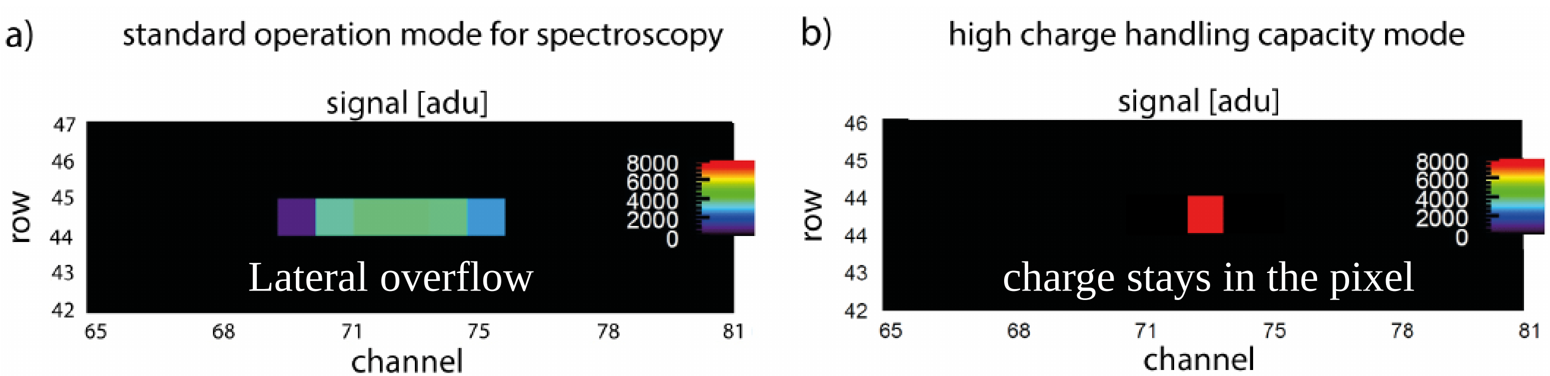
J. Schmidt, JINST 2014

But …

300 000 e- /pixel

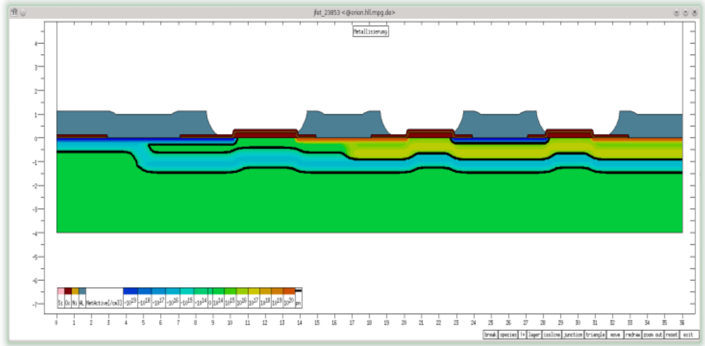
1 800 000 e- stored in pixel

but not seen by the amplifier which is in saturation



On chip JFET is optimized for low noise operation (small input cap. 60fF)

saturates at 8000 ADU (corresponds to 700 000 electrons)



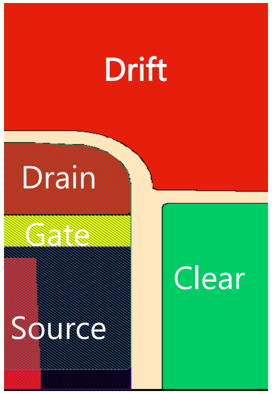
Low noise and *real* HDR operation is impossible with the same detector.

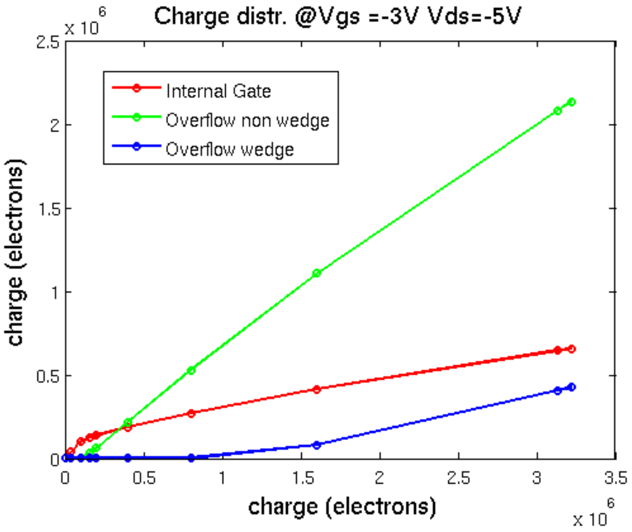
Replace JFET with DEPFET

Why not use DEPFET with signal compression?

The device we developed for the DEPFET electron detector

could do the job. It is even much nore compact than the circular JFET ☺

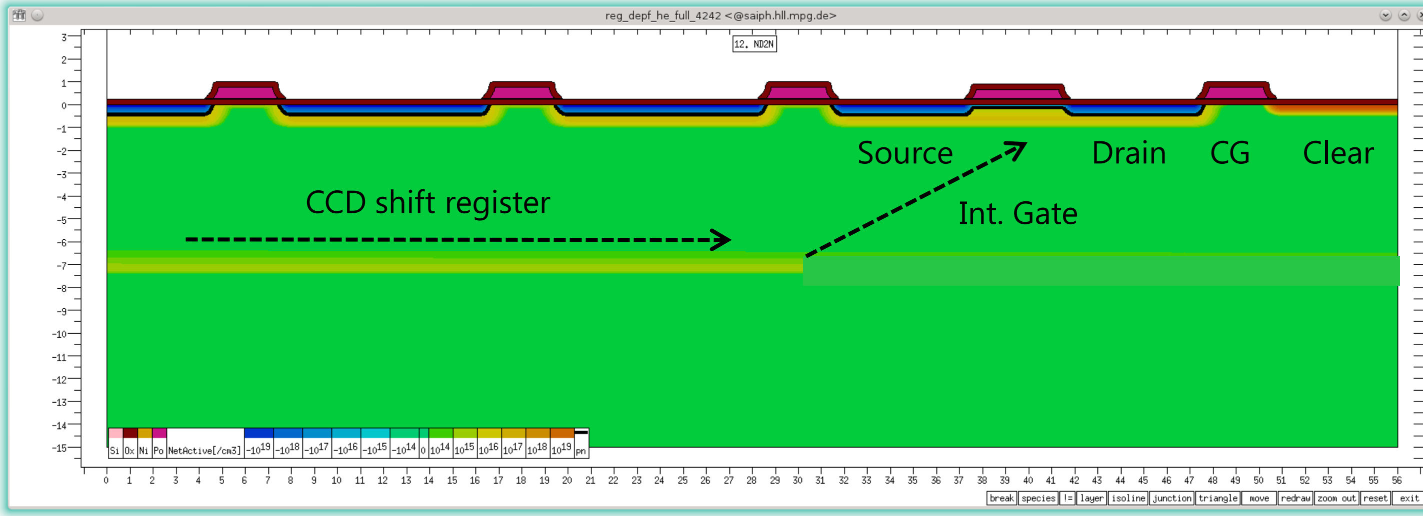


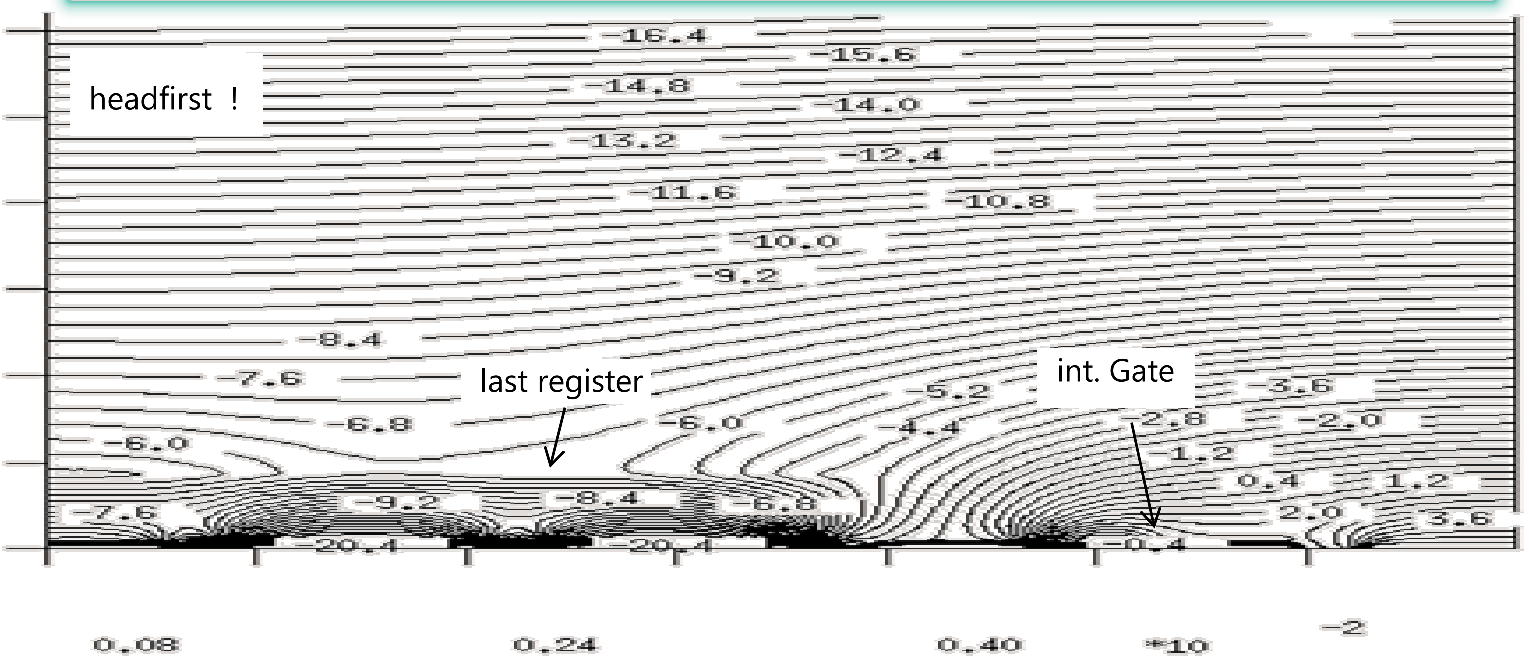


But would about the charge transfer from the deep register

into the shallow internal Gate ?

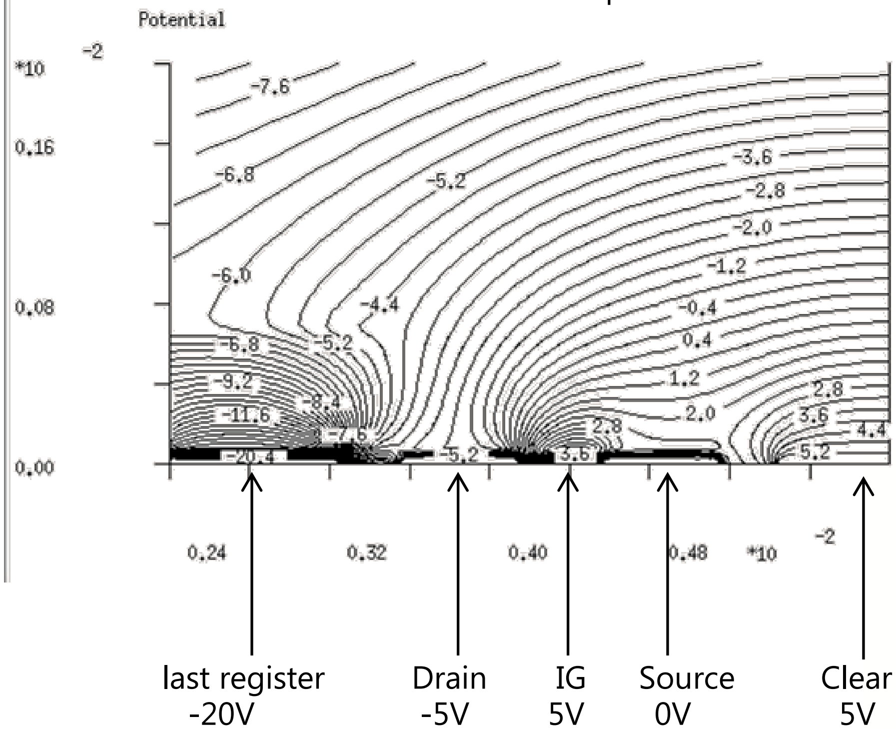
Works in simulations!



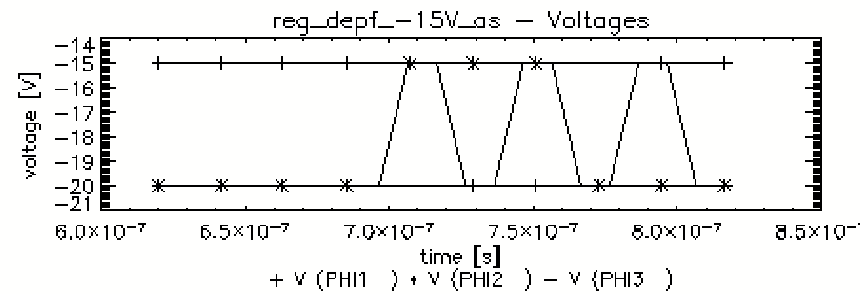


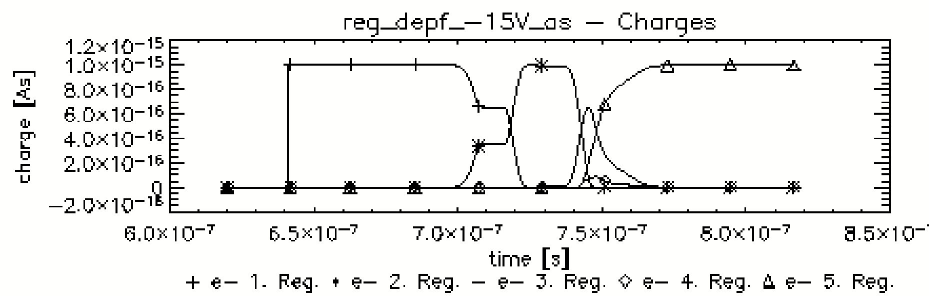
Generation of a test charge of 1fAs at the most left register

Potential map



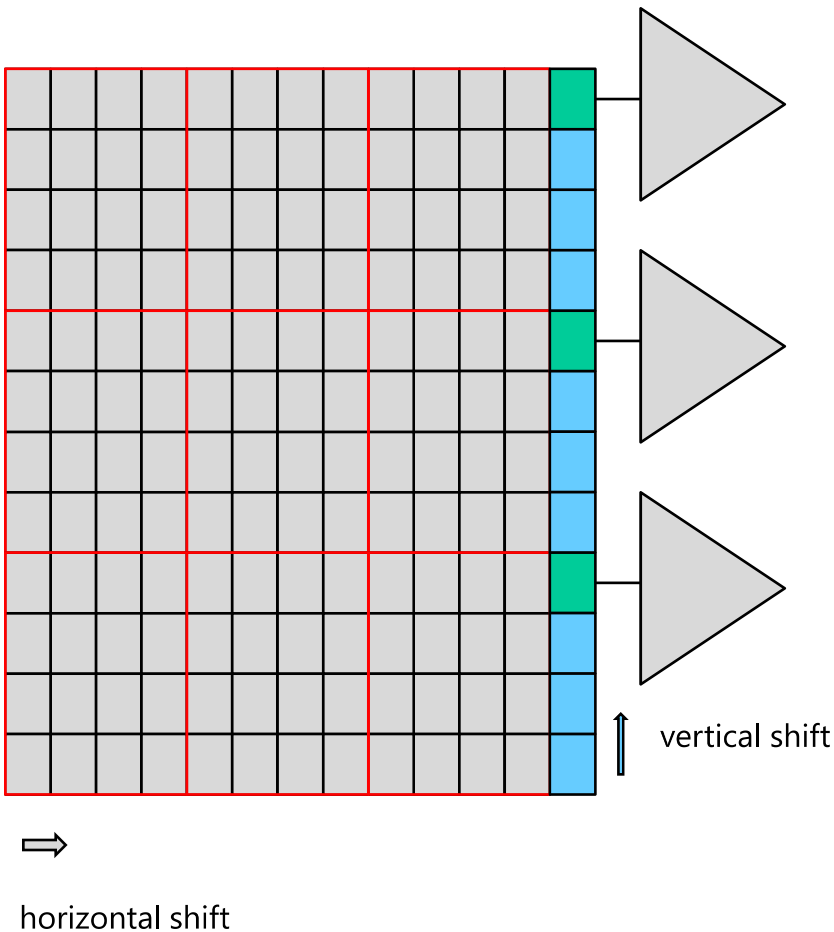
Complete charge transfer, no losses ☺





Smart binning approach for pnCCDs

Read out ASIC has given pitch
finer pixel granulation possible



to read out red area:

fine pitch:

4x(1 hor. shift, RO, 3x (1 vert. shift, RO))

16 x RO

medium pitch:

2x(2 hor. shift, 1 vert. shift) RO, 2 vert. shifts RO)

4 x RO

coarse pitch:

4 hor. shift, 3 vert. shift RO

1 x RO

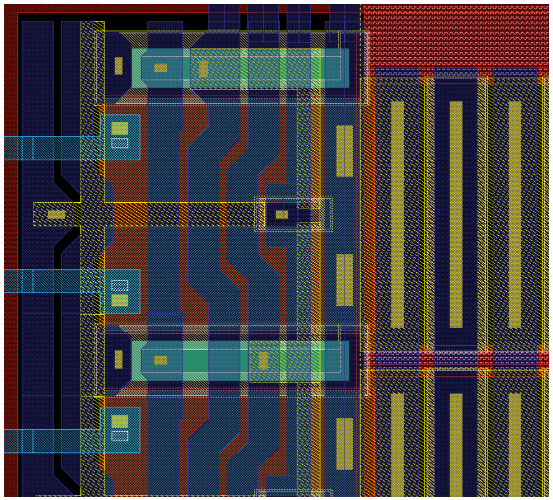
for medium and coarse pitch

cumulation of charge on RO anode

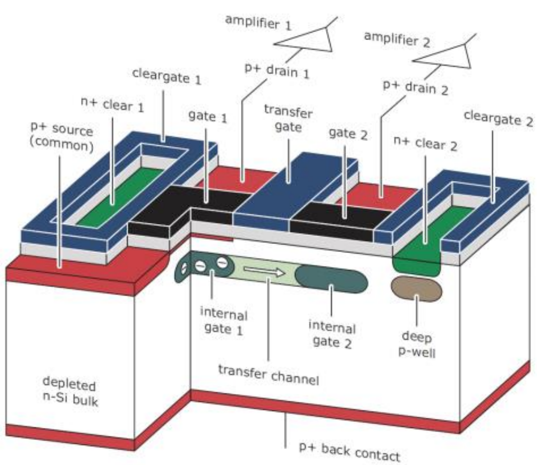
-> readout noise only once

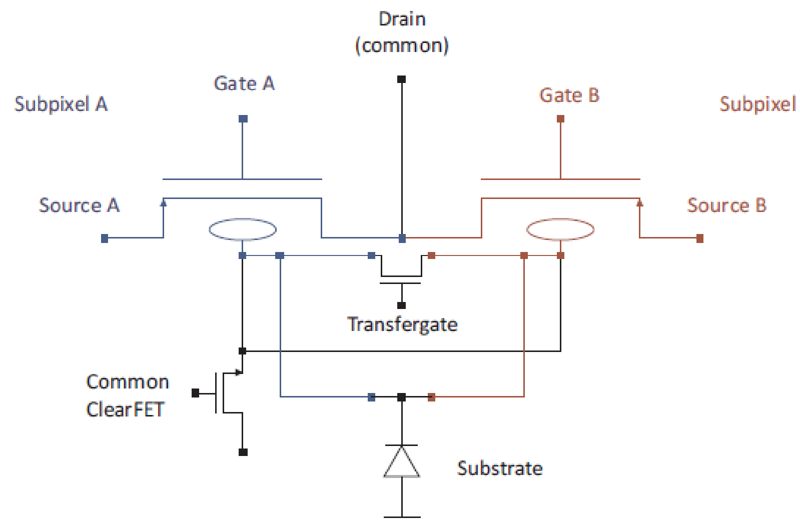
We can also place 2 DEPFETs per column …

Repetitive Non Destructive Readout (RNDR) - ‚Skipper mode'



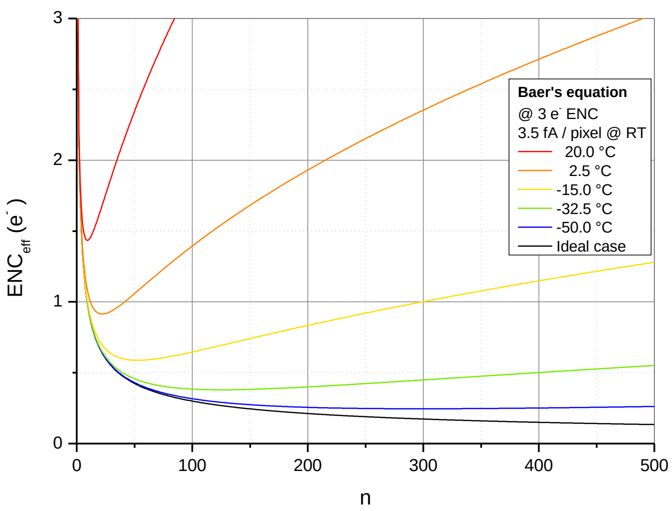
- By measuring the charge multiple (n) time the "effective noise" can be reduced by 1/n .
- Because the collected charge is stored during readout in the DEPFET-RNDR, the very same charge can be measured multiple times.



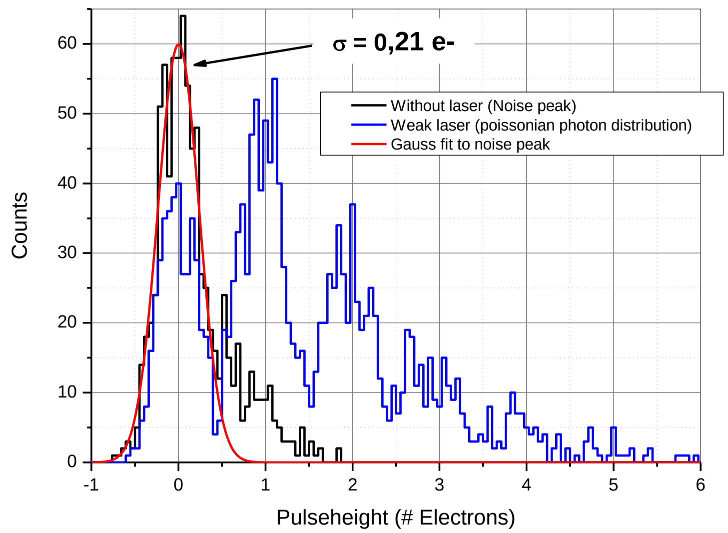


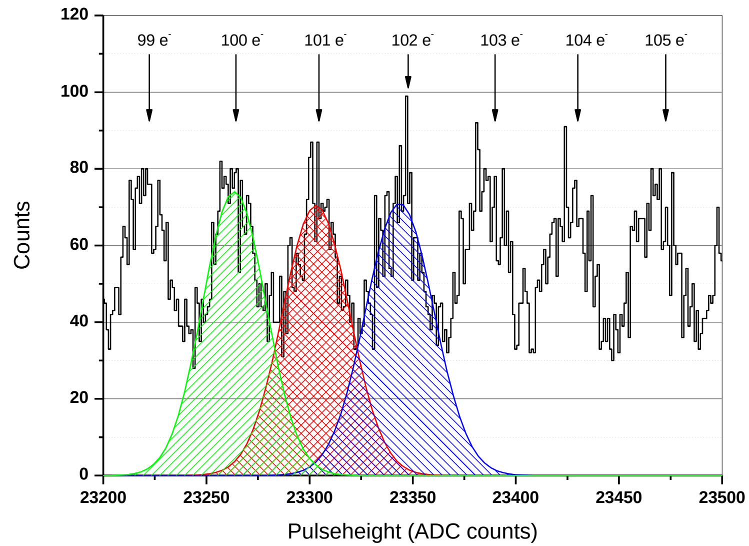
Performance model: Bähr's equation

- Bähr's equation: $$V(\bar{x}) = \frac{\sigma^2}{n} + \Delta\sigma^2 \cdot \left(\frac{1}{2} + \frac{1}{3} \cdot n - \frac{5}{6} \cdot \frac{1}{n}\right)$$
- Optimum number of cycles: $$n_{opt} = \sqrt{3 \cdot \frac{\sigma^2}{\Delta\sigma^2} - \frac{5}{2}}$$
- Optimum effective noise: $$ENC_{eff}^{opt} = \sqrt{\frac{\sigma^2}{n_{opt}} + \Delta\sigma^2 \cdot \left(\frac{1}{2} + \frac{1}{3} \cdot n_{opt} - \frac{5}{6} \cdot \frac{1}{n_{opt}}\right)}$$



Laser spectra taken on DEPFET RNDR superpixel structures





Measurement:

- Charge injection with laser during integration time
- 180 Loops for the readout (duration: 9,18 ms)
- -45 degree
- Measured leakage current:

ca. 0,4 e- in 180 loops

Summary

- The MPG Semiconductor Lab develops and produces radiation sensors and detector systems for a variety of application fields.
- Set up and tailor new technologies to the needs of specific applications
- Using synergy effects and modular design a basic set of sophisticated sensor devices, i.e. DEPFET, pnCCD, SDD can be modified and adapted to new requirements
- Examples with potential for an use in photon science were shown
- New readout options for pnCCDs are proposed

  - by the integration of DEPFET with signal compression as readout amplifiers a high dynamic range operation is not limited anymore by fixed anode capacitances

  - a DEPFET-RNDR (Skipper mode) structure can be attached to each CCD column reducing the noise far below 1 ENC.

Questions?