DepFET detectors in astrophysics and particle physics instrumentation
(and photon science)

Jelena Ninkovic

for the MPG HLL team

MPS Semiconductor Laboratory, Munich

MPS Semiconductor Laboratory (in German: MPG Halbleiterlabor - HLL)

Located in the south-east of Munich on the Siemens Campus in Neuperlach
30 employees: scientists, engineers and technicians
+ guest scientists, engineers and students

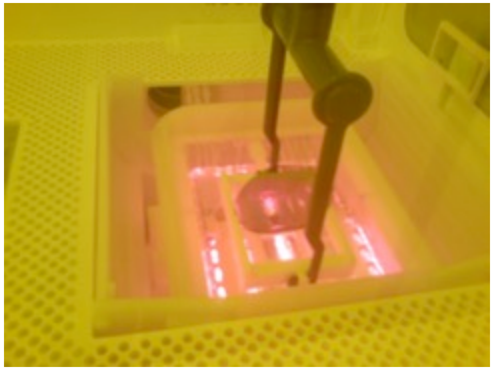
MPG HLL is the only lab worldwide doing fully depleted silicon radiation sensors with integrated electronics optimized for different scientific projects

The MPG HLL history

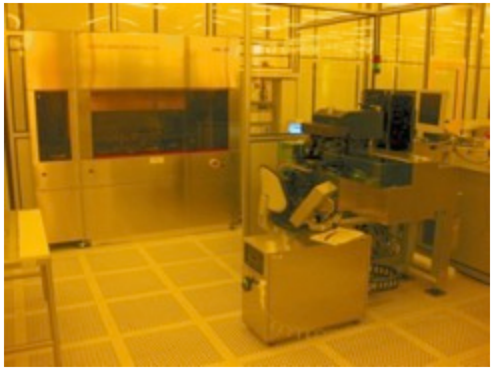
- Started 1983 – NA11 experiment
- 6 inch process line from 2001
- Till 2013 joined lab of the MPI for Physics
  MPI for Extraterrestrial Physics
- From 2013 - Central Unit of the Max-Planck-Society
  - Open to all Max Planck Institutes
  - and to External partners

Inside HLL – Sensor Fabrication

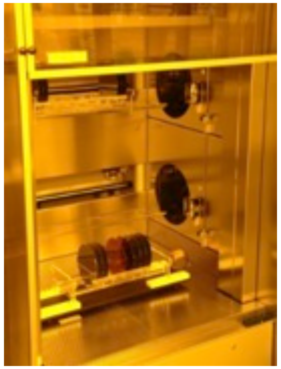
cleaning



lithography

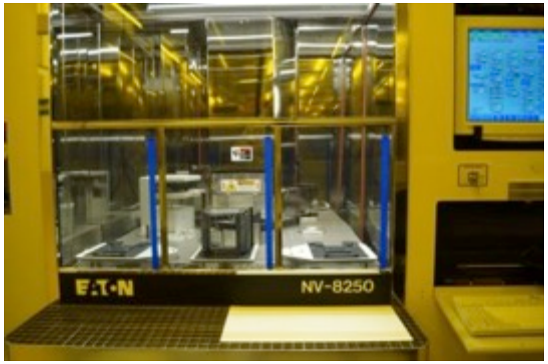


thermal



inspection

implantation



6″ Si full processing line
class 1000 to class 1 in certain areas

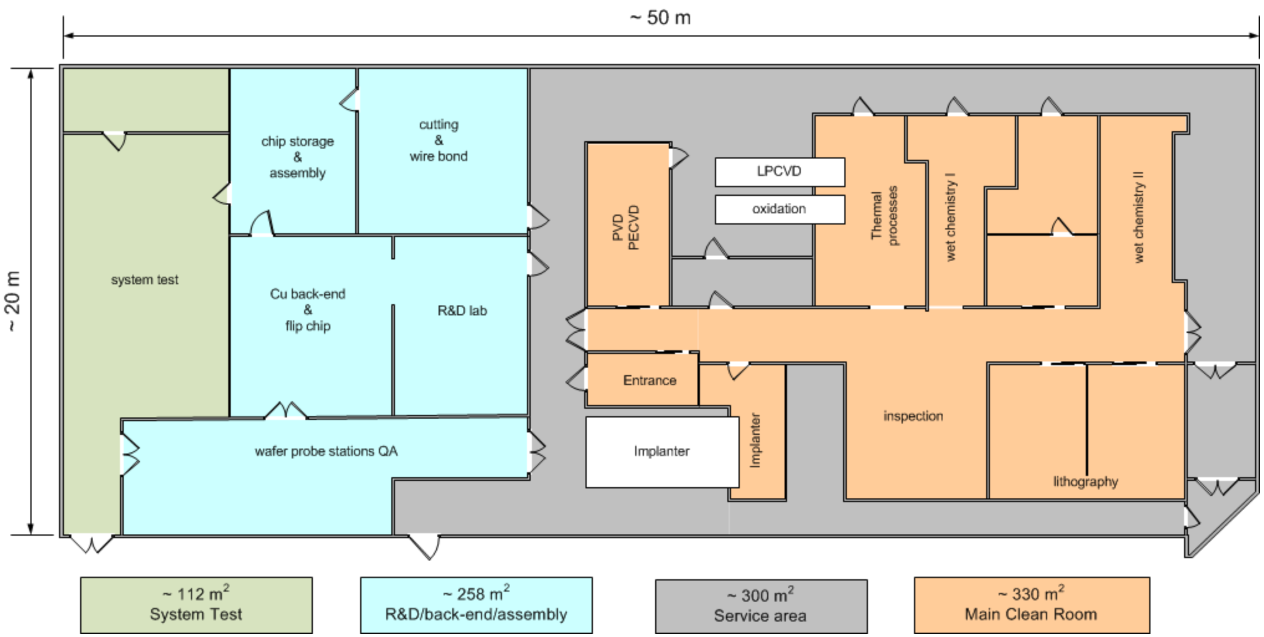
Inside HLL – Sensor Fabrication

plasma and sputter

Cu line

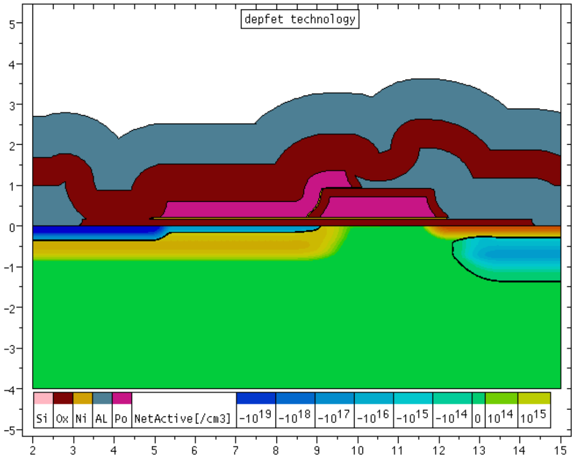
flip chip

assembly and test

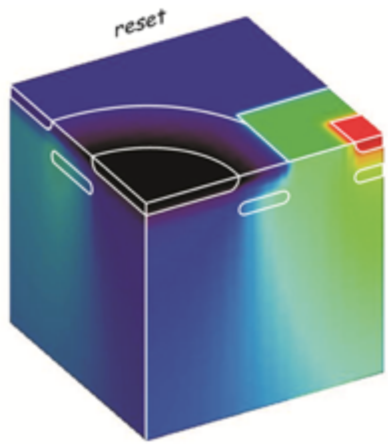


Inside HLL – Sensors and Systems: Design & Test

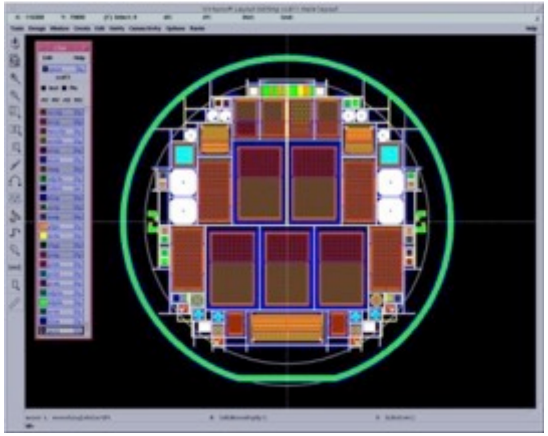
Process simulation



Device simulation, 2D and 3D



State-of-the-art layout tools



Wire bonding, hybrid assembly

@ HLL:

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

System test facilities

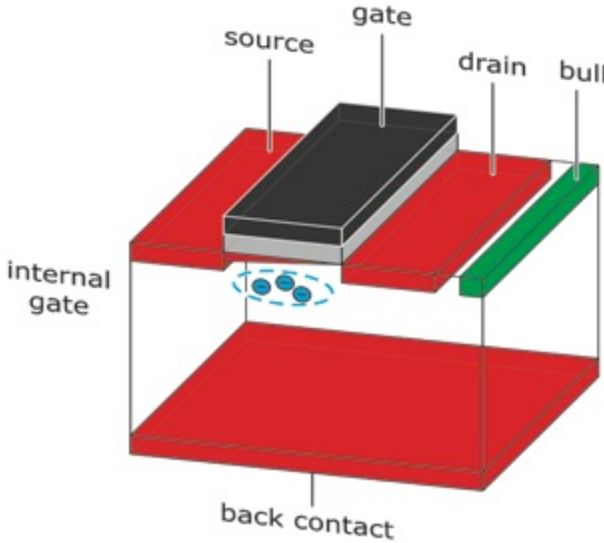
DEPFETs

p-MOSFET on fully depleted n-substrate

- **fully depleted** sensitive volume
  - fast signal rise time (~ns), small cluster size
  - no stitching, 100% fill factor
- **Charge collection in "off" state**, read out on demand
  - potentially low power device
  - Non destructive readout
- **internal amplification**
  - charge-to-current conversion (300 pA/el.)
  - large signal, even for thin devices
  - r/o cap. independent of sensor thickness (20 fF)

Applications:
- unit cell of active pixel sensor
- integrated readout device of SDD, pnCCD, …

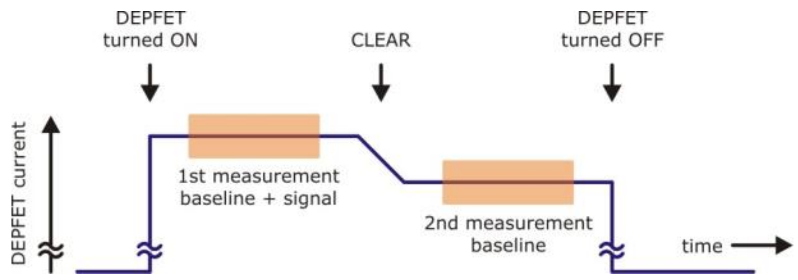
Proposed by
Josef Kemmer &
Gerhard Lutz, 1987



DEPFET detectors

DEPFET readout

▷ readout sequence



➢ Double sampling

- 1st measurement: signal + baseline
- clear: removal of signal charges
- 2nd measurement: baseline
- difference = signal

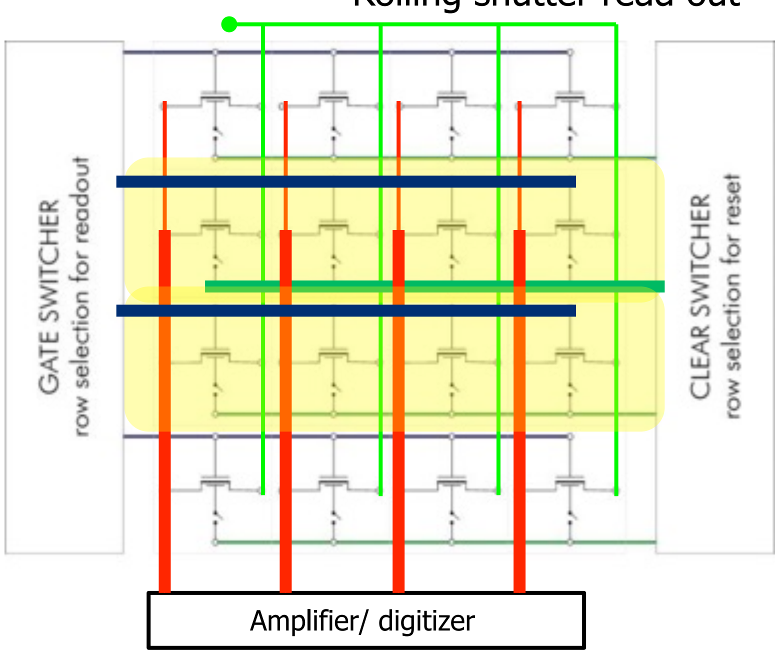
➢ Single sampling

- Measure pedestals and store
- Read once and clear

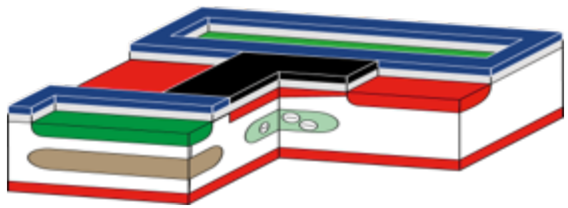
▷ active pixel sensor operation

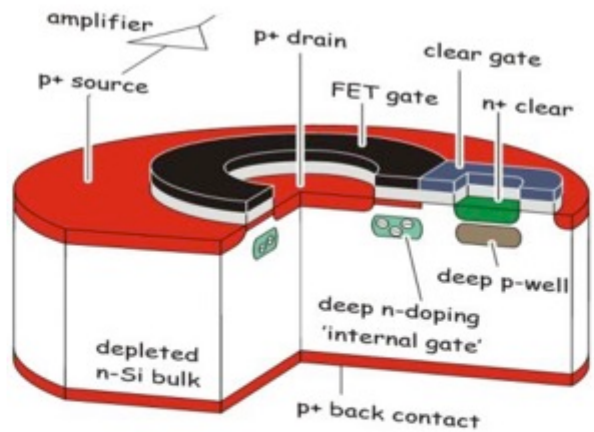
- horizontal supply lines, row selection
- vertical signal lines
- 1 active row, other pixels integrating

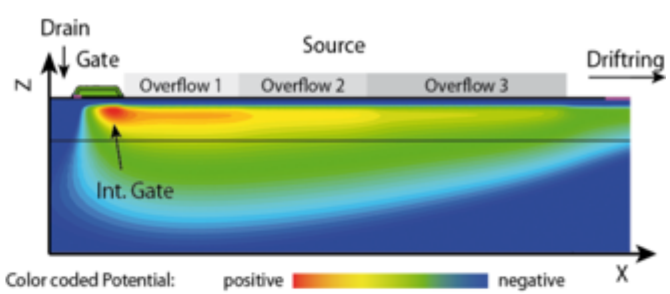
Rolling shutter read out



DEPFET classes







Thin & small pixel: vertex, low E electron detectors (TEM)

pixel size: 20µm…75µm
read out time per row: 25ns-100ns
Noise: ≈100 el ENC
thin detectors: 50µm…75µm → still large signal: 40nA/µm for MIP

Low noise: Spectroscopic X-Ray imaging

pixel size: 100µm, with drift rings several 100s of µm
read out time per row: few µs
Noise: ≈4 el ENC
fully depleted, the thicker the better → large QE for higher E

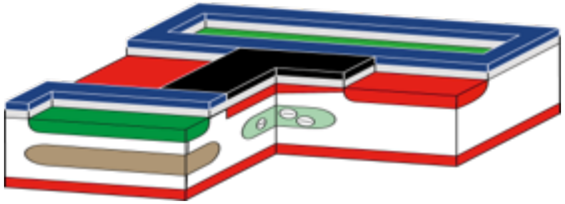
High Dynamic range

DEPFET **S**ensor with **S**ignal **C**ompression
Sensitivity to single photons and high dynamic range
pixel size: 60 -200 µm

Projects using DEPFETs developed and fabricated @ MPG HLL

- Vertex detectors for high energy physics experiments – BELLE II and future ILC
- X-ray fluorescence spectrometer for MIXS on BepiColombo
- X-ray imaging spectroscopy - ATHENA mission – Wide Field Imager (WFI)
- FEL radiation detection – sensors for European XFEL
- Electron Detectors - 80k low E electron detectors

DEPFET classes



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pixel size: 20µm…75µm
read out time per row: 25ns-100ns
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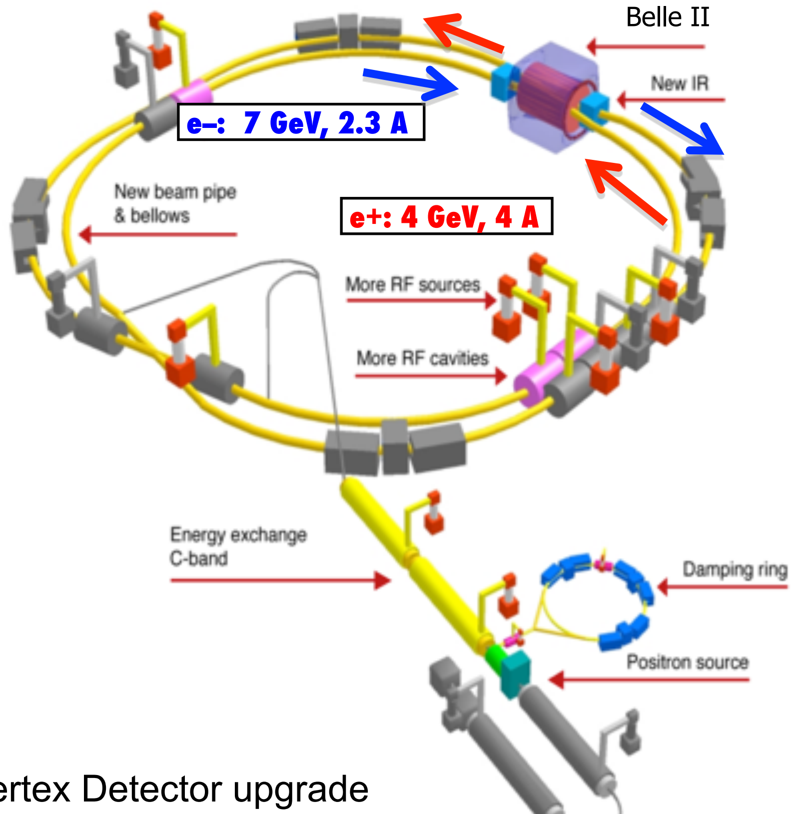
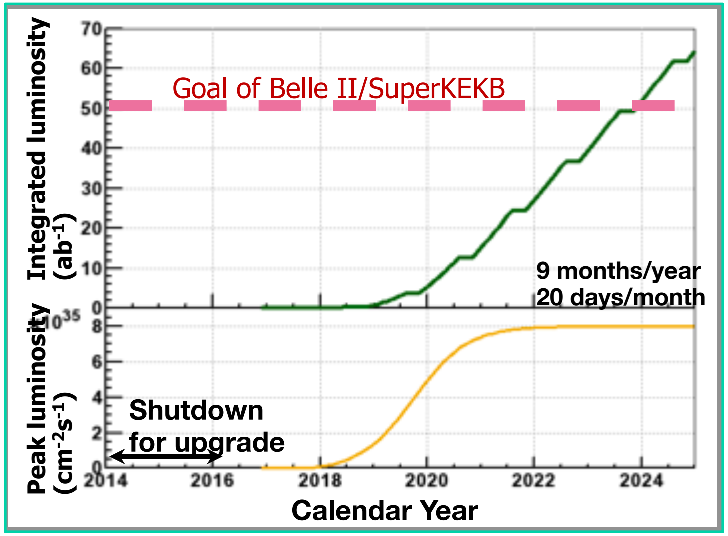
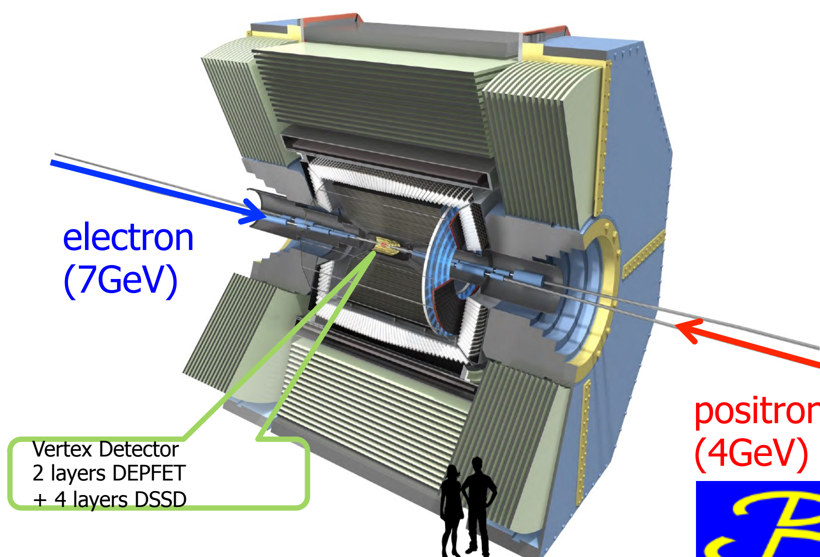
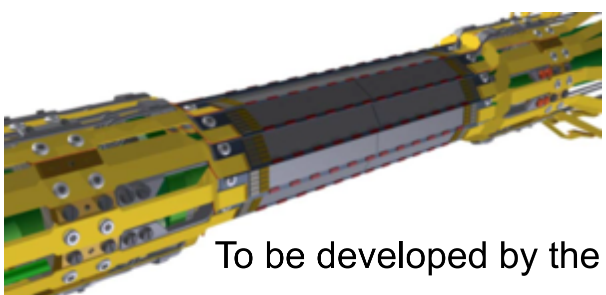
BELLE II @ SuperKEKB





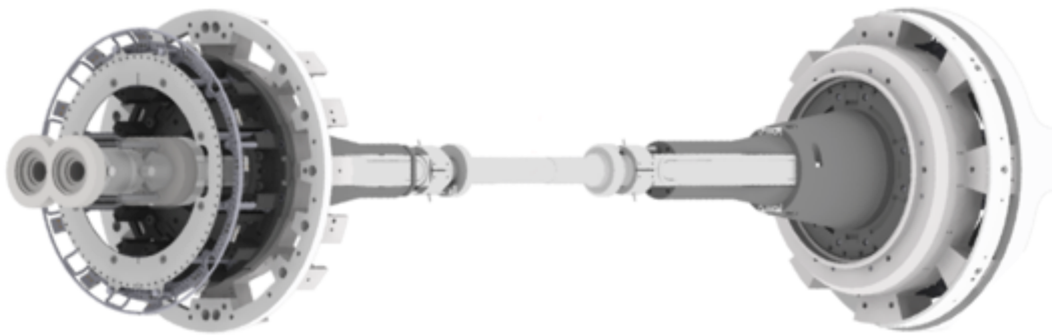


Vertex Detector upgrade
DEPFETs are chosen for the inner layers

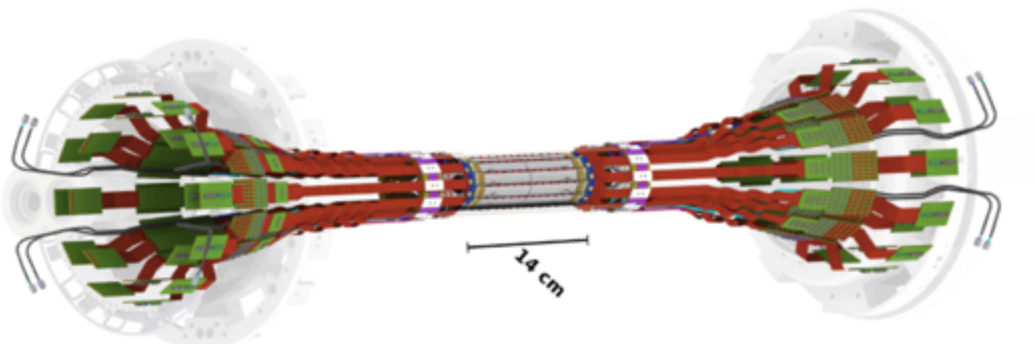


To be developed by the DEPFET collaboration

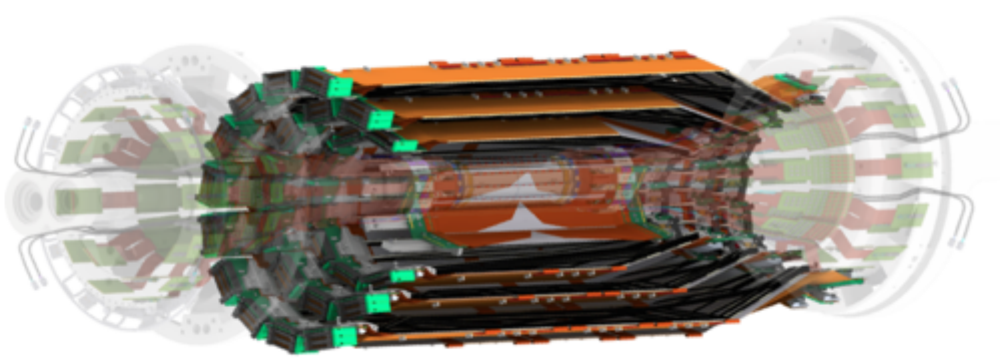
VXD @ BELLE II



Beryllium beampipe:
Radius: 10 mm.



PXD: Pixel Detector
2 layers Si Pixel at R =1.4 & 2.2cm
DEPFET Technology
Thickness: 75μm

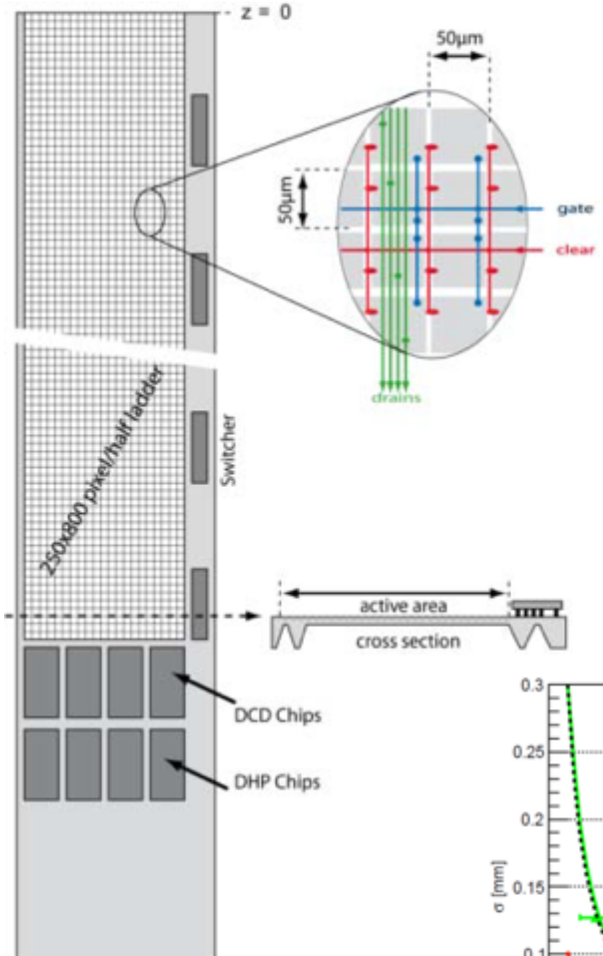


SVD: Silicon Vertex Detector
4 layers double sided Si strip detector
R =3.8, 8.0, 11.5 & 14 cm

DEPFETs for BELLE II vertexing - Module

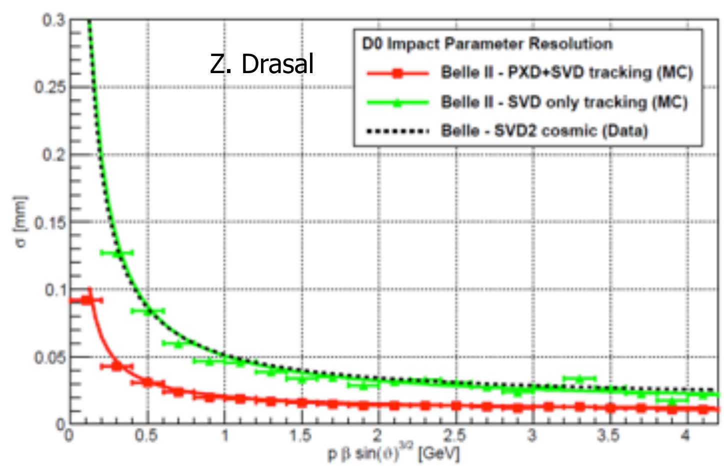
Requirements:
- Single point resolution **~10 µm**
- Radiation **~20 Mrad (10 years)**
- Material budget **0.2 % X_0/layer**
- Frame time **20 µs**

All silicon module

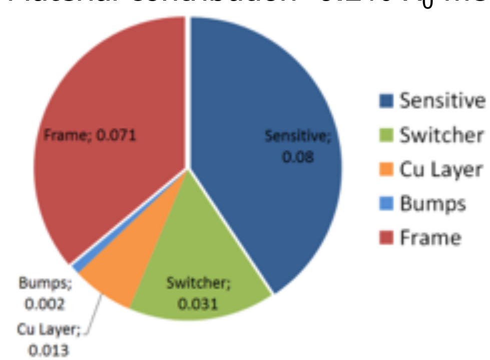


	Inner layer	Outer layer
# ladders	8	12
Sens. length	90mm	123mm
Radius	1.4cm	2.2cm
Pixel size	50x50 µm2	50x75 µm2
# pixels	1600(z)x250(R-ϕ)	
Thickness	**75 µm**	
Frame/row rate	50 kHz/10 MHz	

DCDB & SWB developed by KIT
DHP developed by UNI Bonn



Material contribution 0.2% X_0 measured



DEPFET all-silicon module

DCDB (Drain Current Digitizer)
Analog front-end

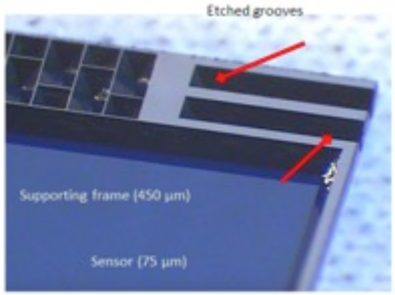
Amplification and digitization of DEPFET signals.

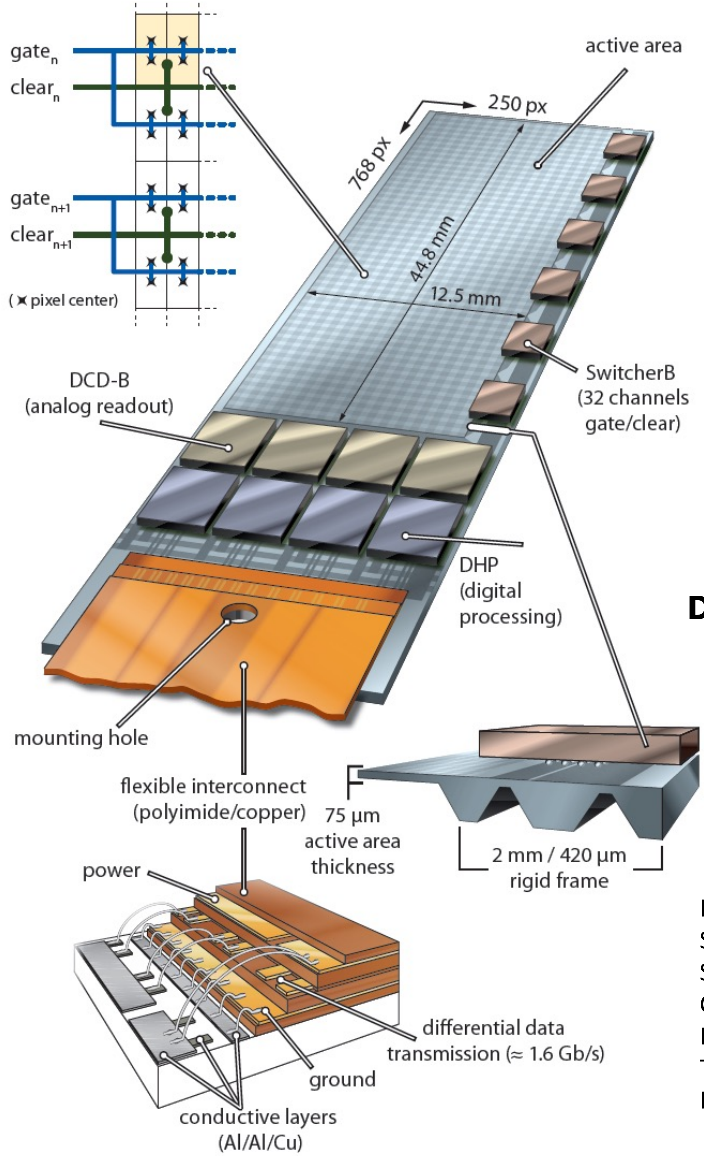
256 input channels
8-bit ADC per channel
92 ns sampling time
UMC 180 nm
Rad hard design

Low mass vertex detectors

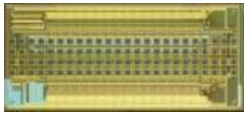
MCMs with highest possible integration!

- Thin sensor area
- EOS for r/o ASICs
- Thin (perforated) frame with steering ASICS



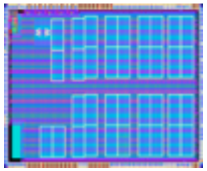


SwitcherB - Row Control



AMS/IBM HVCMOS 180 nm
Size 3.6 × 1.5 mm^2
Gate and Clear signal
32x2 channels
Fast HV ramp for Clear
Rad. Hard proved (36 Mrad)

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
Common mode and pedestal correction
Data reduction (zero suppression)
Timing and trigger control
Rad. Hard proved (100 Mrad)

Thin DEPFETs for BELLE II PXD

Thin (50µm-75µm) self-supporting all silicon module

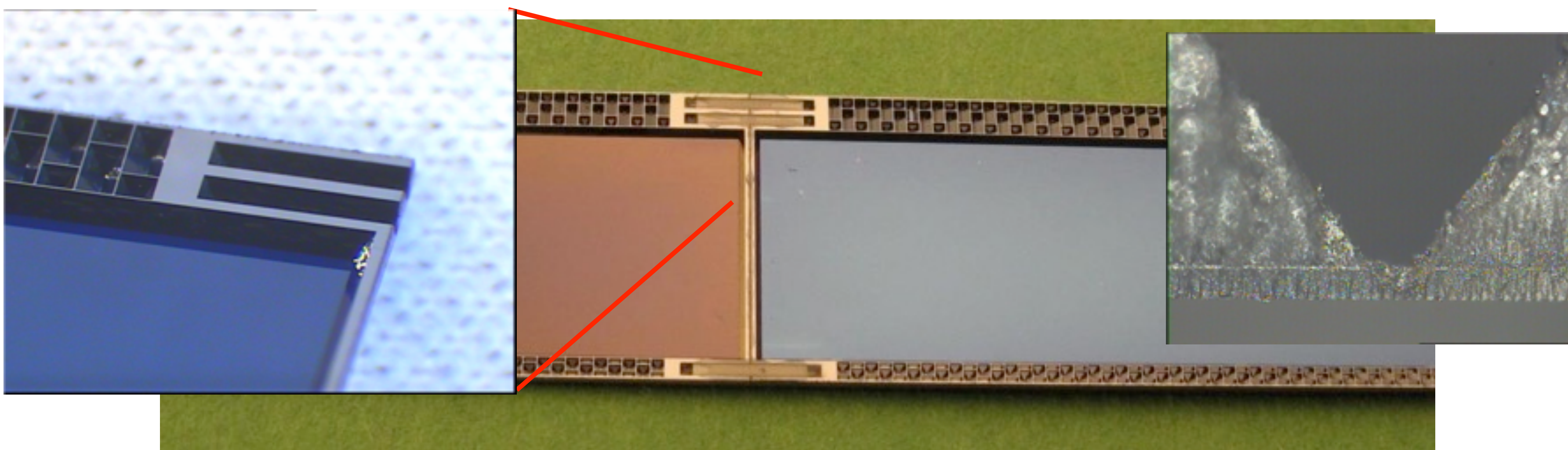
Process backside e.g. structured implant

Wafer bonding SOI process

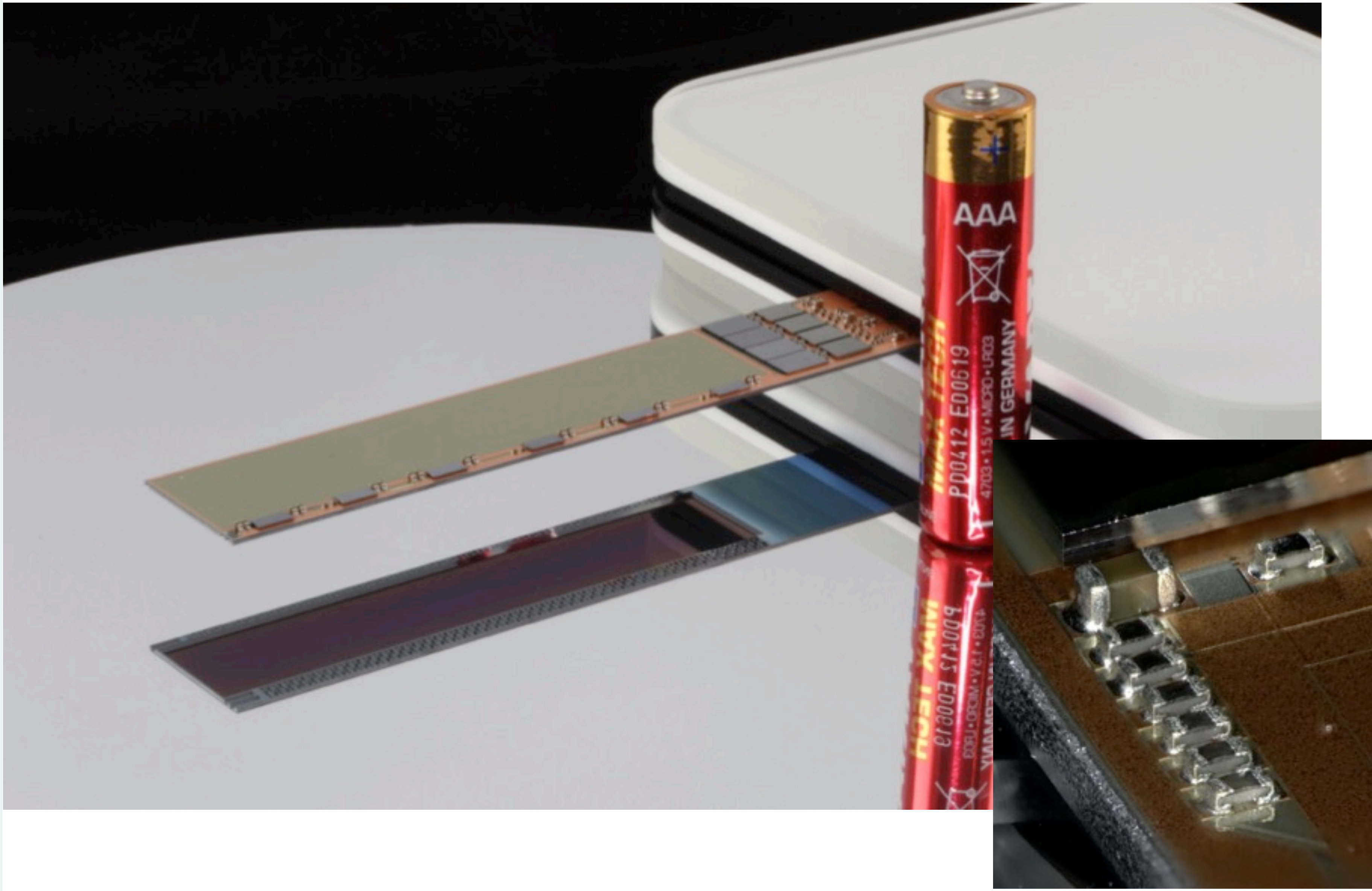
Thinning of top wafer (CMP)

Processing

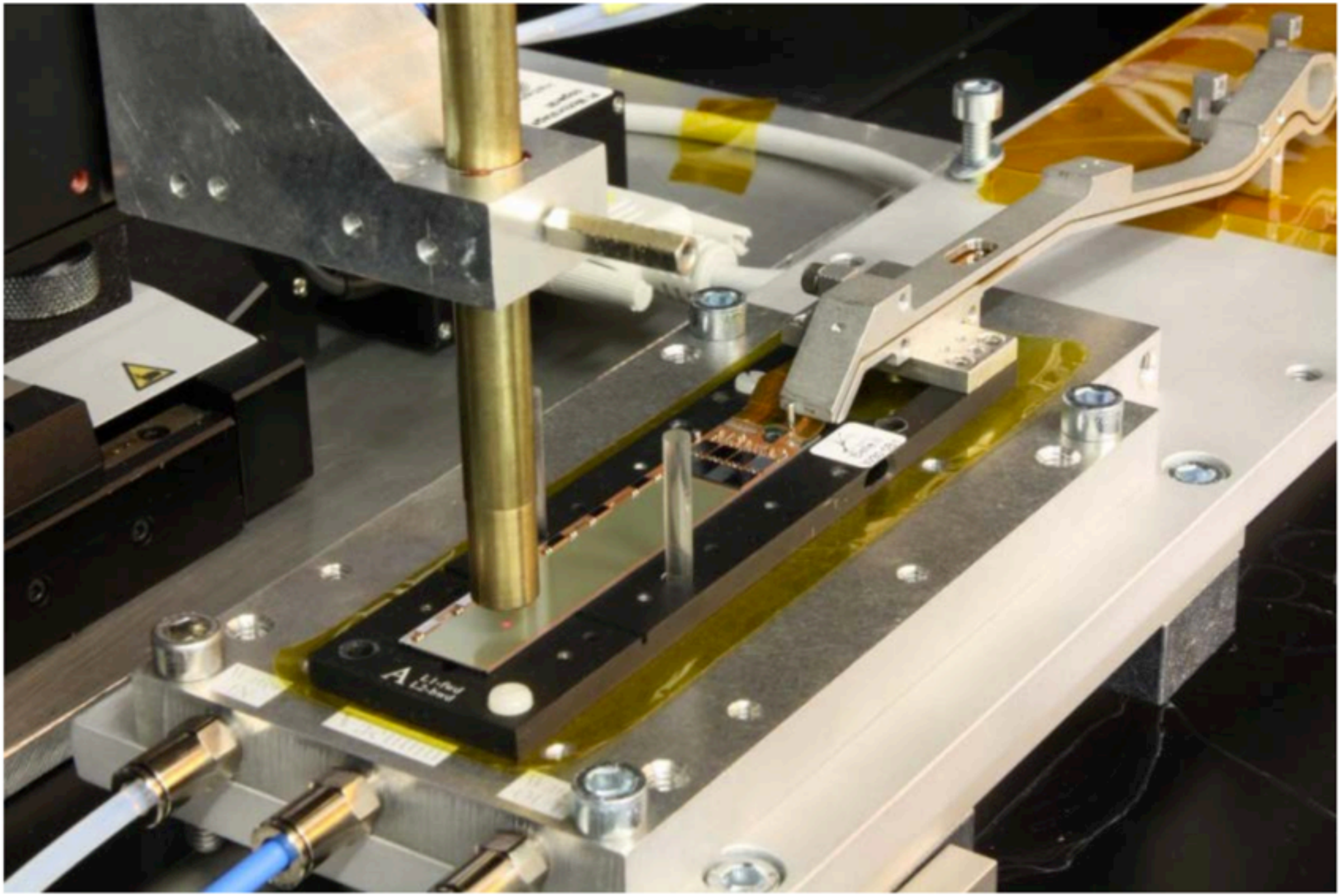
etching of handle wafer (structured)



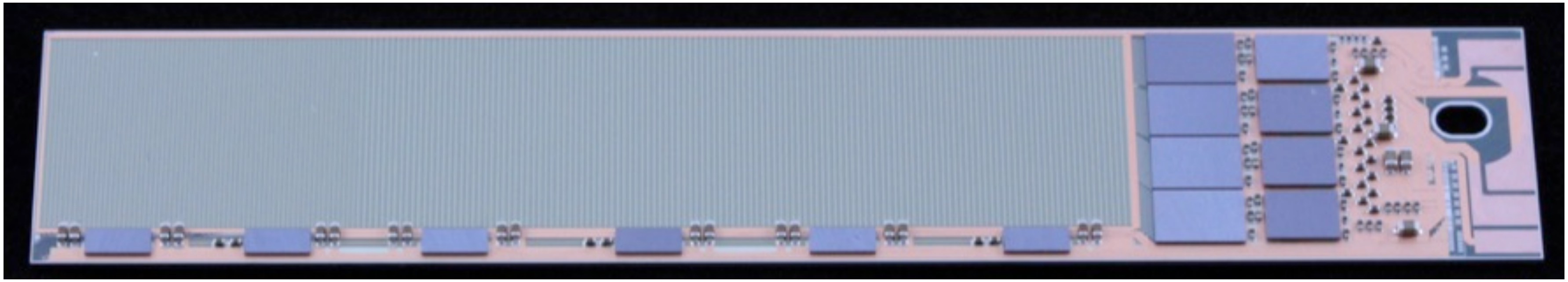
First PXD BELLE II all silicon module



First PXD BELLE II all silicon module

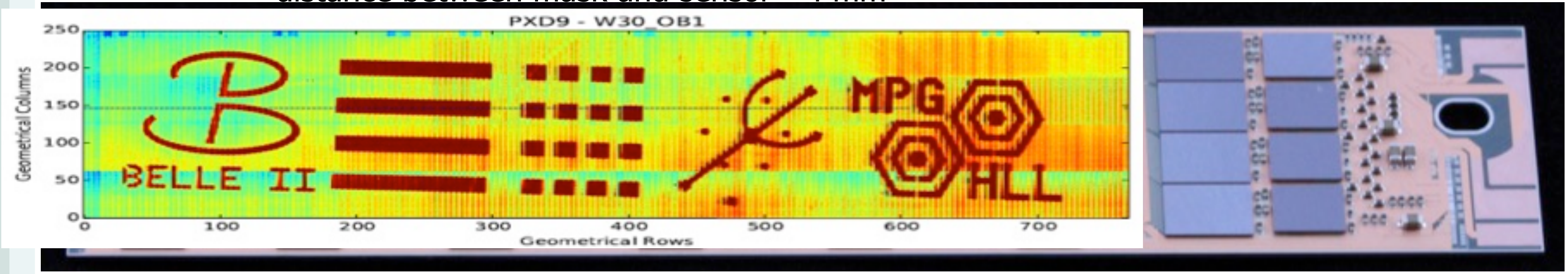


First PXD BELLE II - all silicon module

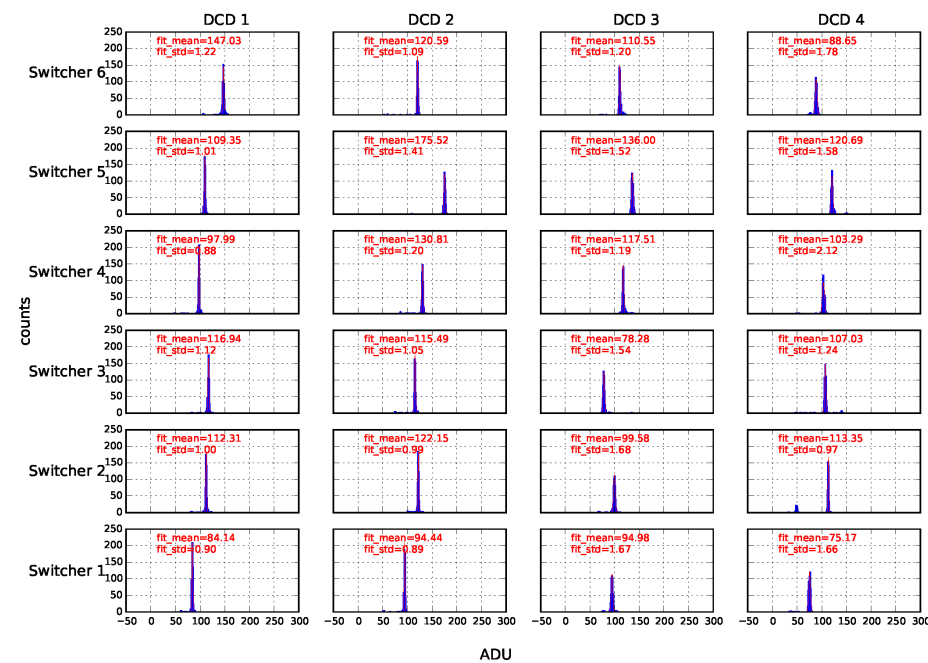


First PXD BELLE II - all silicon module

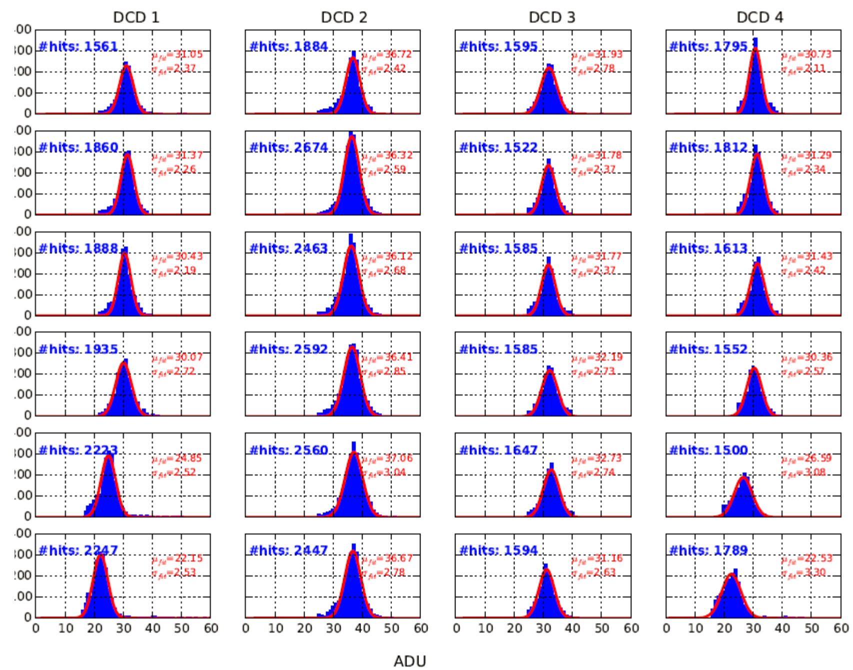
distance between mask and sensor ~4 mm



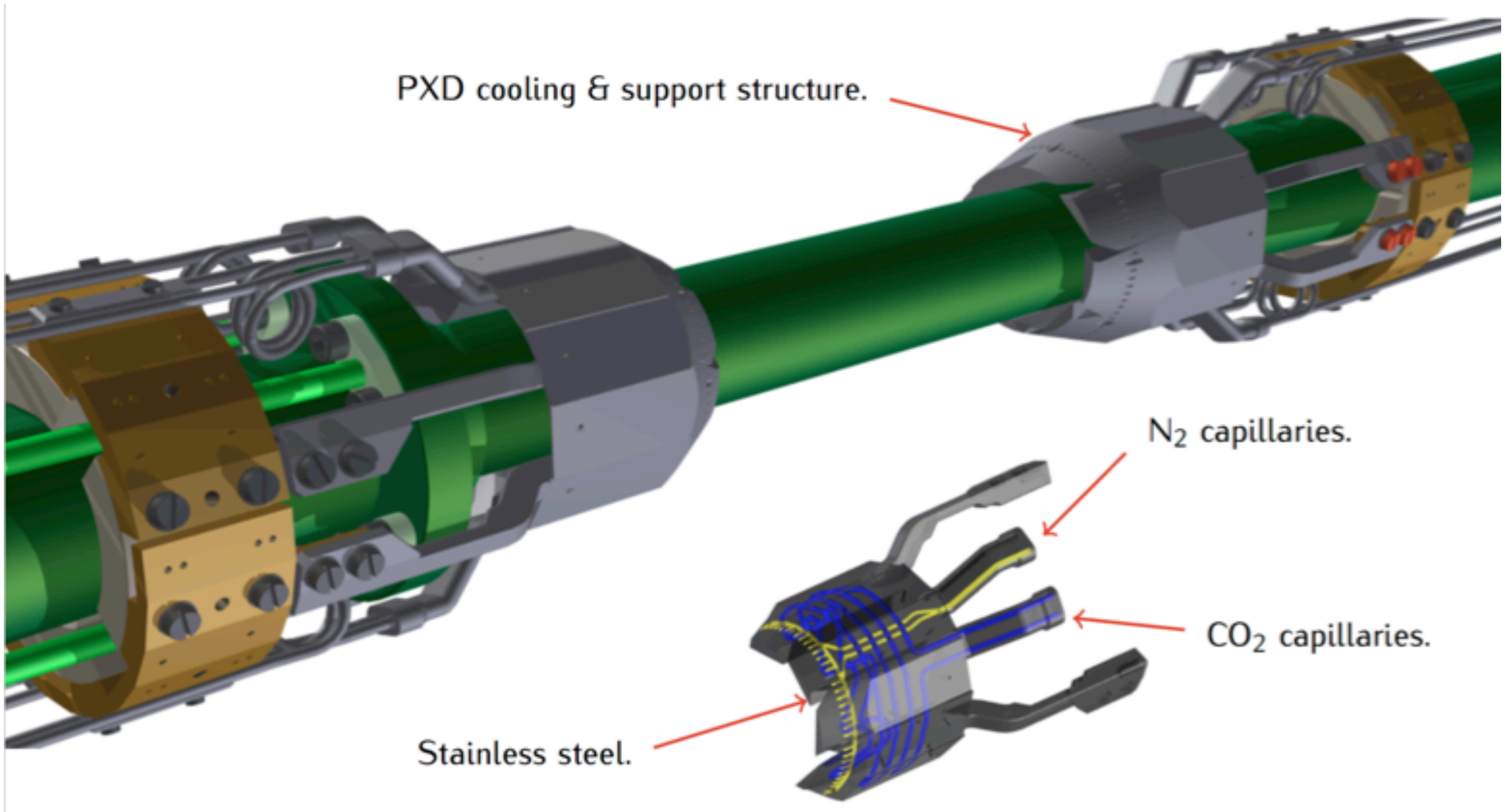
Laser signal ~2-4mip,
read out at full speed (105ns/row)



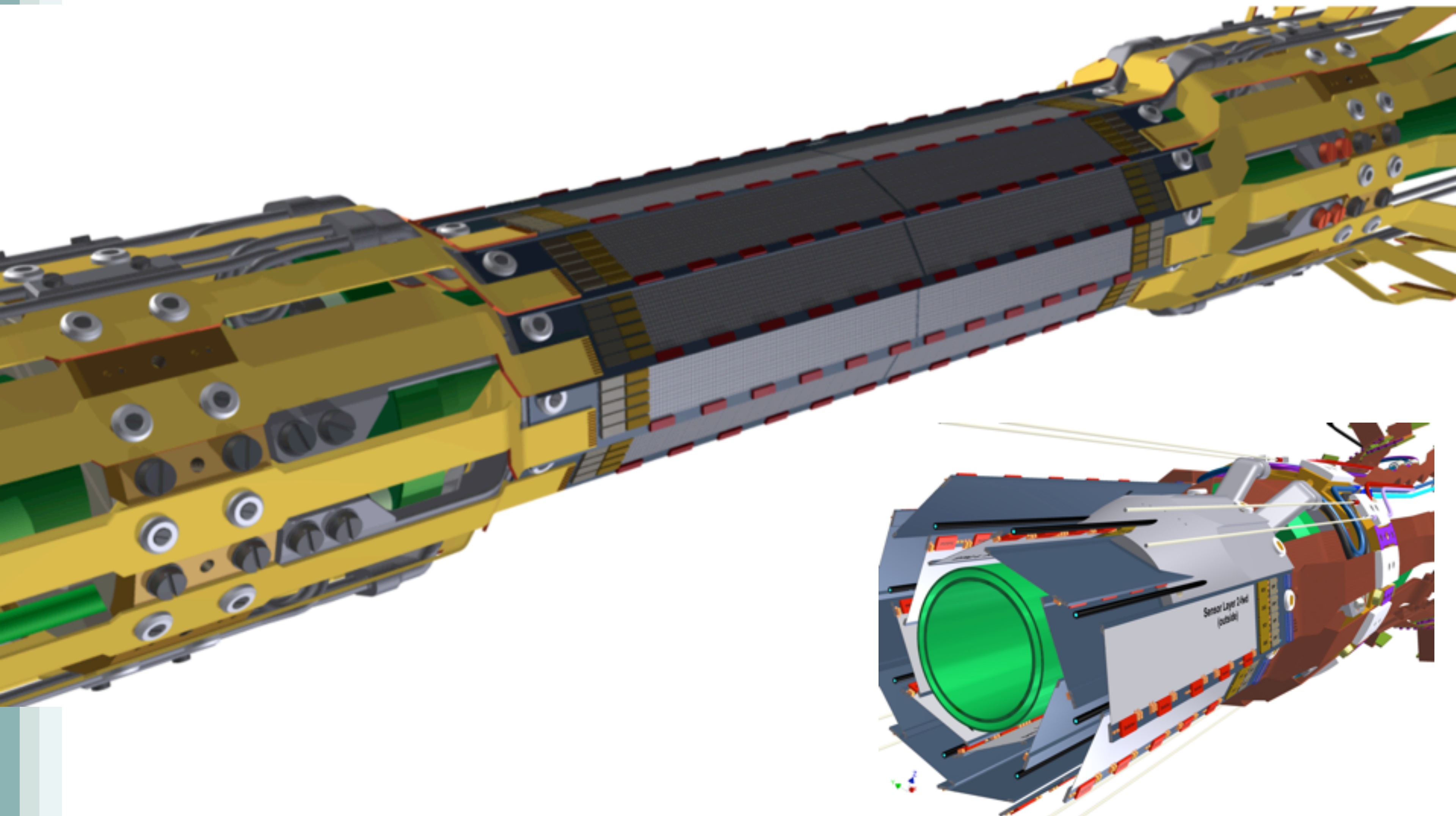
^{109}Cd Source measurement – 250MHz
Non optimal sensor settings **S/N>30**



PXD @ BELLE II


PXD cooling & support structure.
N_2 capillaries.
CO_2 capillaries.
Stainless steel.

PXD @ BELLE II



BELLE & ILC

- Both detectors have very similar requirements

	ILC	Belle II
Occupancy	0.13 hits/µm^2/s	0.1 hits/µm^2/s
Radiation	< 100 krad/year	2 Mrad/year
Duty cycle	1/200	1
Frame time	25-100 µs	20 µs
Momentum range	All momenta	Low momentum (< 1 GeV)
Acceptance	6º-174º	17º-155º

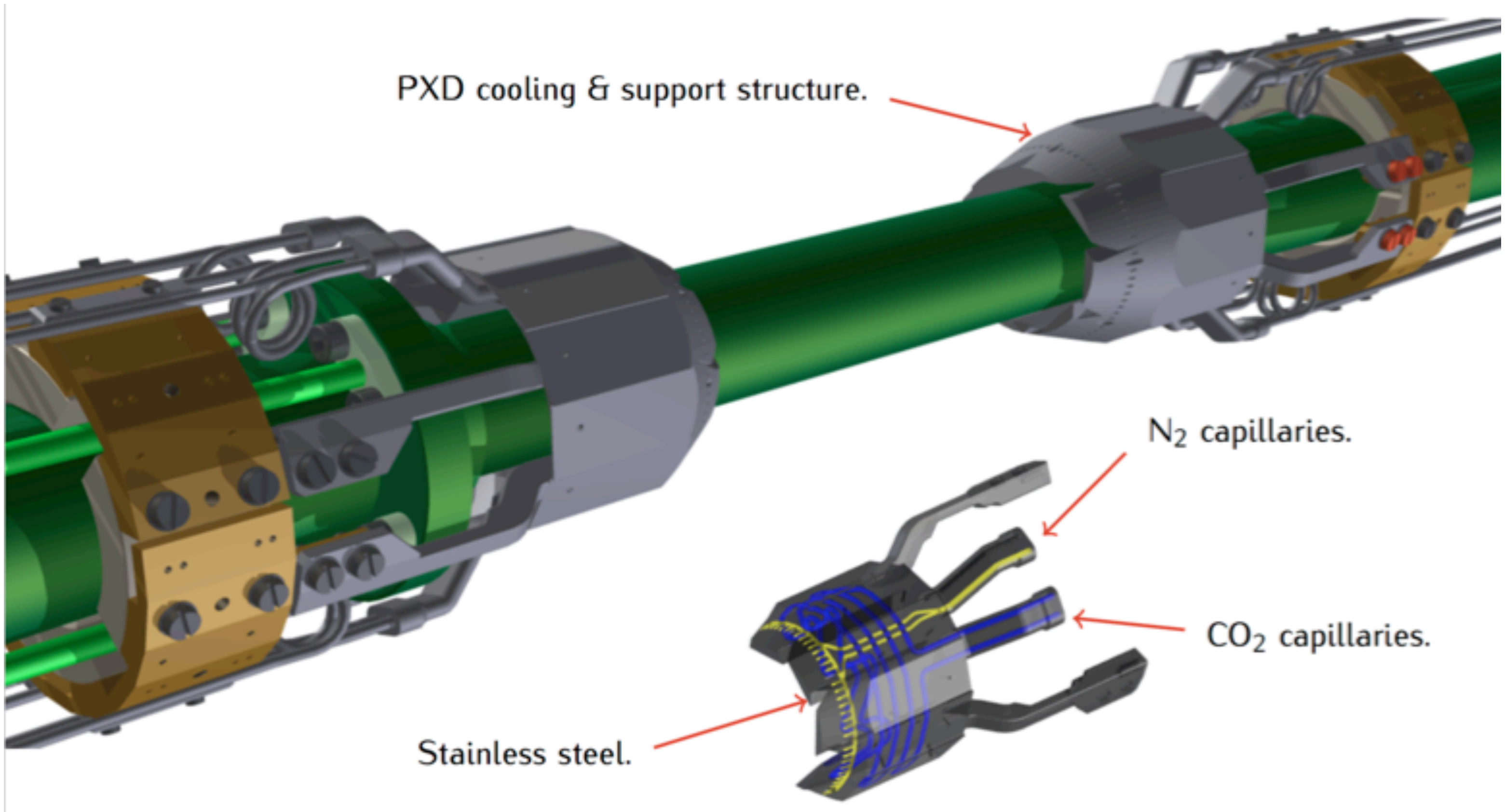
- ILC
  - Excellent single point resolution (3-5 µm) → Small pixel size 25 µm^2
  - Low material budget (0.1%X_0/layer)

- Belle II
  - Modest spatial resolution (10 µm) → Moderate pixel size (50 x 75 µm^2)
  - Few 100 MeV momenta → Lowest possible material budget (0.2% X_0/layer**)

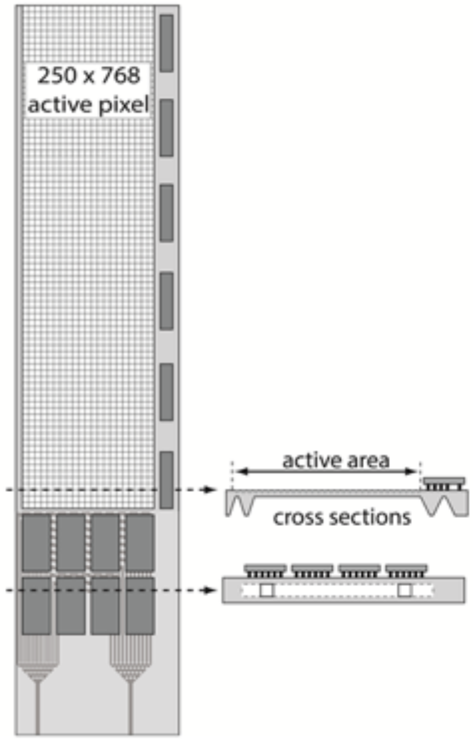
** Including support Si, bumps and metal layers

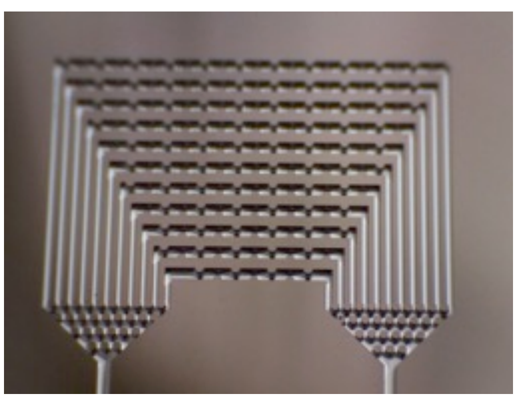
Beyond BELLE II …. ILC

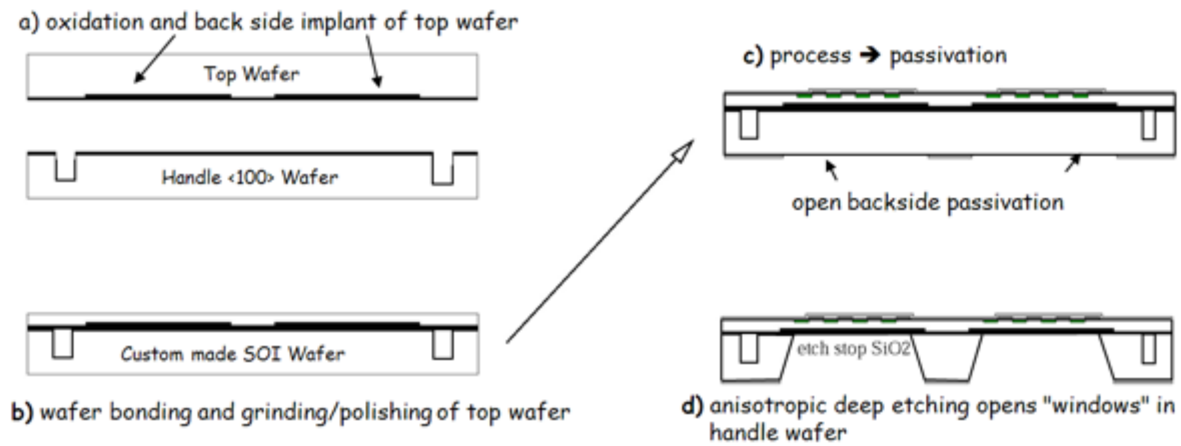
Modules developed for BELLE II can be seen as prototypes for ILC but we do even more …



Future all silicon modules - Integrated micro-channels



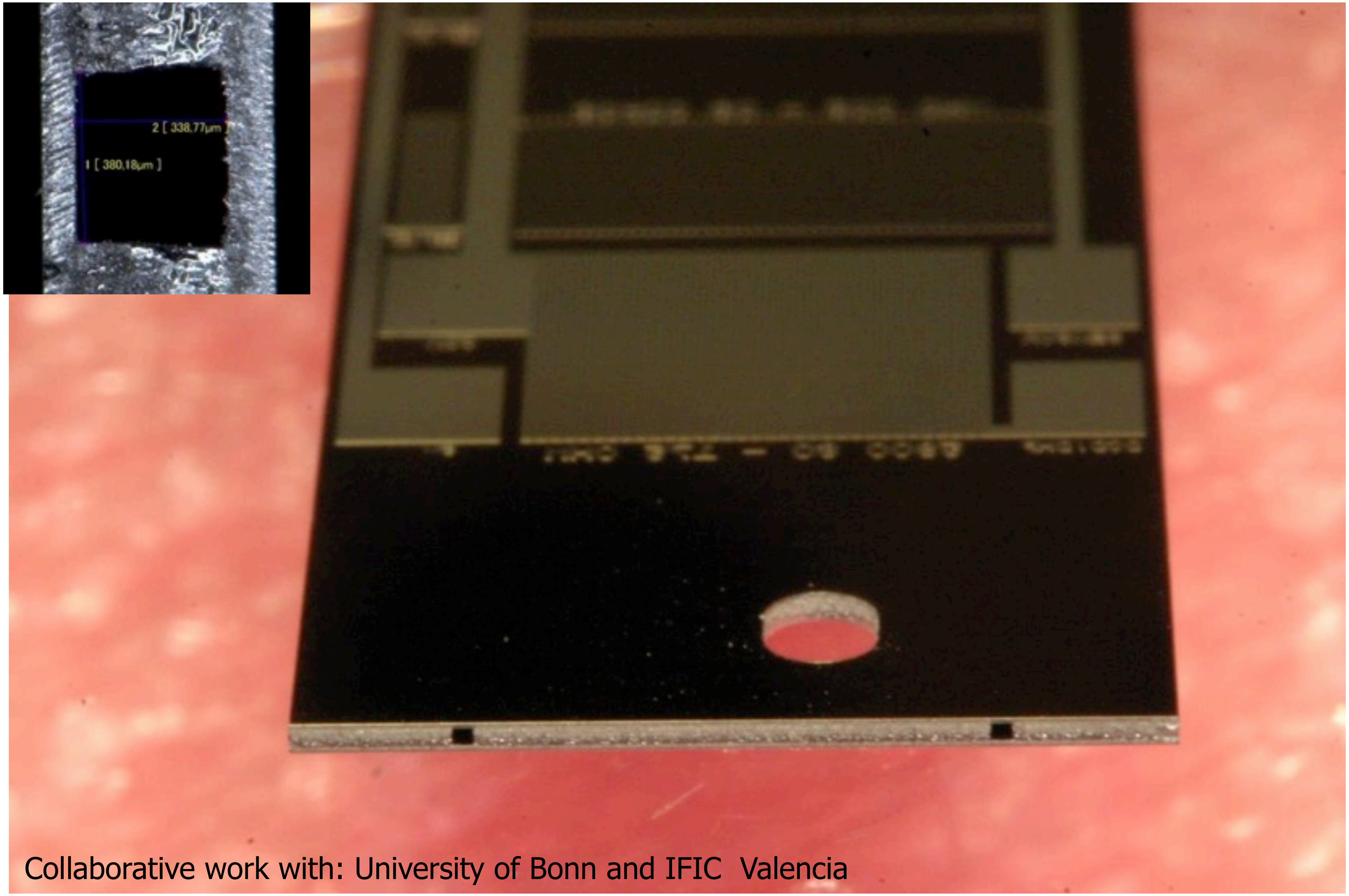




The SOI approach: thinned all-silicon module with integ. cooling

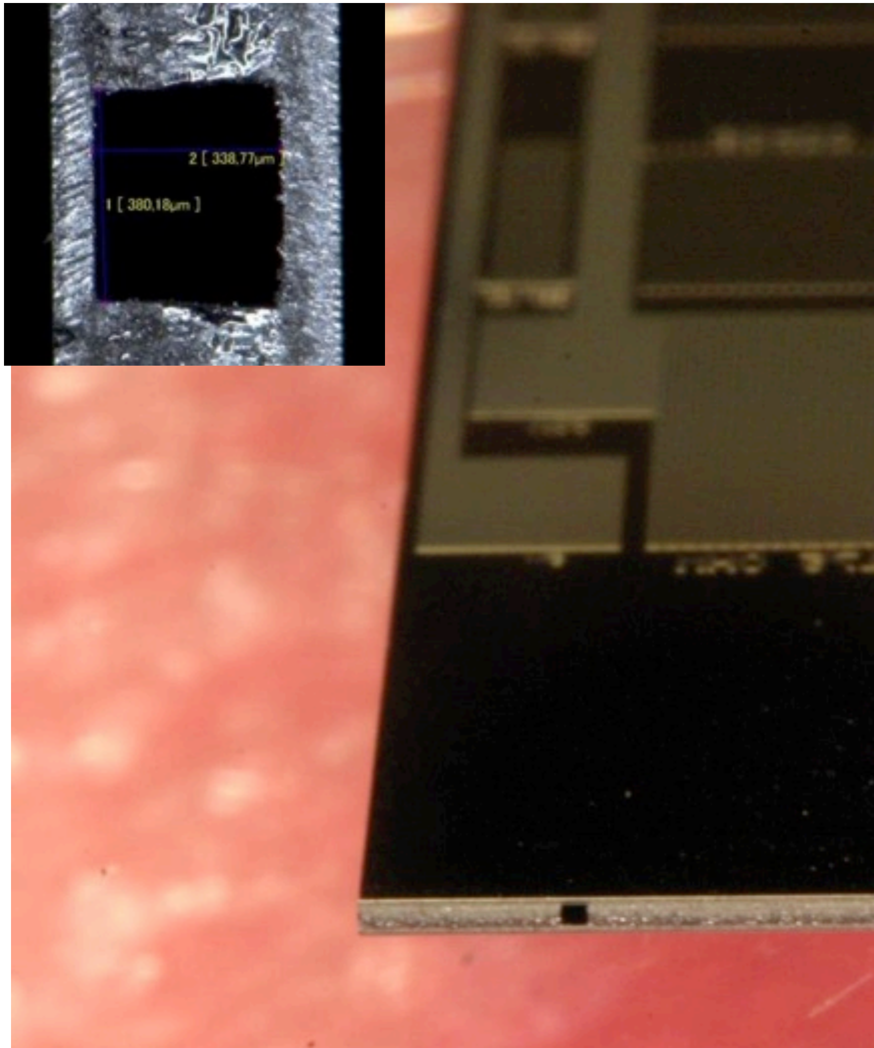
- most heat generated by read-out ASICs
- idea: integrate channels into handle wafer beneath the ASICs
- make use of the thick handle wafer at the end-of-module
- channels etched before wafer bonding → cavity SOI (C-SOI)
- full processing on C-SOI, thinning of sensitive area
- micro-channels accessible only after cutting (laser)

Future all silicon modules / First prototypes for thermal studies



Collaborative work with: University of Bonn and IFIC Valencia

Future all silicon modules / First prototypes for thermal studies



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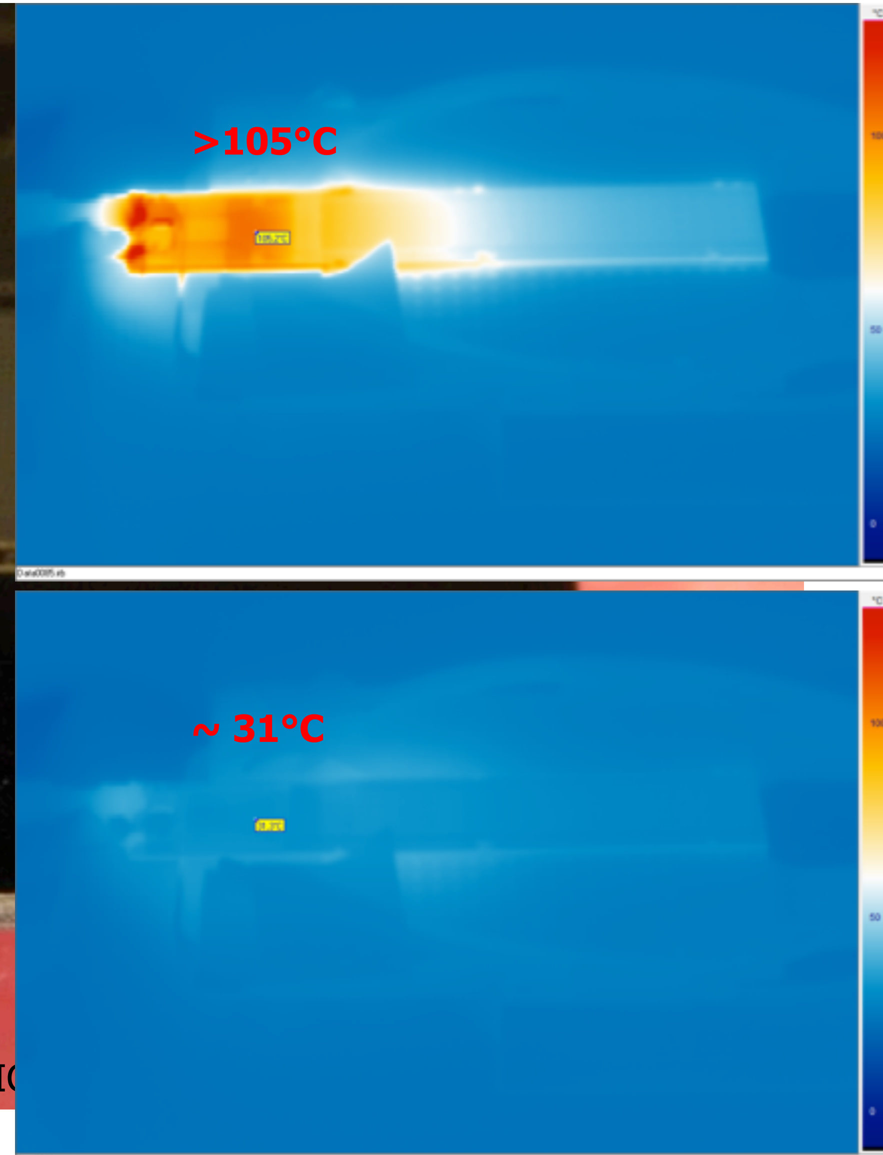
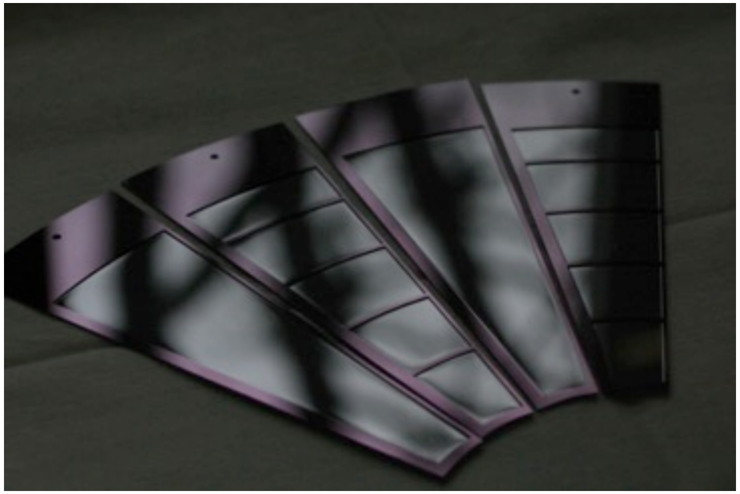
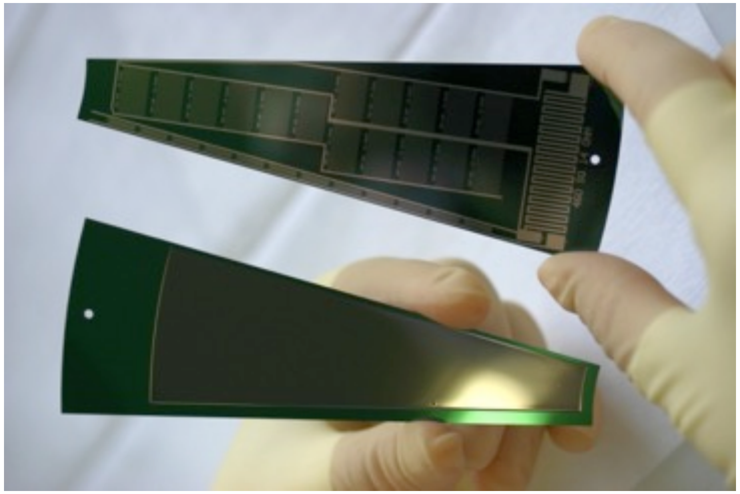


Future all silicon modules - Forward tracking disks in ILD

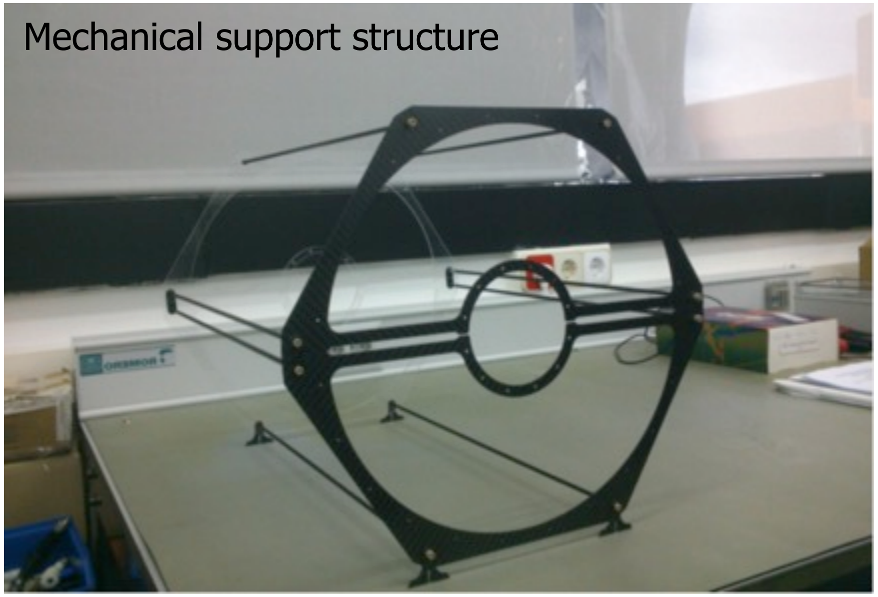
Thermo mechanical Si modules





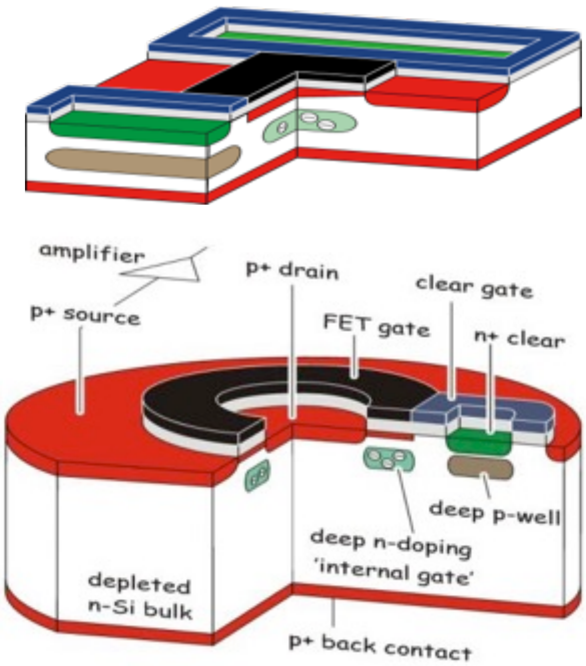
FTD pixel disk mock up

- DEPFET mechanical petals
  - 75 μm Silicon (<0.2% X_0)
- Support disk
  - 1mm (0.09% X_0 avg. area)
- CF connection tubes



Collaborative work with: University of Bonn and IFIC Valencia

DEPFET classes



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read out time per row: 25ns-100ns
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thin detectors: 50µm…75µm → still large signal: 40nA/µm for MIP

Low noise: Spectroscopic X-Ray imaging

pixel size: 100µm, with drift rings several 100s of µm
read out time per row: few µs
Noise: ≈4 el ENC
fully depleted, the thicker the better → large QE for higher E

X-ray fluorescence spectroscopy: MIXS on BepiColombo

MIXS - First Imaging X-ray spectrometer for planetary X-ray fluorescence

- is the first planetary XRF instrument using a high performance imaging optics, not just a collimator.

Much better spatial resolution!
Look inside craters, identify more features!

- is the first planetary XRF instrument using an energy dispersive solid-state detector

with excellent energy resolution and low energy threshold.
Allows to observe the important lines of Iron, Silicon, Magnesium etc. directly!

DEPFET Macropixel Matrix

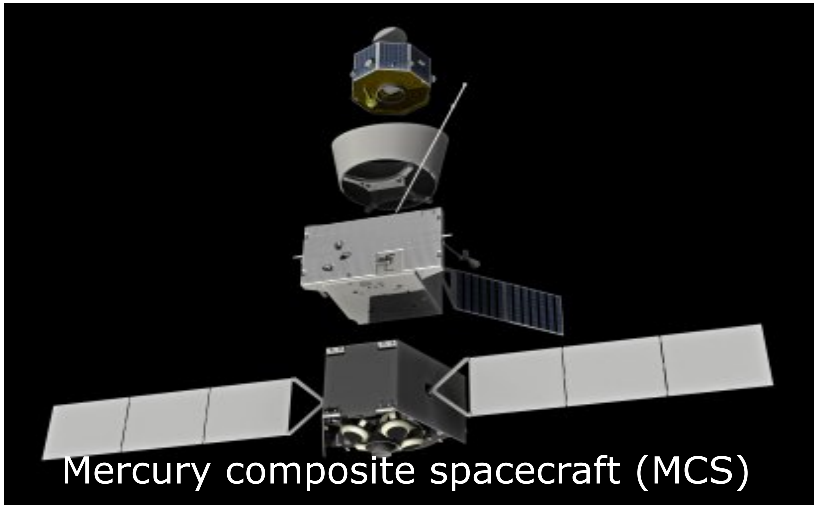
▷ Format
- **1.92 x 1.92** cm^2
- **64 x 64** pixels
- **300 x 300 μm²** pixel size

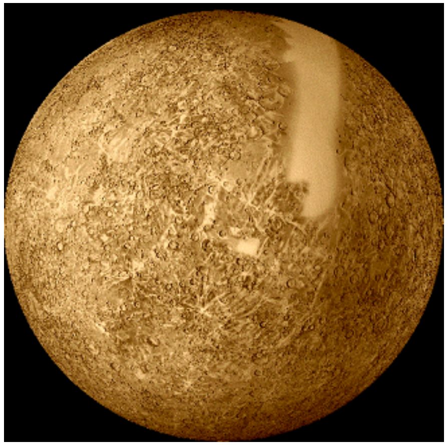
▷ Energy resolution
- **200 eV FWHM @ 1 keV**
- QE > of 80 % @ 500 eV

▷ Time resolution
- **< 1 ms** due to dynamics

▷ Radiation hardness
- ~ 20 krad ionizing
- 3 x 10^{10} 10 MeV p/cm^2
- **equivalent to** 1.11 x 10^{11} 1 MeV n/cm^2

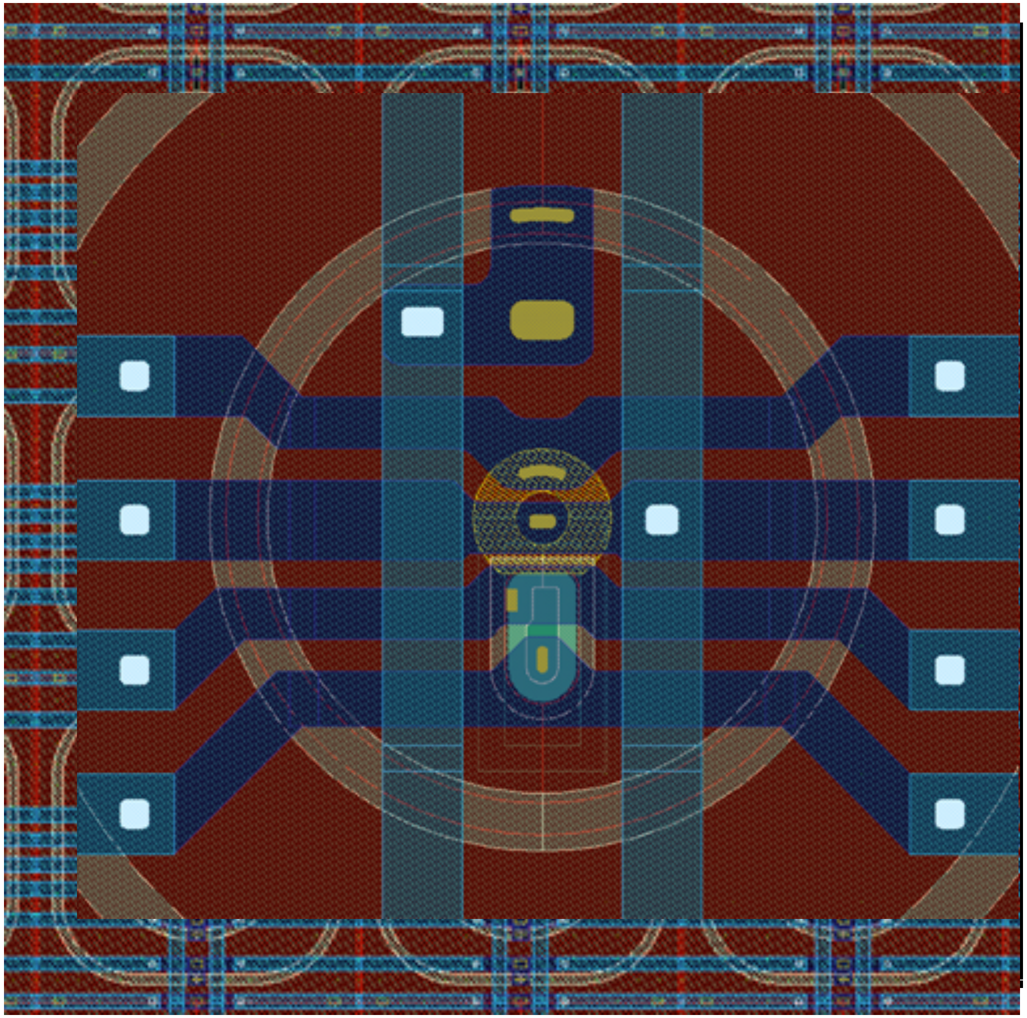
(collaboration partner MP Solar System Research)



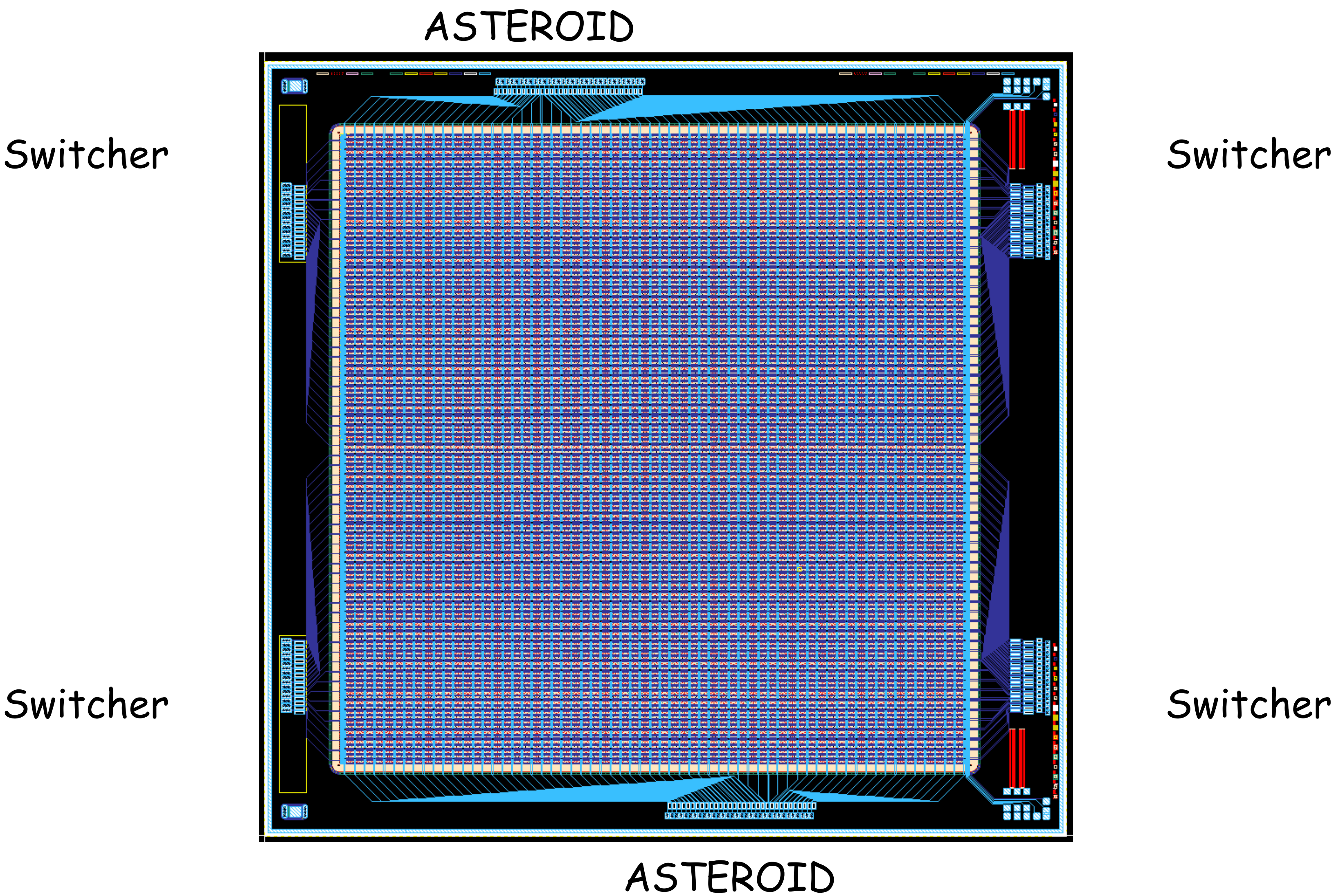


Mercury surface as seem by Mariner 10

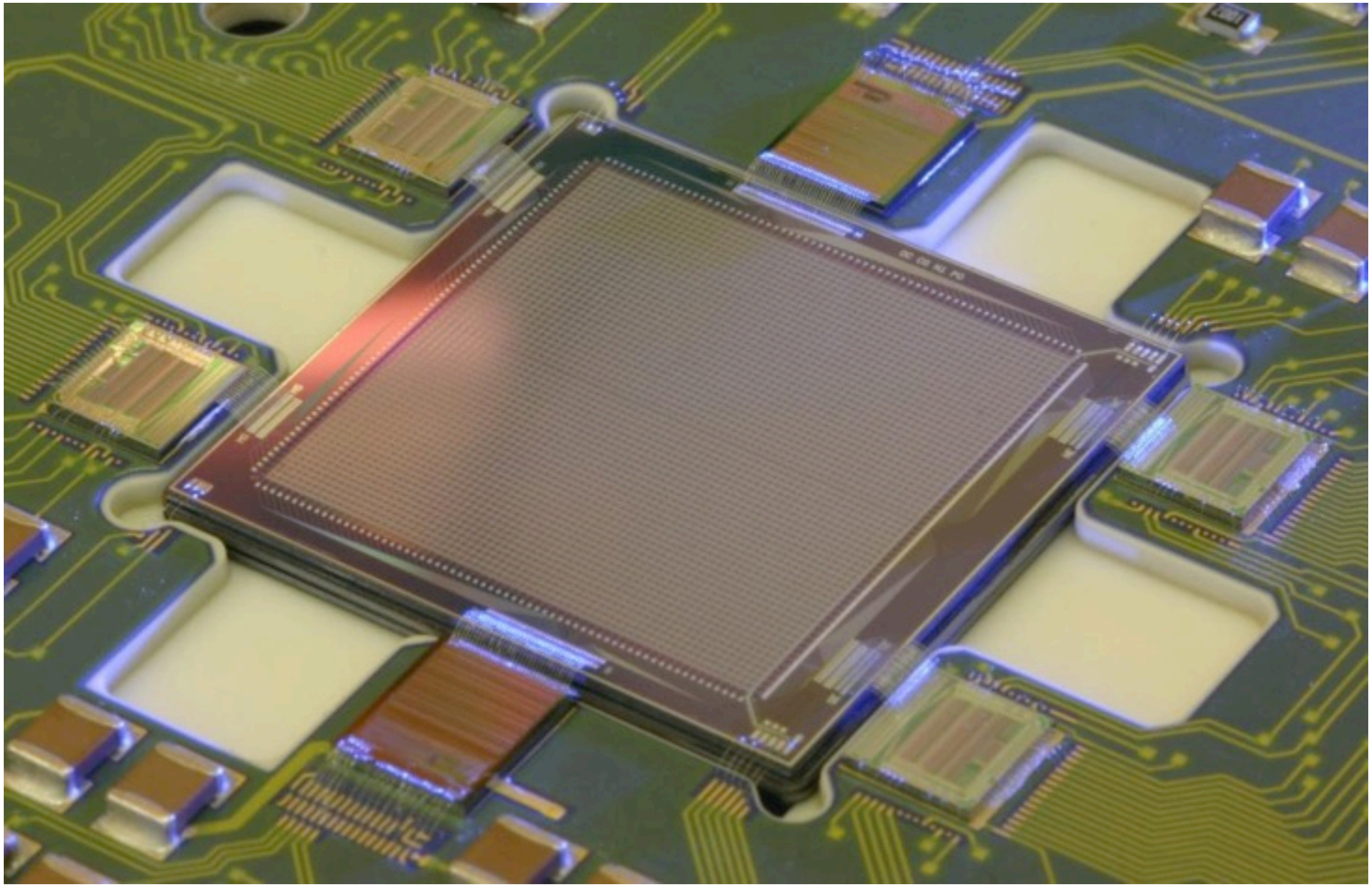
Detector overview



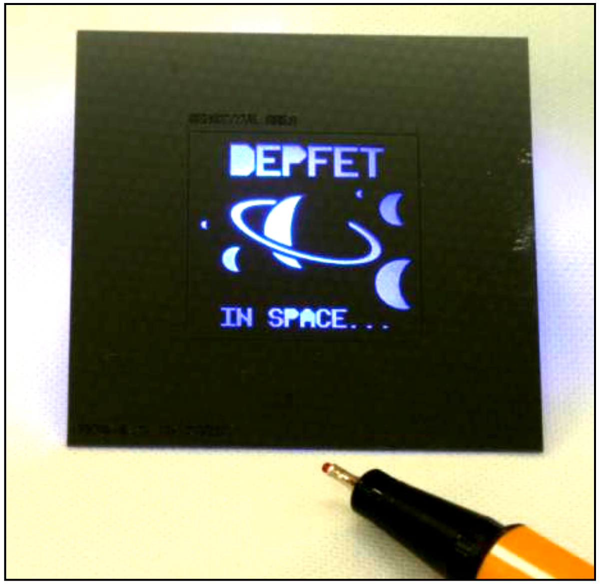
Detector overview

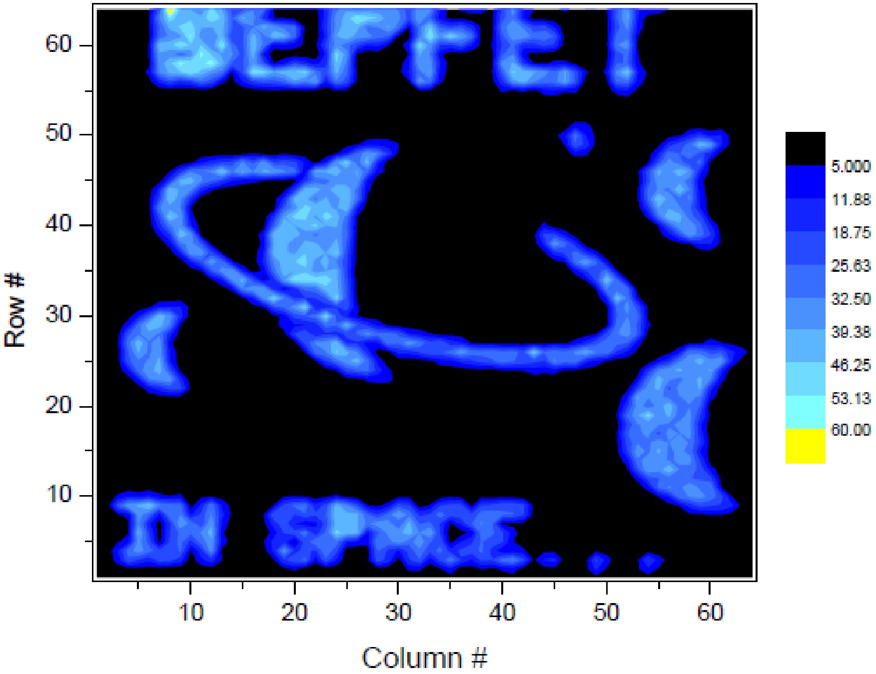


MIXS hybrid



Measurements

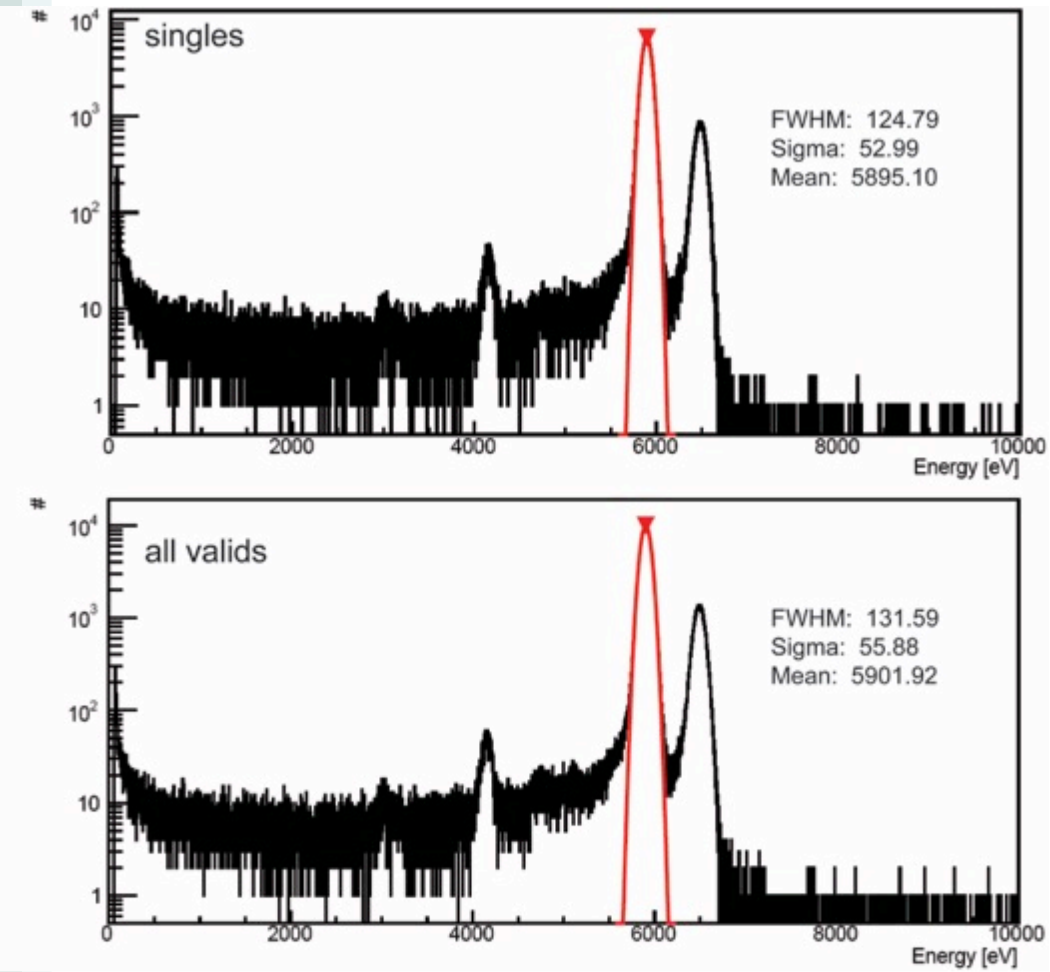


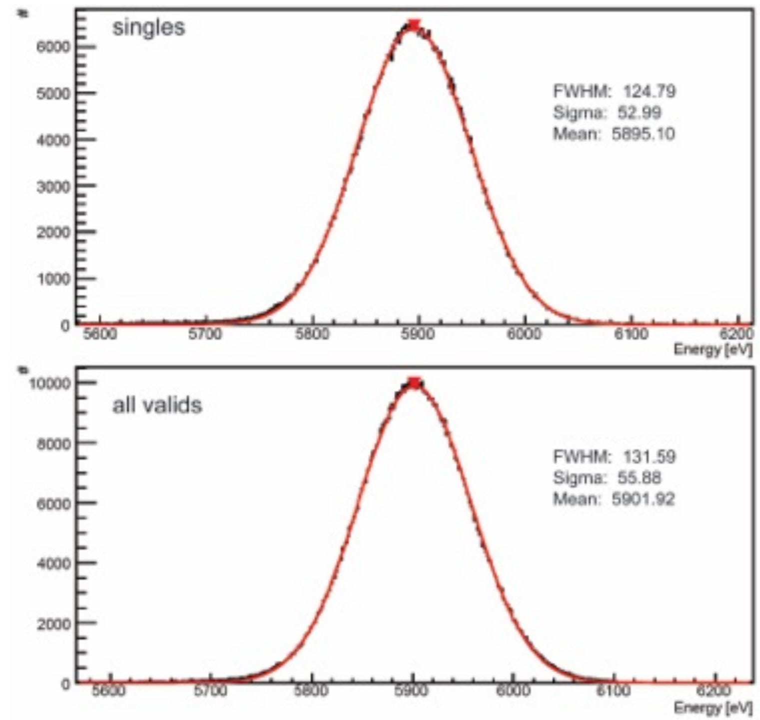


- **Operating conditions**
  - -40 °C
  - T_{row} = 5.2 μs
  - T_{frame} = 167 μs / frame
  - Framerate ~ 6 kfps
  - I_{pixel} = 125 μA

Shadow image of a 450 μm thick silicon baffle with an ^{55}Fe source mounted directly in front of the sensor

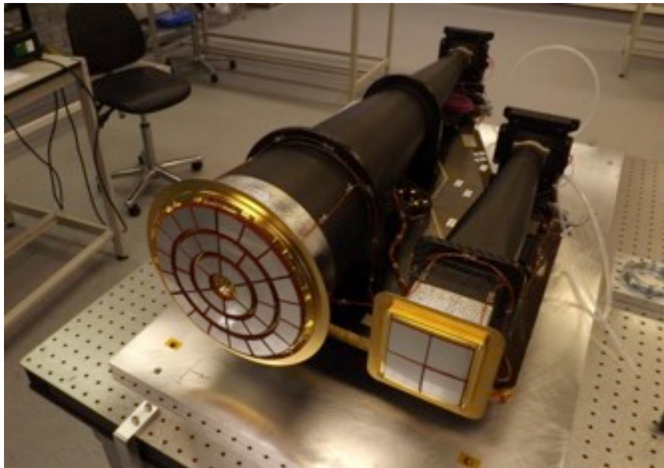
Spectral performance





- ^{55}Fe source
- singles: FWHM = 124.8 eV @ 5.9keV
- T ~ -85°C
- 415 µs/frame

Fully assembled MIXS module



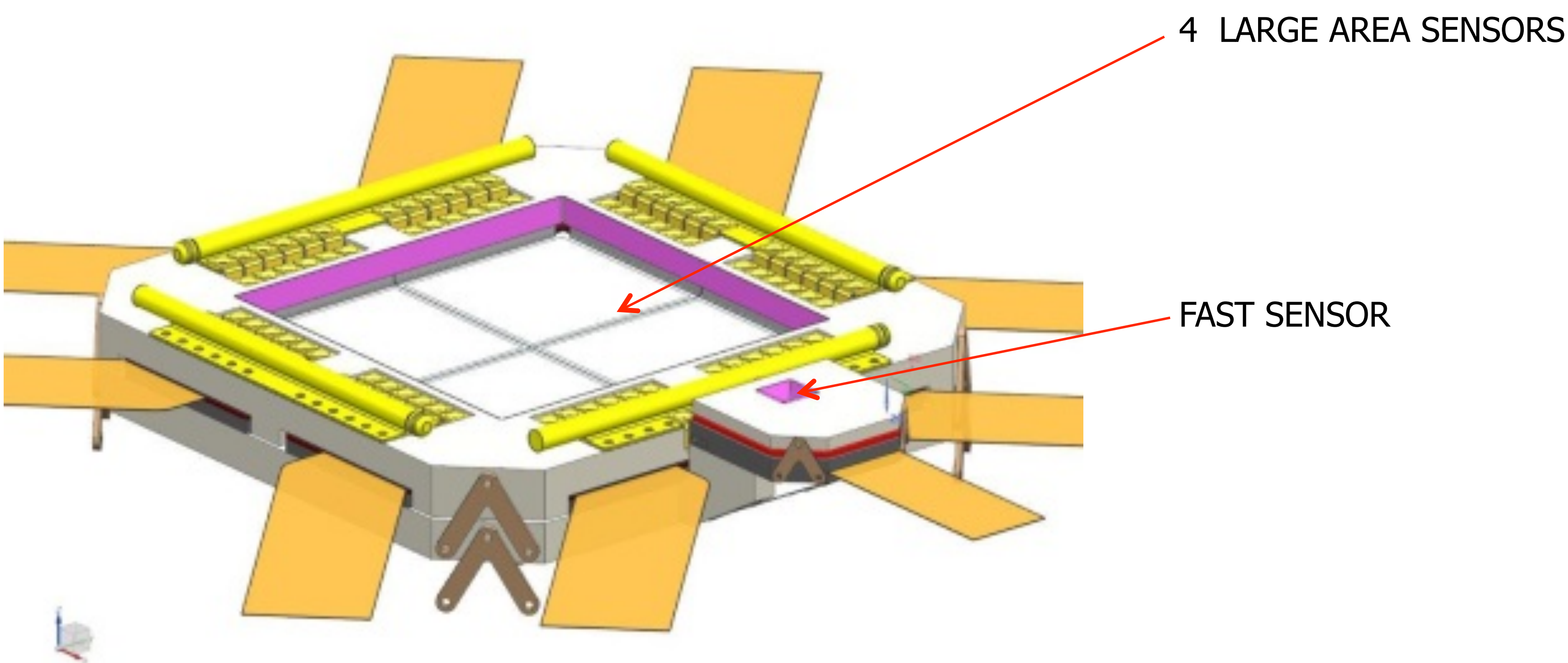
ATHENA mission – Wide Field Imager (WFI)

Athena (the Advanced Telescope for High-Energy Astrophysics), has been proposed as ESA's next-generation X-ray astronomy observatory (Launch slot 2028).

(collaboration partner MP Extraterrestrial Physics)

To address two key questions in modern astrophysics:

- How does ordinary matter form the large-scale structures that we see today?
- How do black holes grow and shape the Universe?

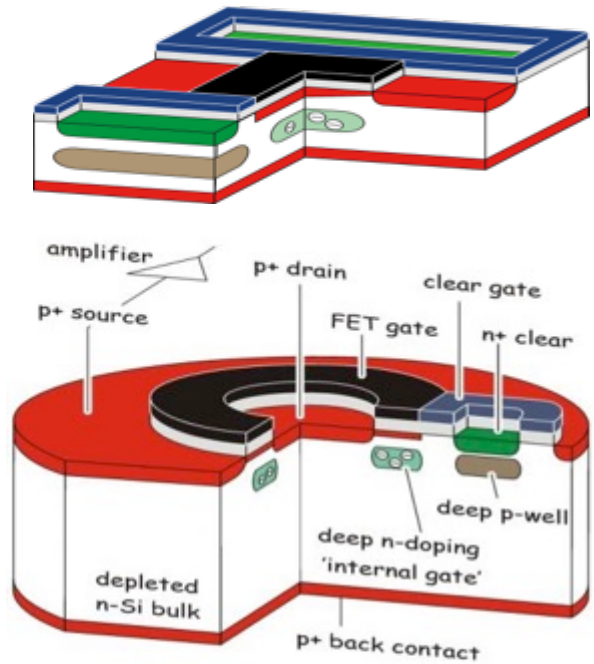


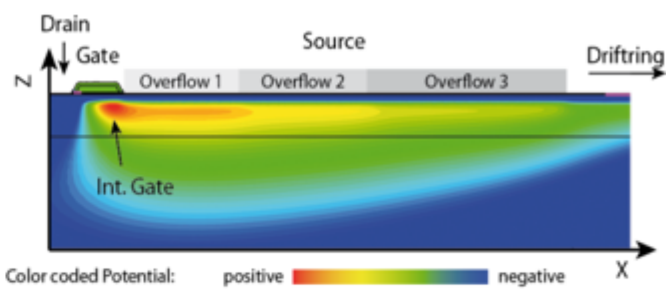
ATHENA mission – Wide Field Imager (WFI)

Parameter	**Value**
Energy Range	0.2-15 keV
Field of View	40′ x 40′
Angular Resolution **Pixel Size**	PSF=5`` (on-axis) 130 x 130 $\mu m^2$ (2.2``)
Large DEPFET detector	1024 x 1024 pixel
Fast DEPFET detector	2 x (32 x 64 pixel)
Quantum efficiency on-chip + external filter	20% @ 277 eV 80% @ 1 keV 90% @ 10 keV
Energy Resolution (end of life)	FWHM(6 keV) ≤ 150 eV
Time Resolution full frame Fast detector Large detector	 80 µs <5 ms
Count Rate Capability	1 Crab: >80% throughput, <1% pile-up
Particle Background (L2 orbit)	$< 5 \times 10^{-3}$ cts cm^{-2} s^{-1} keV^{-1}

To be launched 2028

DEPFET classes





Thin & small pixel: vertex, low E electron detectors (TEM)

pixel size: 20µm…75µm
read out time per row: 25ns-100ns
Noise: ≈100 el ENC
thin detectors: 50µm…75µm → still large signal: 40nA/µm for MIP

Low noise: Spectroscopic X-Ray imaging

pixel size: 100µm, with drift rings several 100s of µm
read out time per row: few µs
Noise: ≈4 el ENC
fully depleted, the thicker the better → large QE for higher E

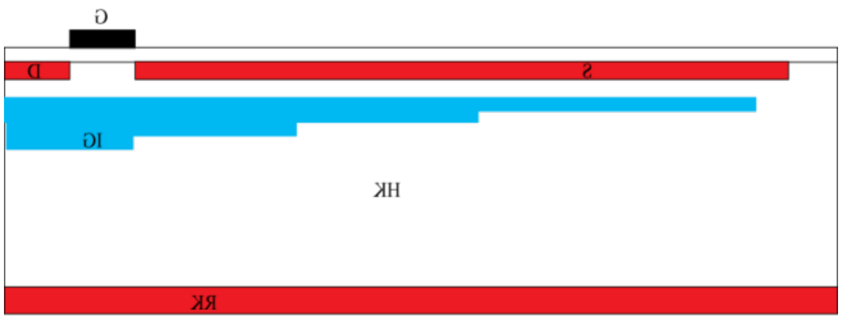
High Dynamic range

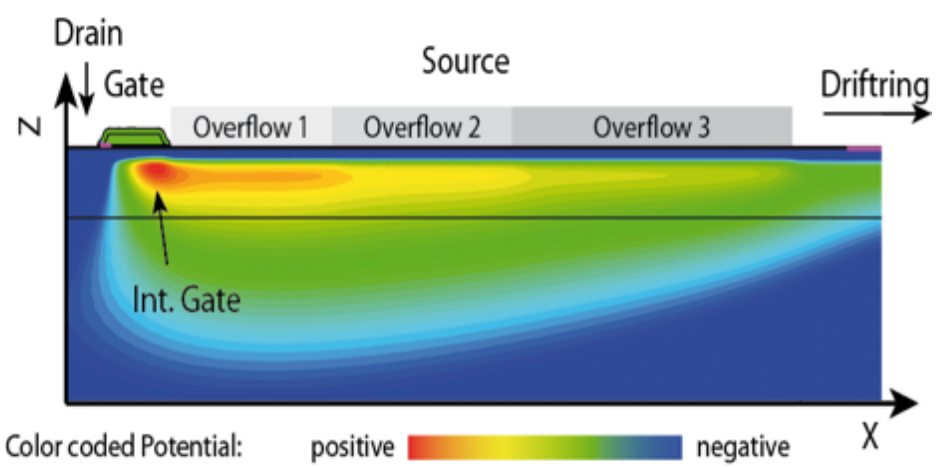
DEPFET **S**ensor with **S**ignal **C**ompression
Sensitivity to single photons and high dynamic range
pixel size: 60 -200 µm

Detector Concept – DEPFET with signal compression

Motivation: develop detector with high dynamic range and preserve other advantages of DEPFETs

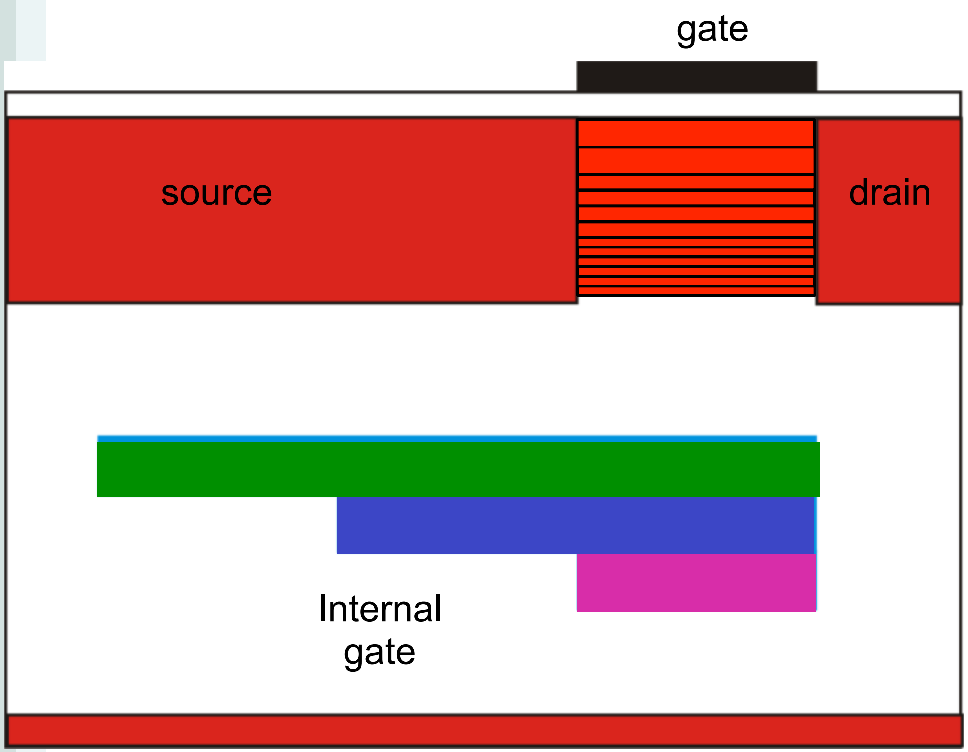
DSSC - **D**EPFET **S**ensor with **S**ignal **C**ompression

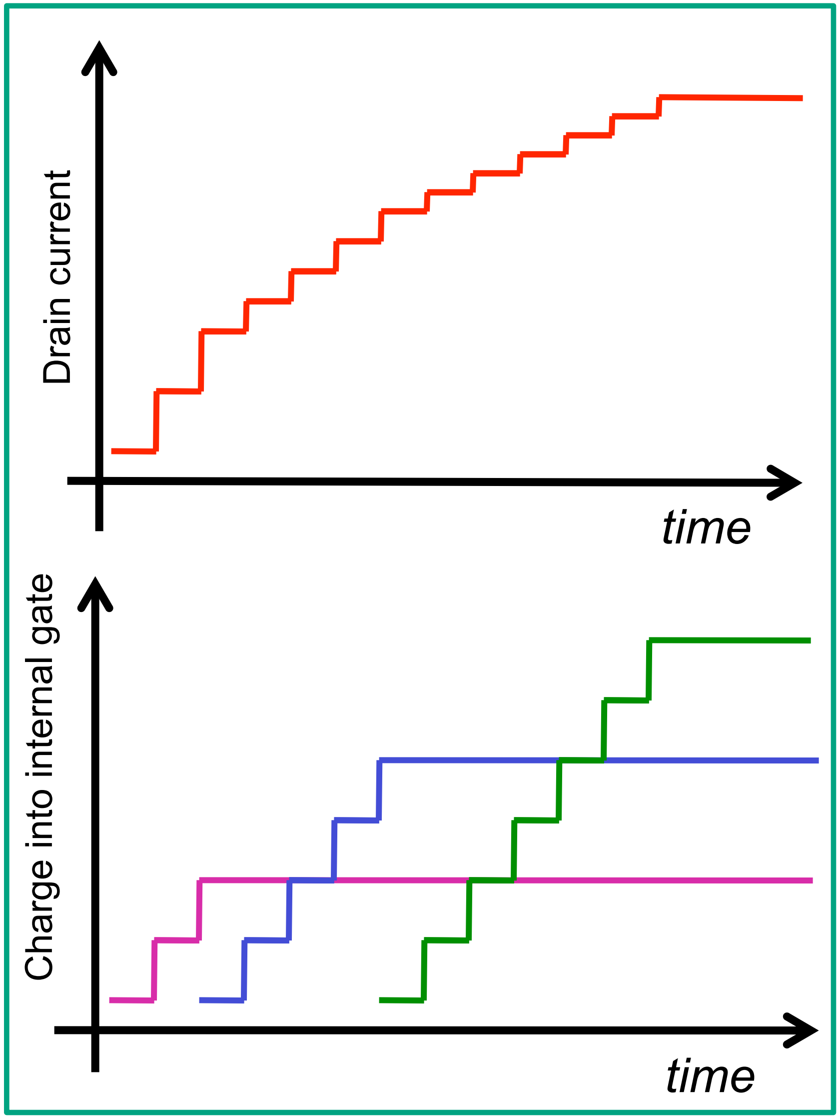




- The internal gate extends into the region below the source
- Small signals assemble below the channel, being fully effective in steering the transistor current
- Large signals spill over into the region below the source. They are less effective in steering the transistor current.
- 200 x 200 μm pixel has been designed and produced
- 60 x60 μm pixel has been designed and is being produced now

Detector Concept – Working principle





- A constant charge is injected at fixed time intervals and the internal gate regions are progressively filled
- In the experiment the charge is deposited at once but the DEPFET response is the same

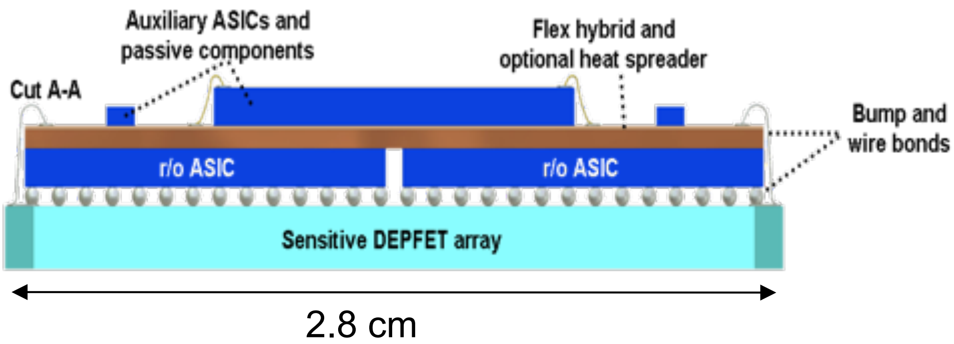
Requirements for the XFEL detectors

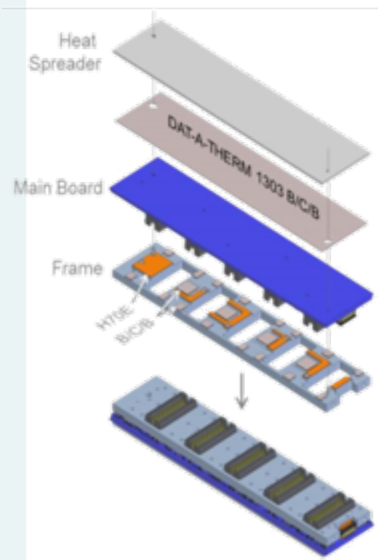
Integrating Area Detector

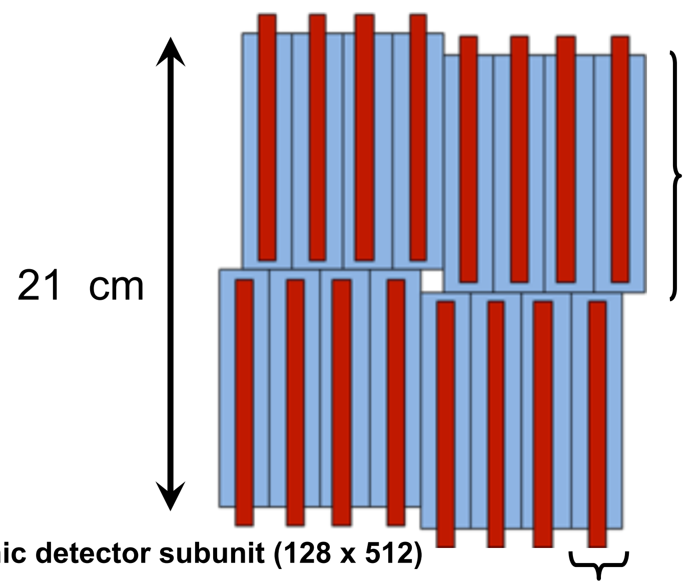
	XFEL (e.g. XPCS)	DEPFET array system
single photon resolution	yes	yes
energy range	0.5< E < 24 (keV)	0.5 < E < 25 [keV]
ang. resolution or pixel size	4 µrad	200 µm
sig.rate/pixel/bunch	10^3	10^3@10KeV
quantum efficiency	> 0.8	> 0.8 from 0.3 to 12 keV
number of pixels	512 x 512 (min.)	1024 x 1024
frame rate/repetition rate	10 Hz	yes, triggerable
XFEL burst mode	5 MHz (3.000 bunches)	4.5 MHz
Readout noise	< 150 e^- (rms)	< 50 e^- (rms)
cooling	possible	- 20° C optimum, room temperature possible
vacuum compatibility	yes	yes
preprocessing	no (yes) ?	possible upon request
4-side buttability	yes	yes

DSSC - Focal Plane

Submodule 128x512







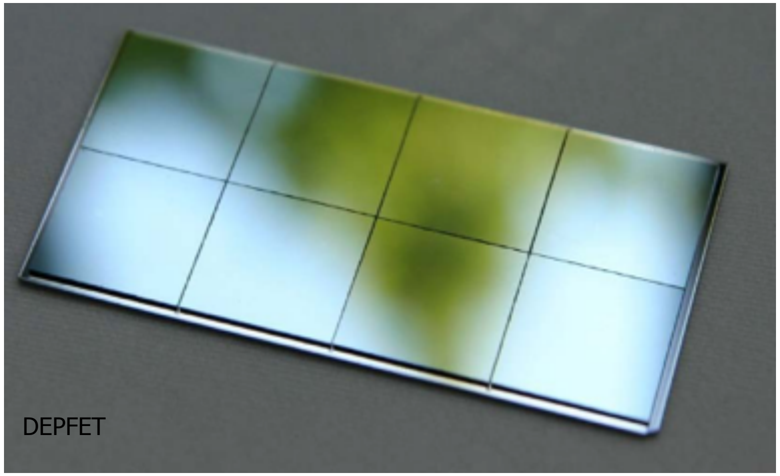
Monolithic detector subunit (128 x 512)

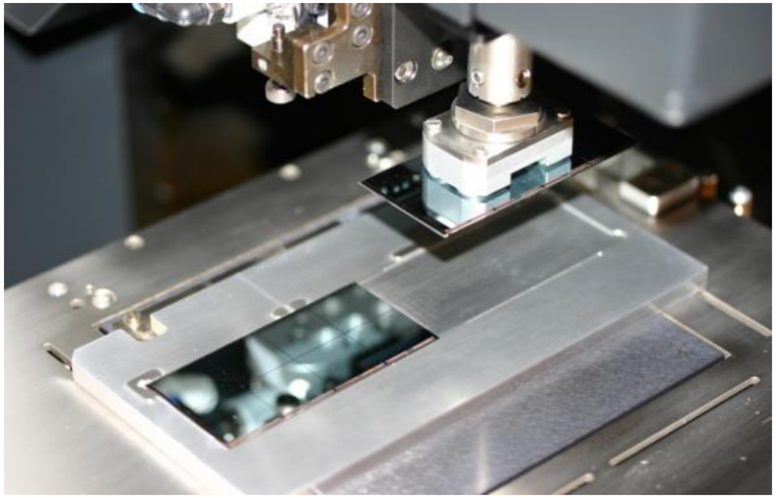
Multi Chip Modules

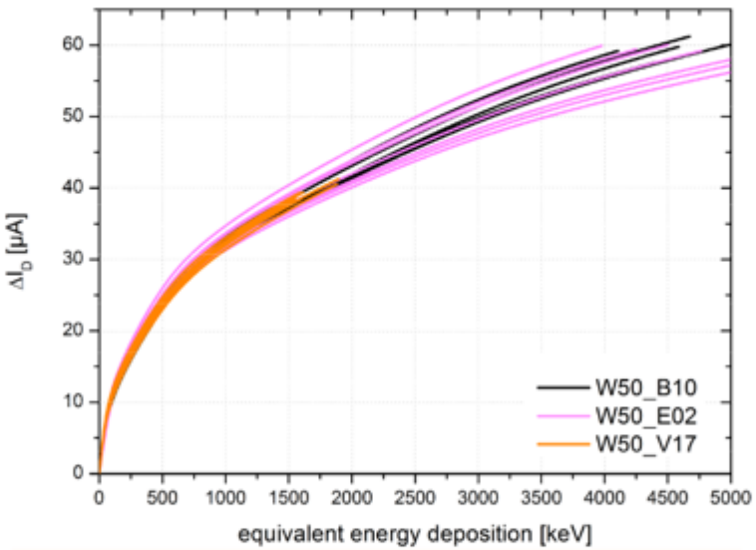
- ▷ DEPFET Sensor bump bonded to Readout ASICs
- ▷ Optional Heat spreader
- ▷ Flex Hybrid with passive components and auxiliary ASICs (e.g. voltage regulators)
- ▷ Sensor (512x128 pixels) 2.56×10.24 cm^2
- ▷ 16 readout ASICs (64x64)
- ▷ Dead area: 10-15%

Sensor development by MPG HLL
System development by DSSC collaboration

DSSC - sensors

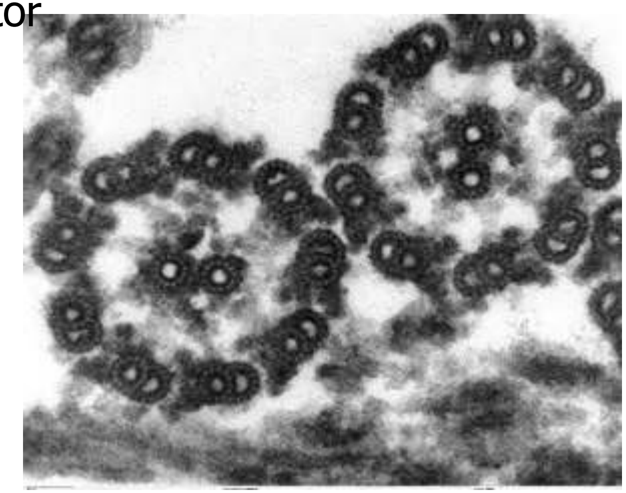




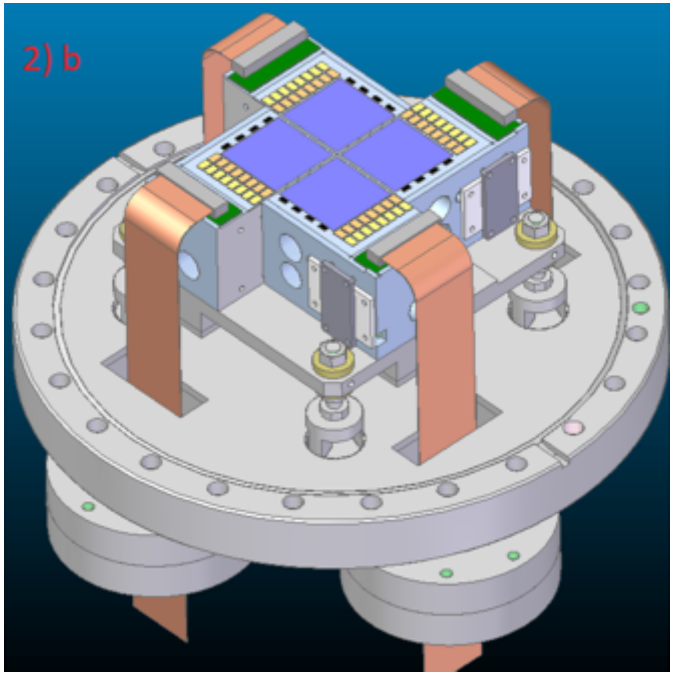


DEPFETs for low E electron detectors

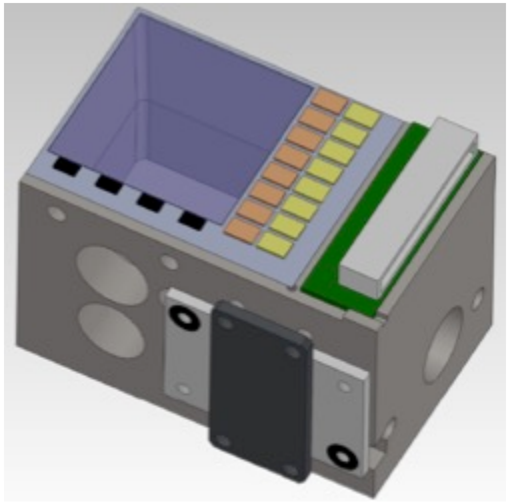
Goal: develop high speed direct hit low energy electron detector
Solution: thin, nonlinear DEPFETs with 80kHz frame rate



- 1Mpix, 60µm DEPFET pixel, 4 quadrants, 6x6 cm² sensitive
- 1-3 M electrons to store into internal gate
- 30-50µm thin sensitive area
- Bidirectional 4-fold read out, frame rate: 80kHz
- memory to store ~100 frames



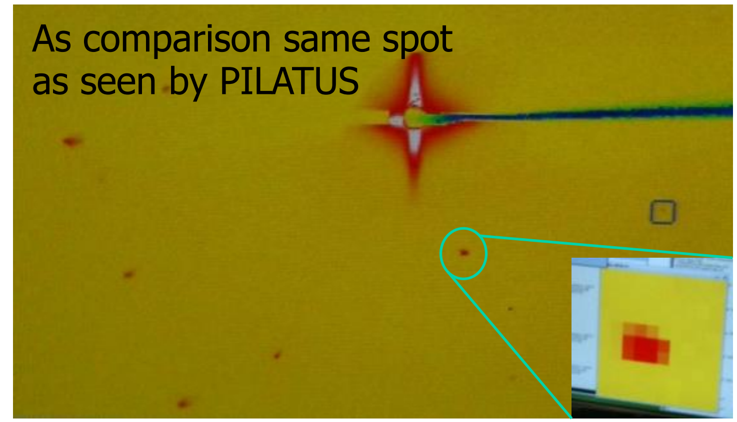
(collaboration partner MP Structural Dynamics)



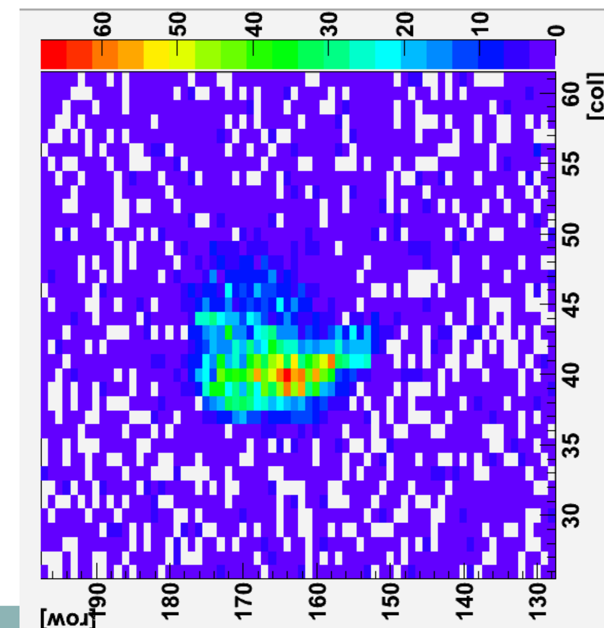
BELLE & ILC DEPFETs for Photon Science

First tests: slow readout system 2.3ms frame readout time (signal integration time) with about 150Hz DAQ readout rate (one frame is read out every 6ms)

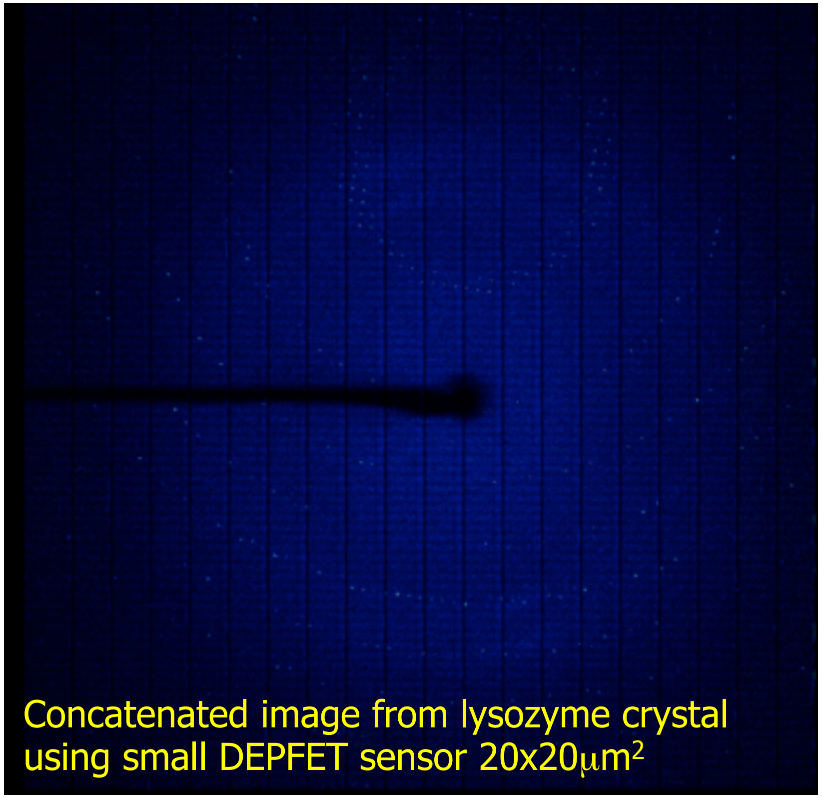
Matrix – ILC type 24x32μm^2 pixel 450μm thick
5120μm x 1280μm (256 x 64 pixels)



Lysozyme crystal – position of diffraction spots defined by PILATUS and then DEPFET matrix driven to that point



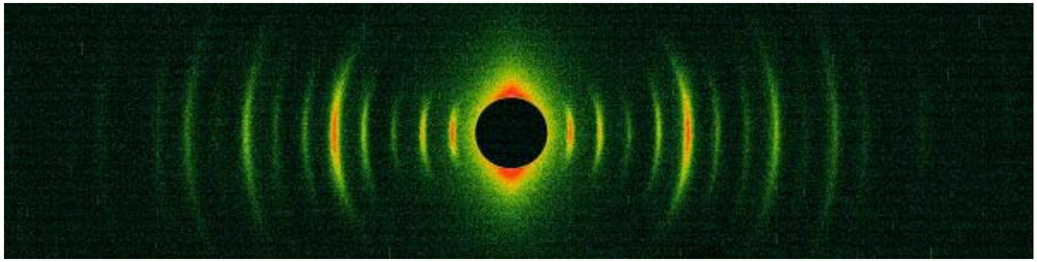
BELLE & ILC DEPFETs for Photon Science



X-ray Diffraction Image from the Protein Crystal

X-ray energy 12.4 keV
(wavelength=1.0Å)
@ BL-5A

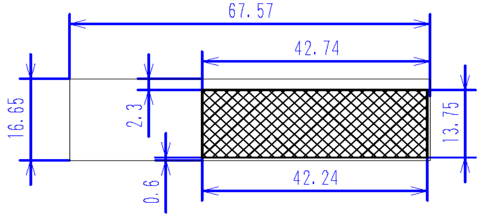
X-ray solution scattering image

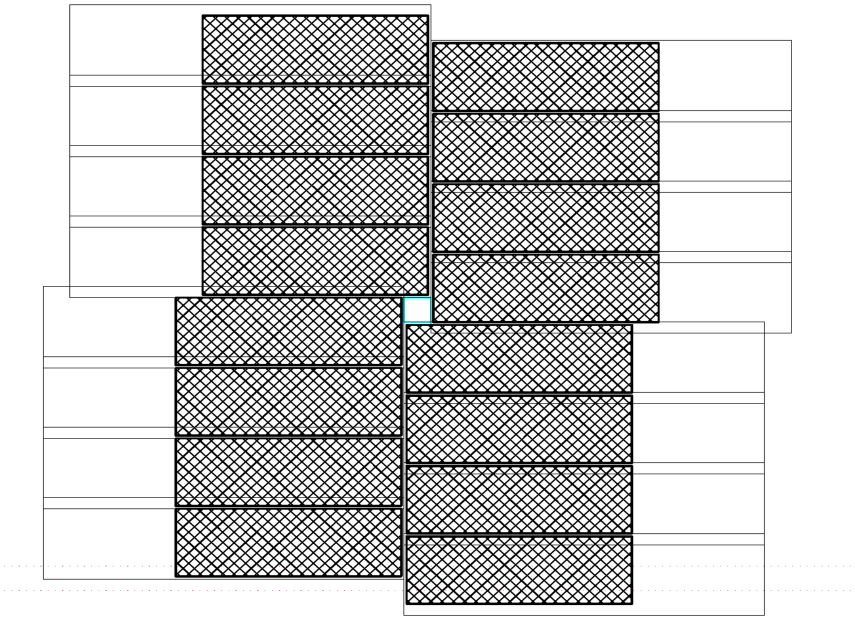


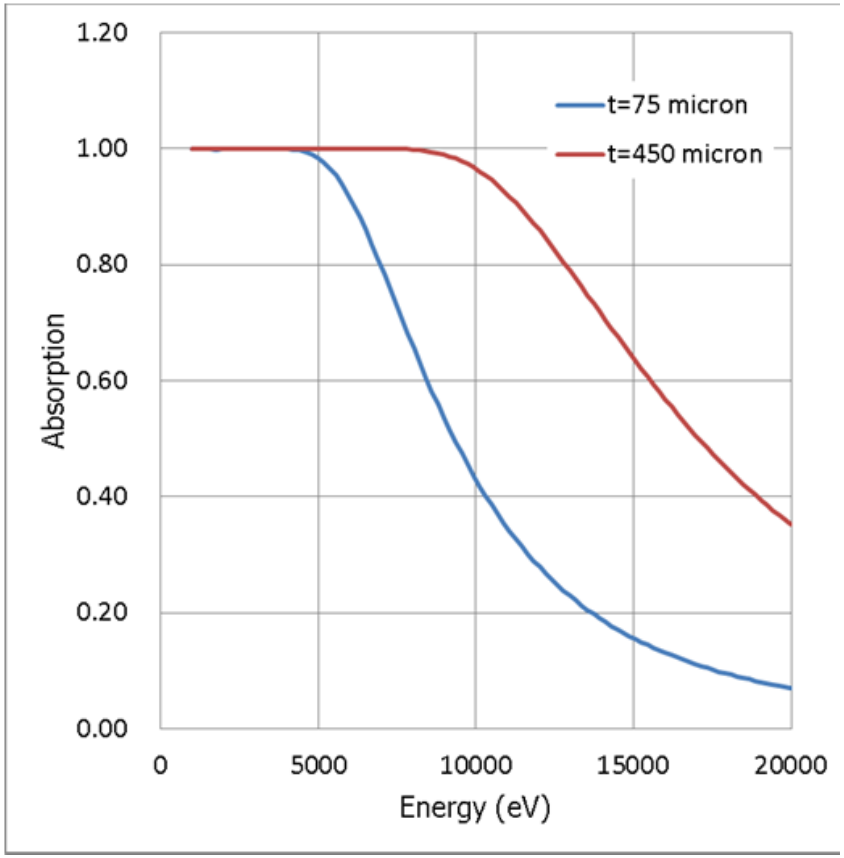
Collagen from Chicken Achilles tendon
o X-ray energy 8.33 keV (wave length=1.488Å)
@ BL-10C
o 1-dimentional orientation
o Lattice spacing: d=653Å

BELLE like sensors (20μs) for PF KEK

pixel size: 55 um x 55 um
number of rows and columns: 250 x 768







Summary

I showed :

- Some very attractive DEPFET devices developed and produced at MPS Semiconductor Laboratory
- Some of the potentials of those devices are used in current projects
- Still space to explore much more …

Thank you for your attention …