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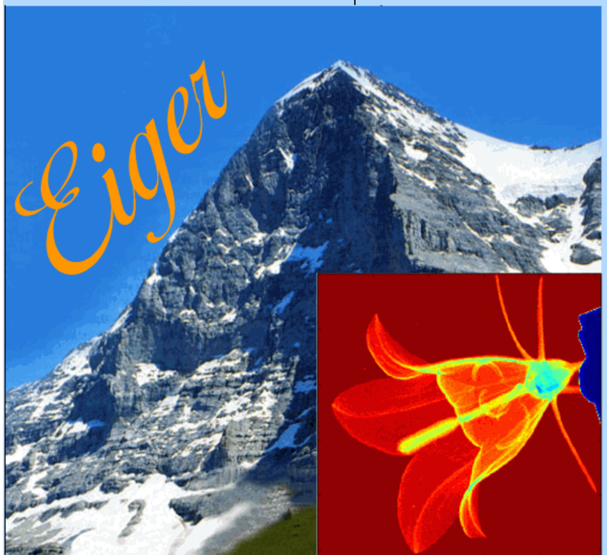
Wir schaffen Wissen – heute für morgen



Paul Scherrer Institut

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Single photon counting detectors for X-ray applications

OUTLOOK

- Introduction of Paul Scherrer Institut
- Chip design at PSI
- Basics of X-ray synchrotron radiation emission
- Detectors developed by the SLS Detector group for X-ray detection
  - Single photon counting detectors

1. PILATUS (2D)
2. MYTHEN (1D)
3. EIGER (2D)

OUTLOOK

EIGER: next generation single photon counting detector for X-Ray applications

- Motivation
- Main features and comparison with Pilatus II
- The pixel
- Readout architecture
- Testing a single photon counting detector

OUTLOOK

Charge integration detectors for X-ray applications

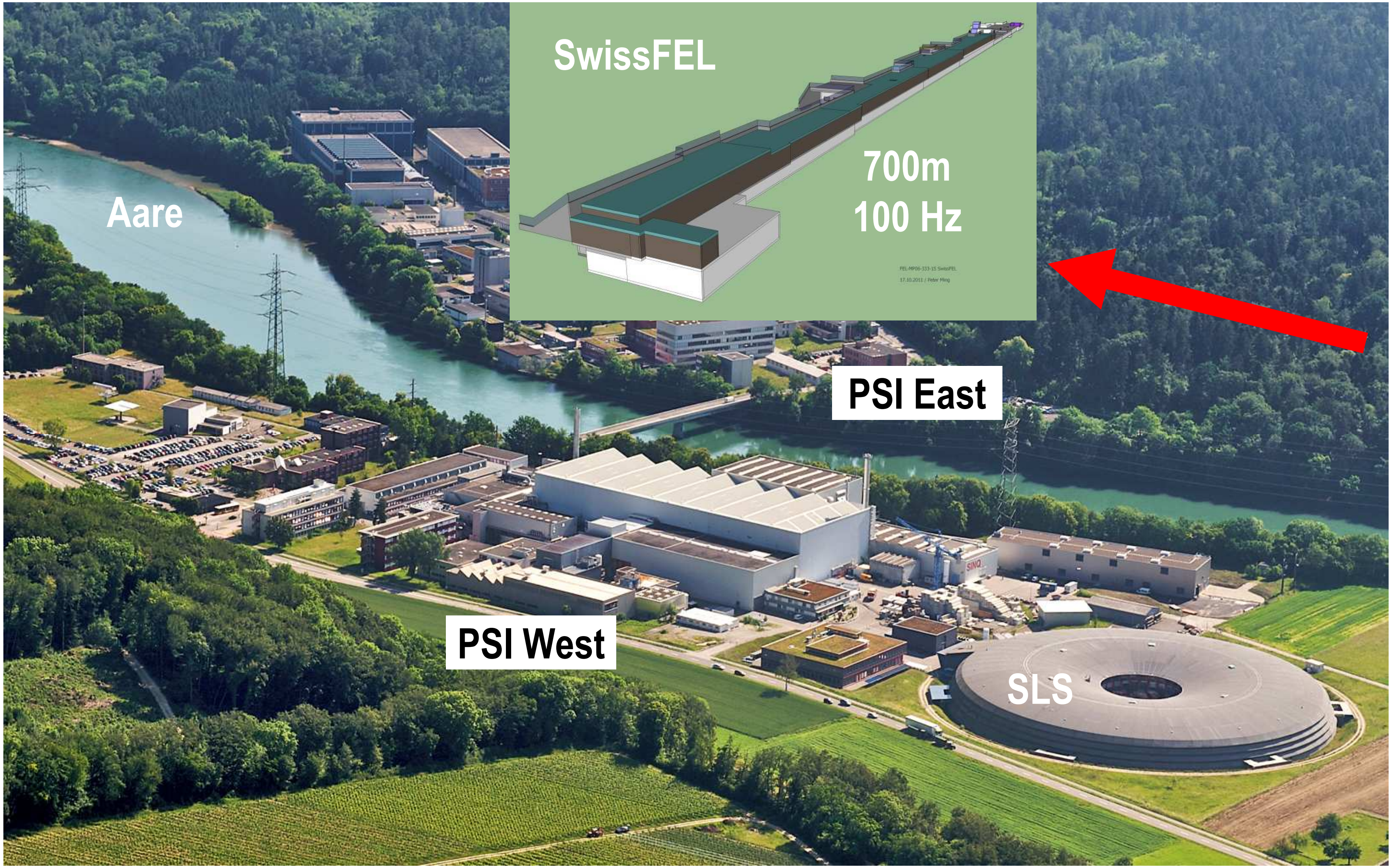
Wednesday 16:45

- Quick summary of first talk
  - Charge integration detectors

1. AGIPD (2D, XFEL)
2. GOTTHARD (1D, XFEL & Synchrotron)
3. JUNGFRAU (2D, XFEL & Synchrotron)
4. MÖNCH (2D, XFEL & Synchrotron)

- MÖNCH, a small pitch, integrating hybrid pixel detector for X-ray applications

PAUL SCHERRER INSTITUT (2011)



~1700 Staff employees; 30Km from Zurich

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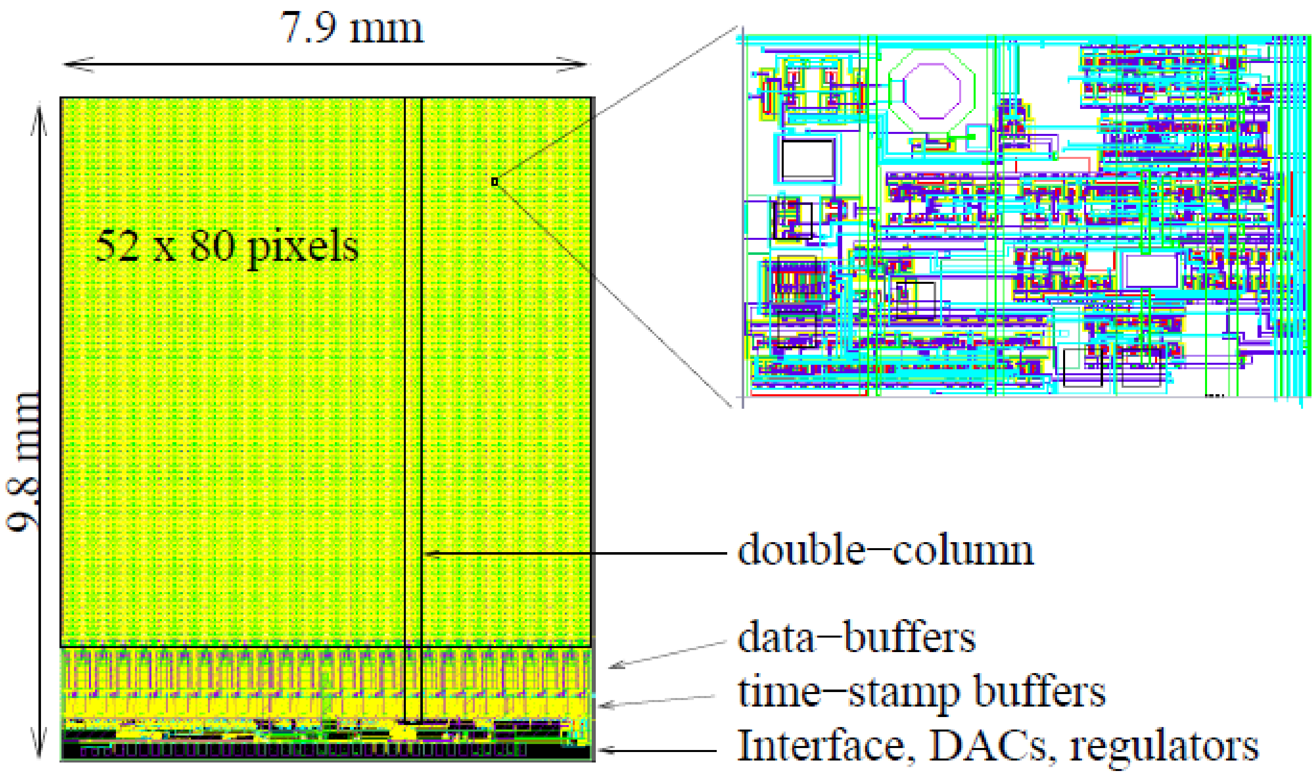
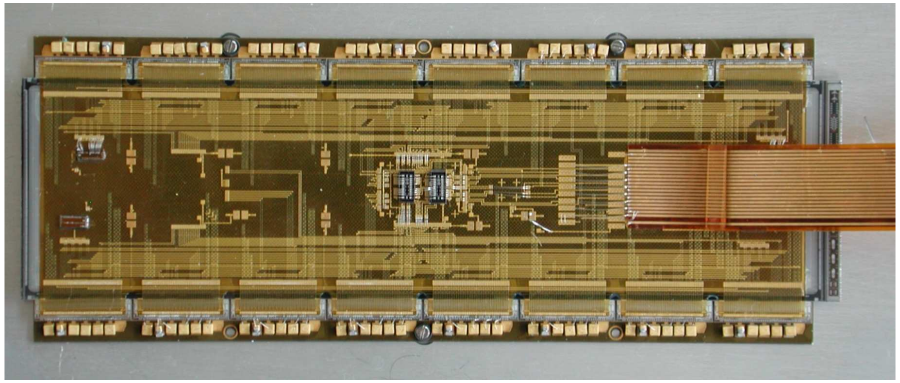
The CMS Pixel Chip (Roland Horisberger)



- Technology: 0.25 um IBM
- Pixel size 150x100 um^2
- Tested up to 100MHz/cm^2 ~ 20 kHz/pixel
- Time resolution: 25 ns
- Deadtime/ pixel: 100ns
- Module: 416 x 160 pixels (62.4 x 16 mm^2)

CMS module based on PSI46 Chip



Chip design at PSI

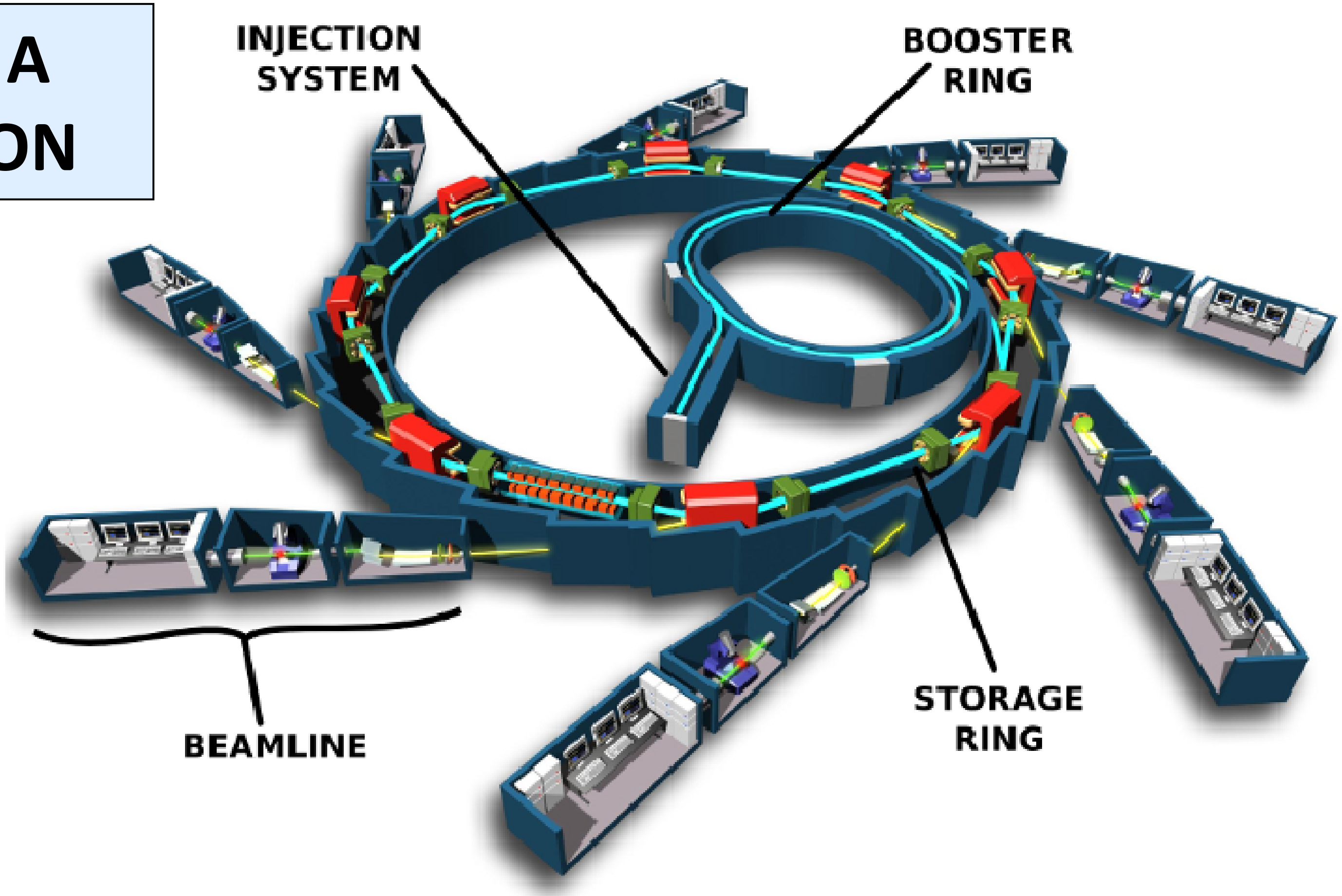
Particle physics	CMS	Pixel chip for the inner tracker New version for LHC luminosity upgrade
	MEG	Domino sampling chips (DRS4) New version for MEEE (DRS5)

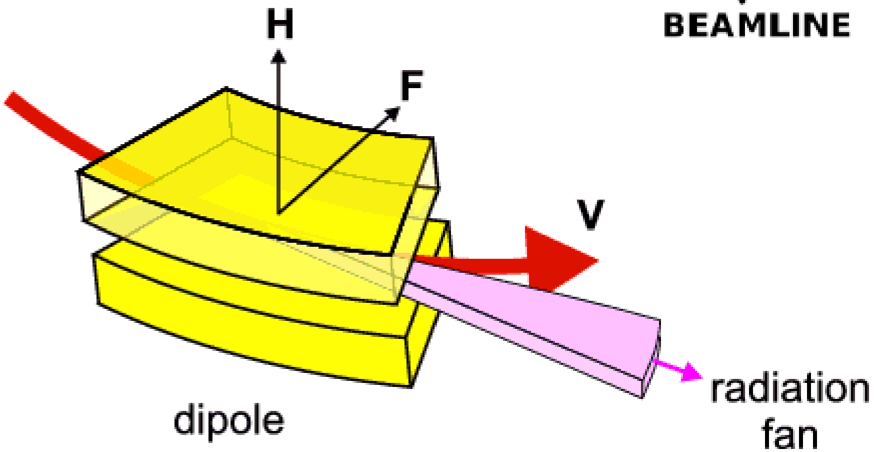
X-ray detection	Synchrotron light (Mythen,Pilatus,Eiger) XFEL light (Agipd, Gotthard, Jungfrau, Mönch)

Astronomy Research	Sensor design HiZ – Neutrons – Low energy X-ray – Electrons Detectors

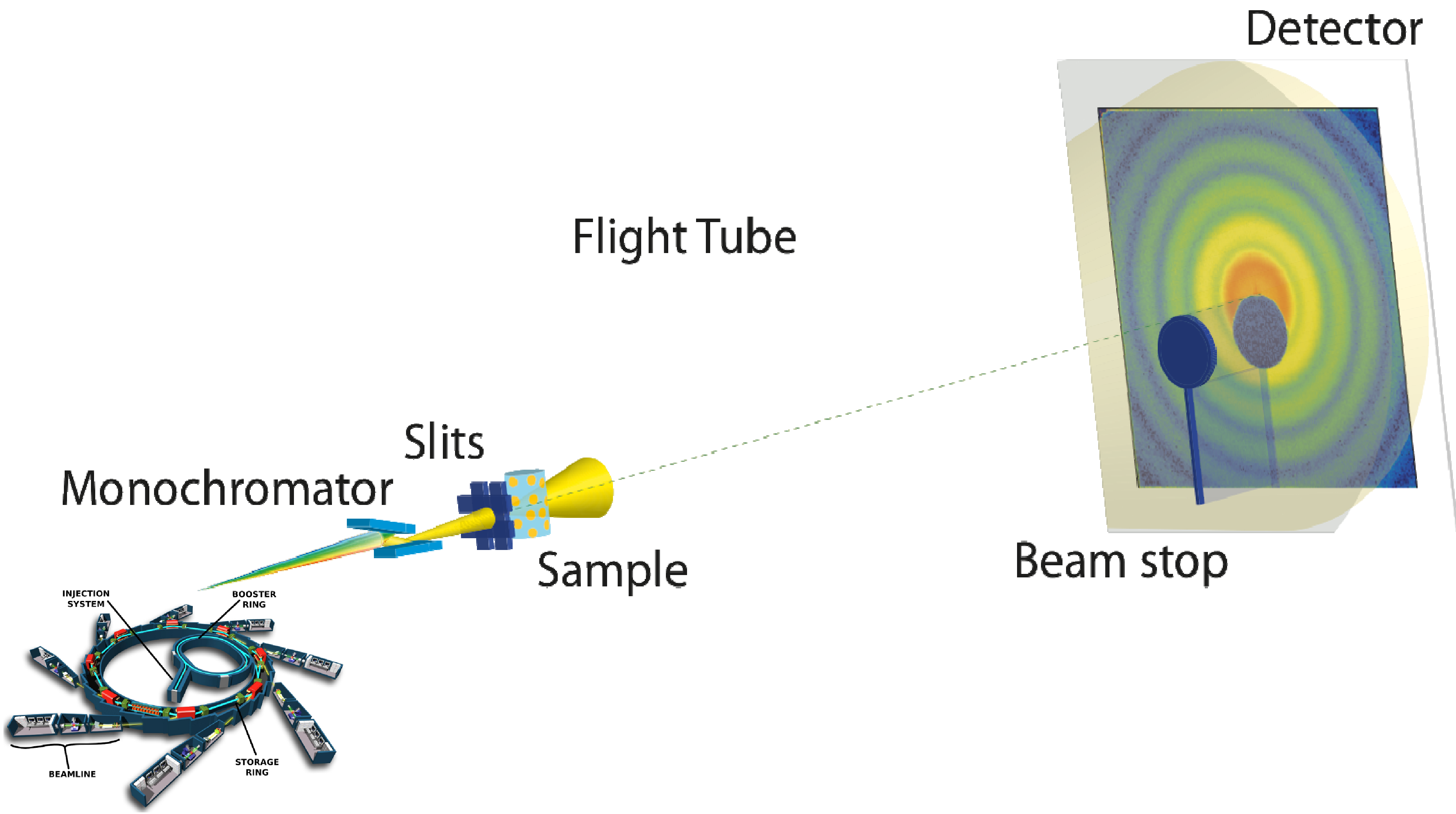
Basics of X-ray synchrotron radiation

SCHEME OF A SYNCHROTRON

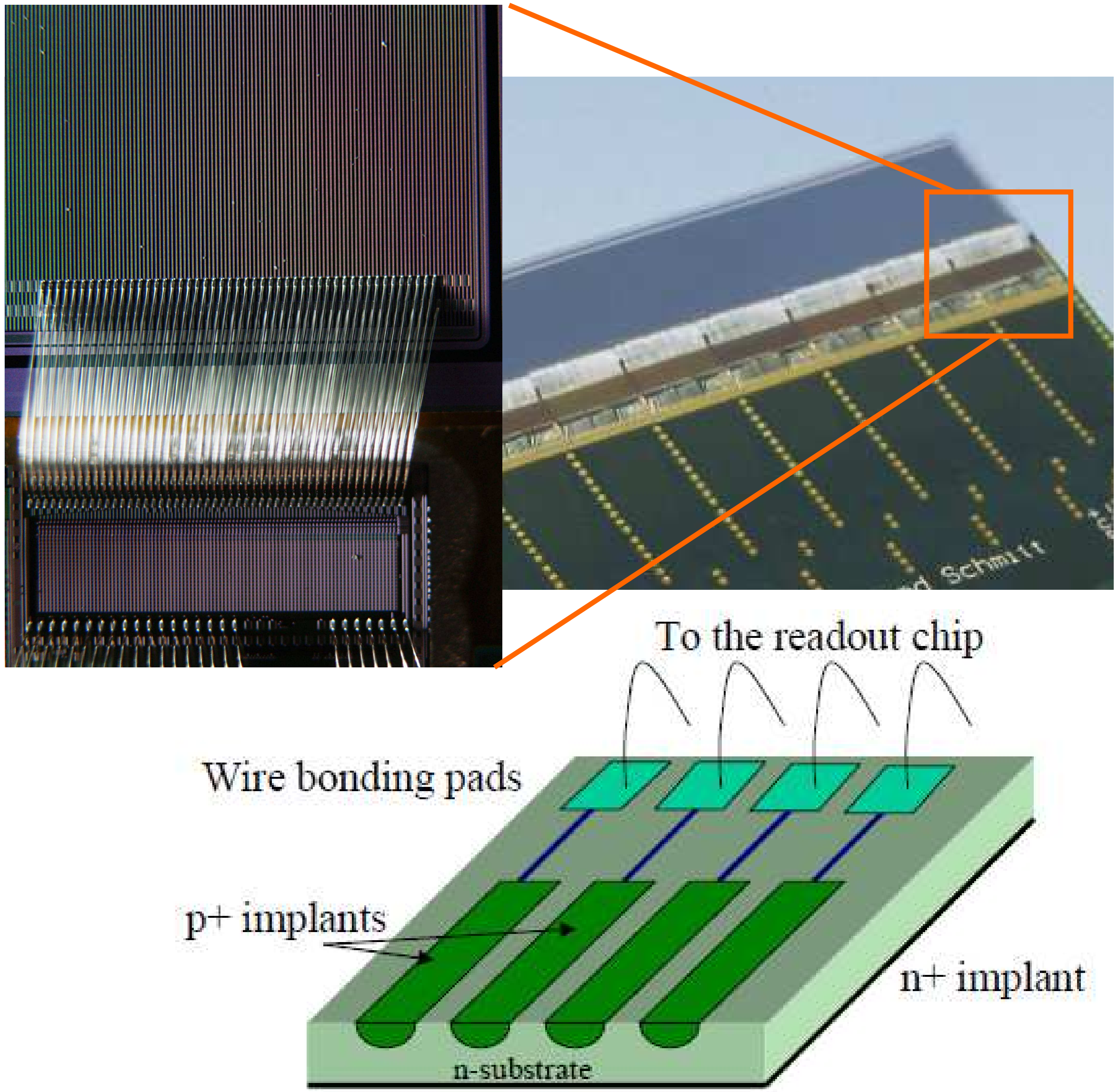




Basics of X-ray synchrotron radiation



1D hybrid detectors (strips)



Strip detectors

- High segmentation
- Small data throughput
- Lower cost per area

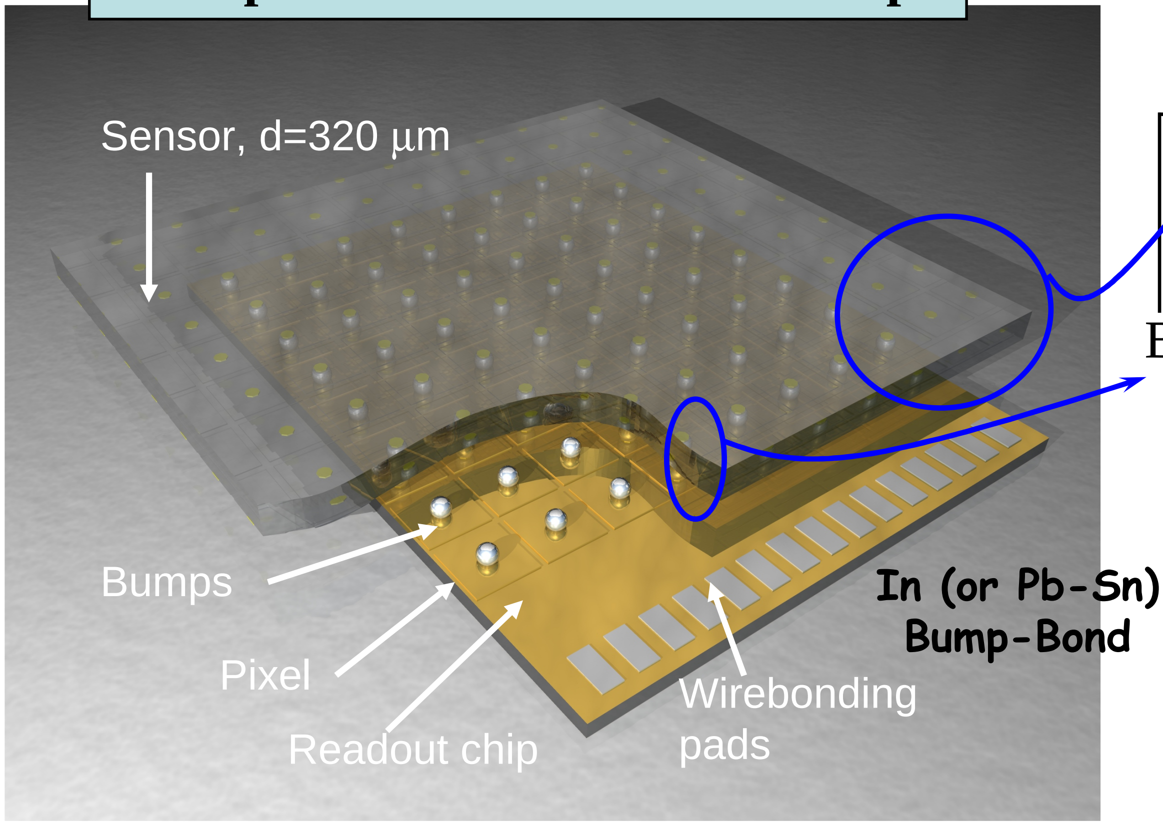
Powder diffraction

Fluorescence emission spectrometers

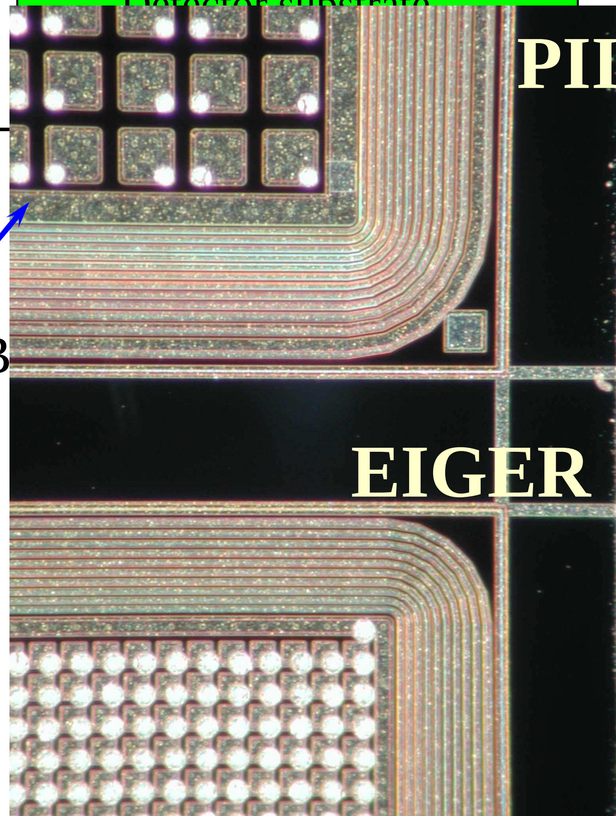
Beam position monitors

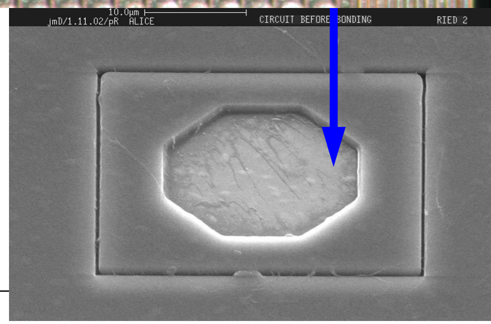
2D hybrid detectors (pixels)

A silicon detector bump-bonded with a readout chip



n-diffusion

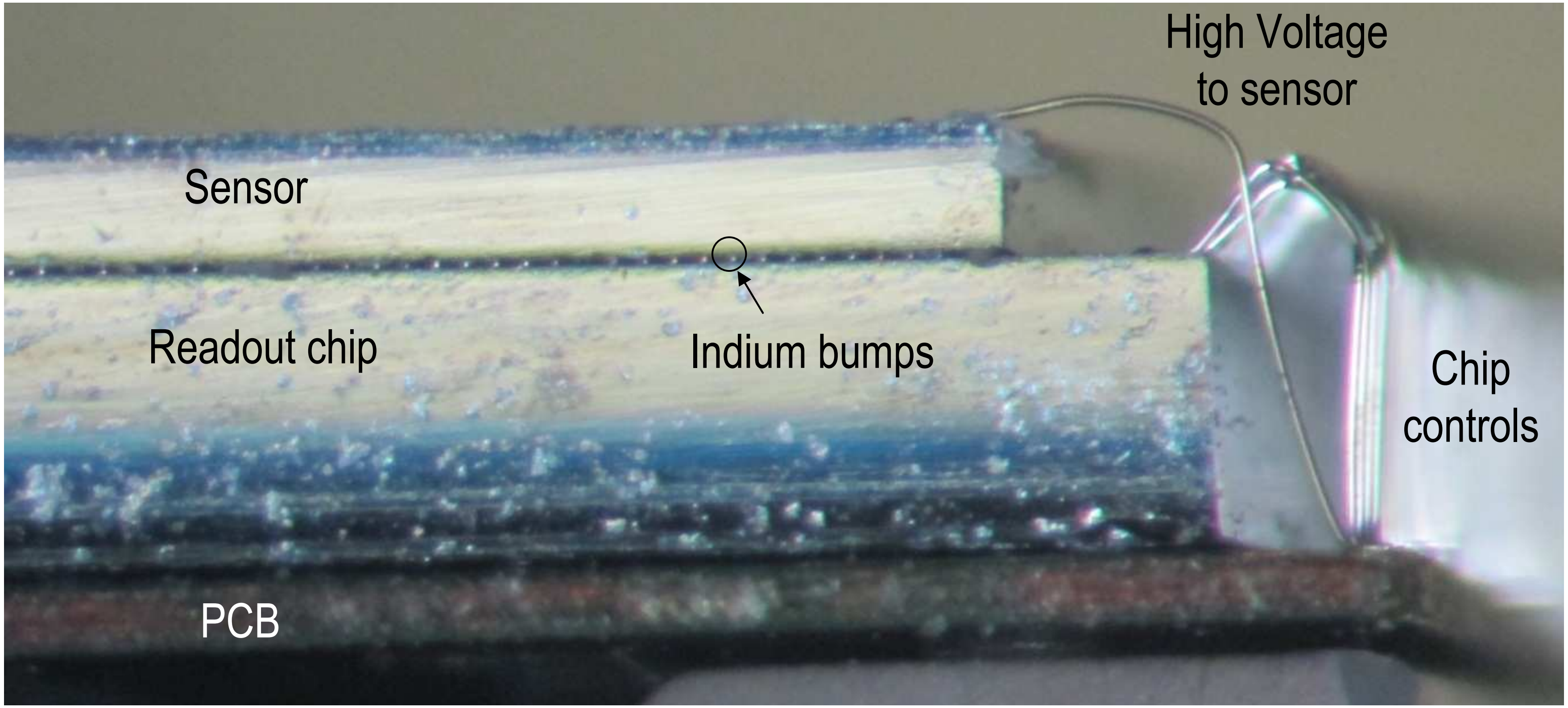




Bump-bond metal pad

2D information!

Bump bonded pixel sensor



- Bump bonding require additional processing of the chip and sensor surface to deposit an under-bump-metallization and the indium
- After reflow in the oven, the indium forms bumps

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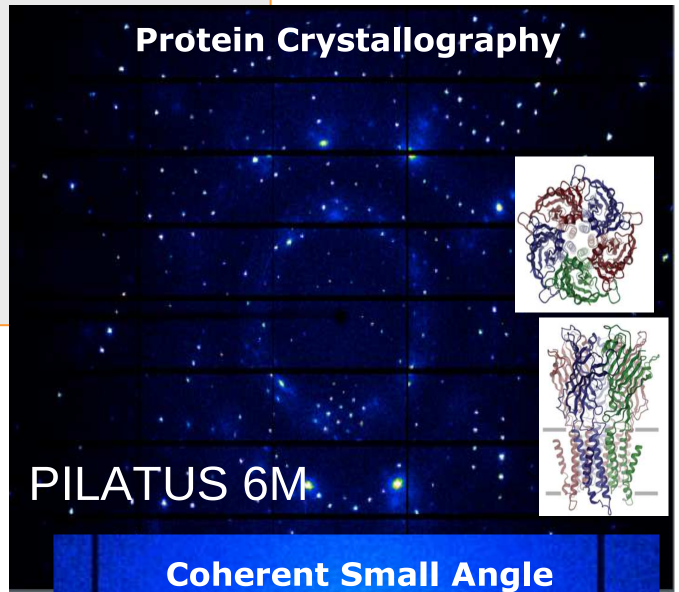
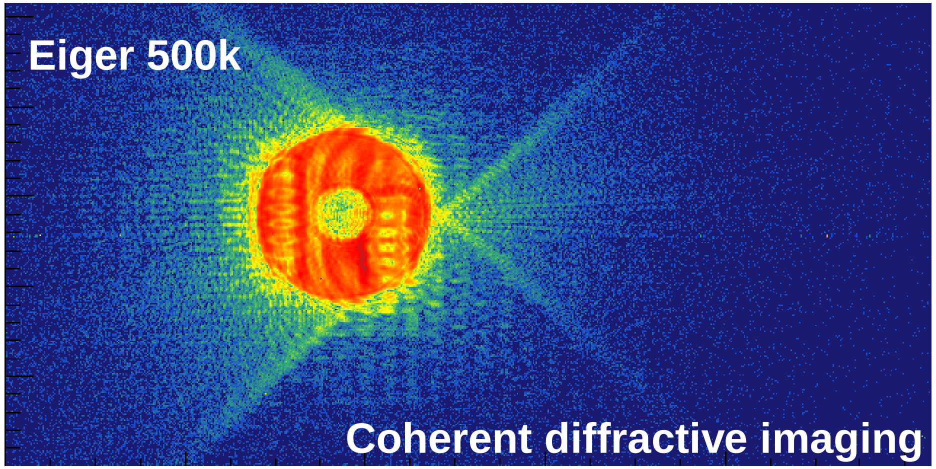
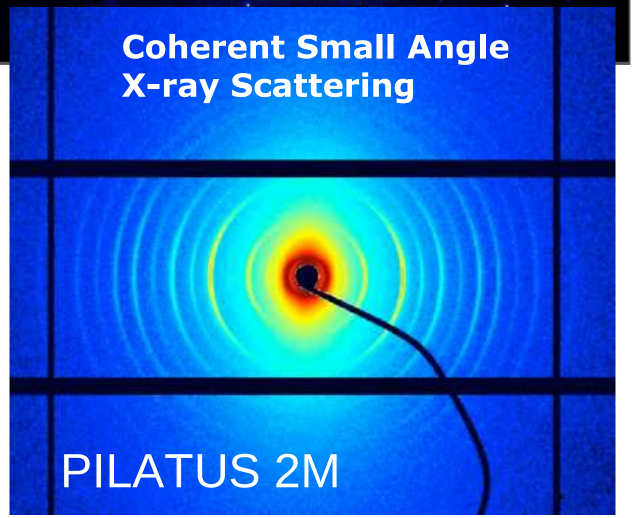
2D detectors at synchrotrons

Single photon counting hybrid pixel detectors for synchrotron applications are aimed towards diffraction experiments

- Protein Crystallography
- Coherent Small Angle X-ray Scattering
- Coherent Diffractive Imaging
- X-ray Photon Correlation Spectroscopy







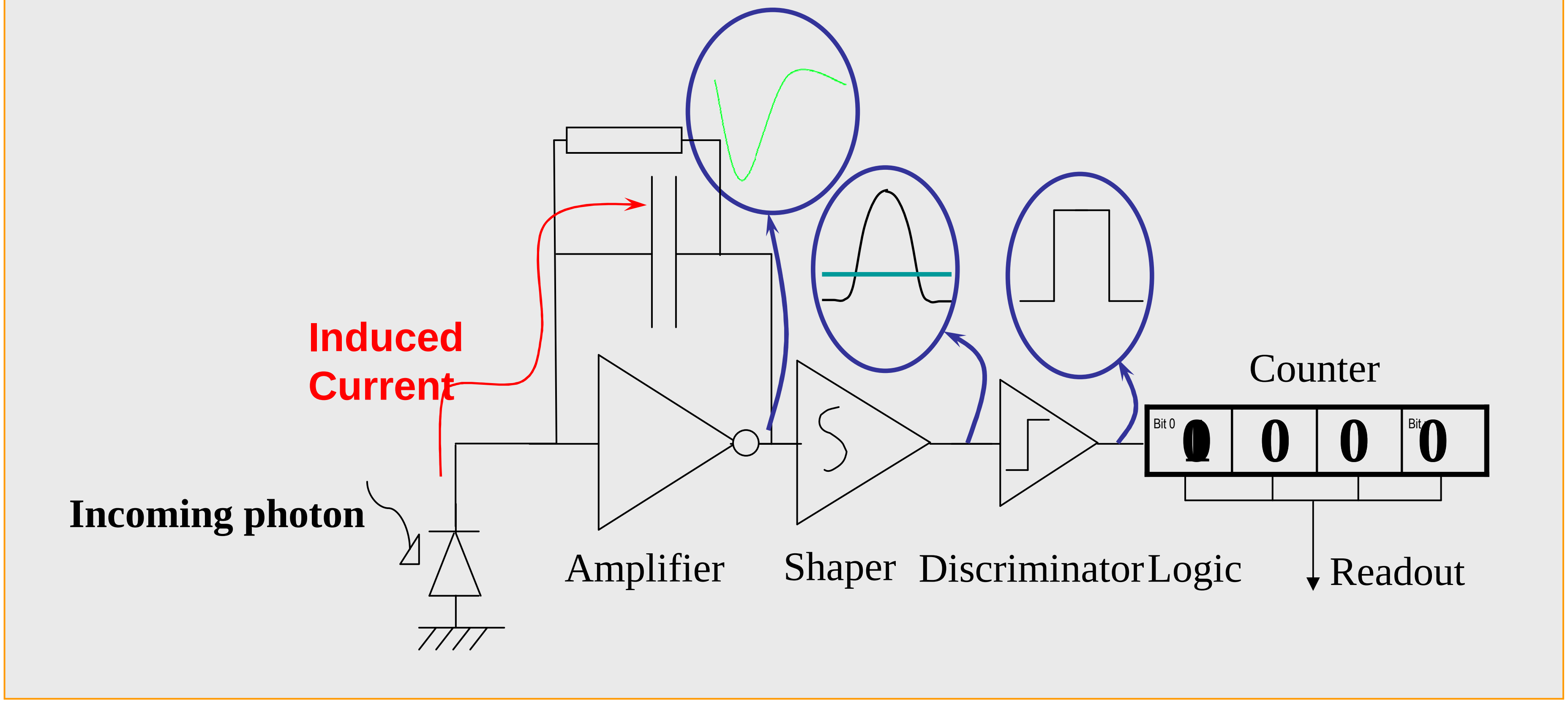
Tasks that we perform at PSI

- Specs definition
- Chip design CAD mantainance (HW and SW)
- ASIC design
- Sensor design
- Bump-bonding masks design
- Bump bonding
- Wirebonding
- Design of the ASIC test system (HW,firmware,SW)
- ASIC tests

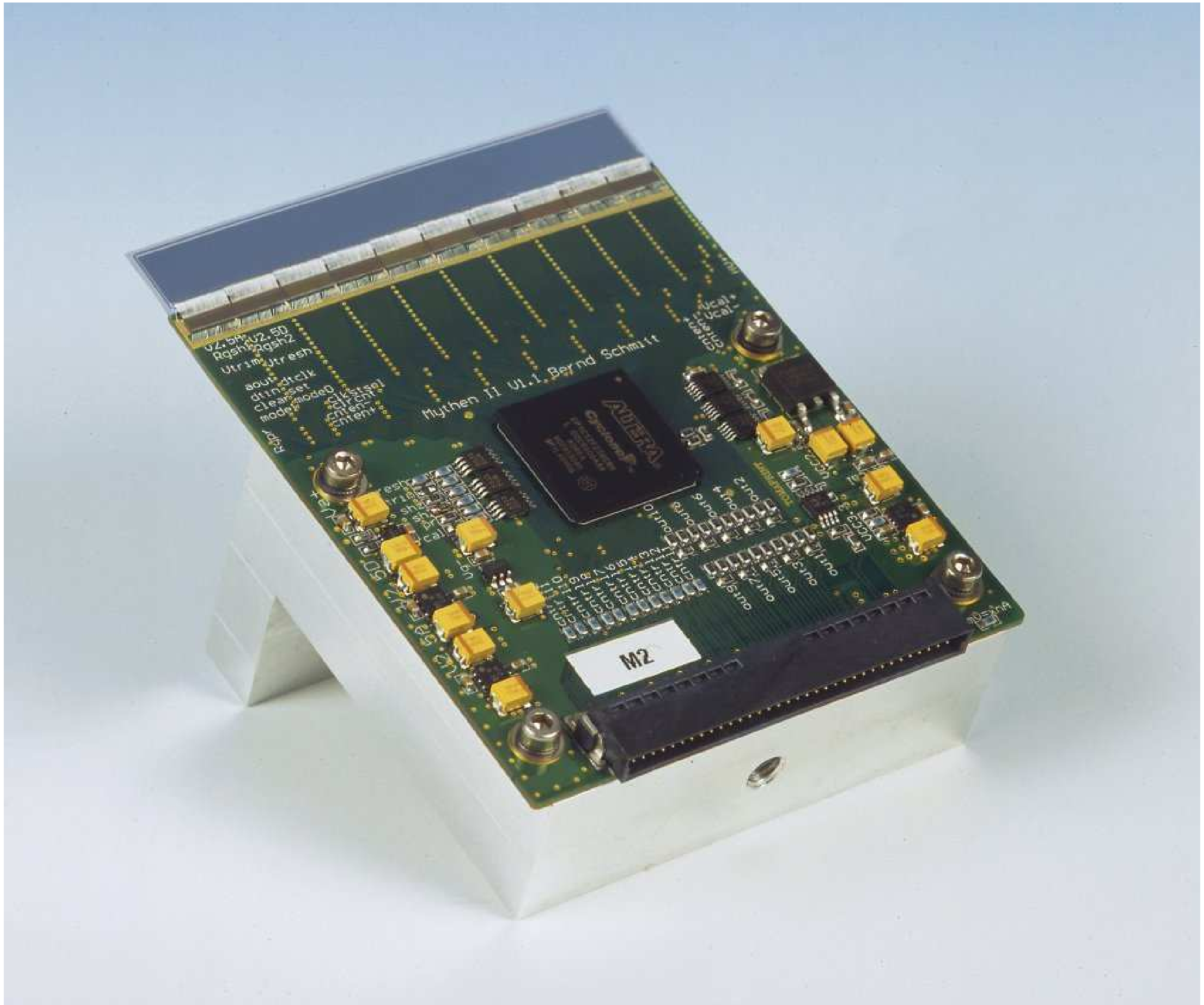
Tasks that we can perform at PSI

- Full readout system (HW,firmware,SW)
- Mechanics and cooling design (and partly production)
- Data transfer to long term storage
- Design of the wafer testing system
- Detector assembly
- Detector tests
- Detector commissioning
- Detector „mass“ production
- Detector support

Simplified working scheme of a channel



Mythen II



Mythen II specifications

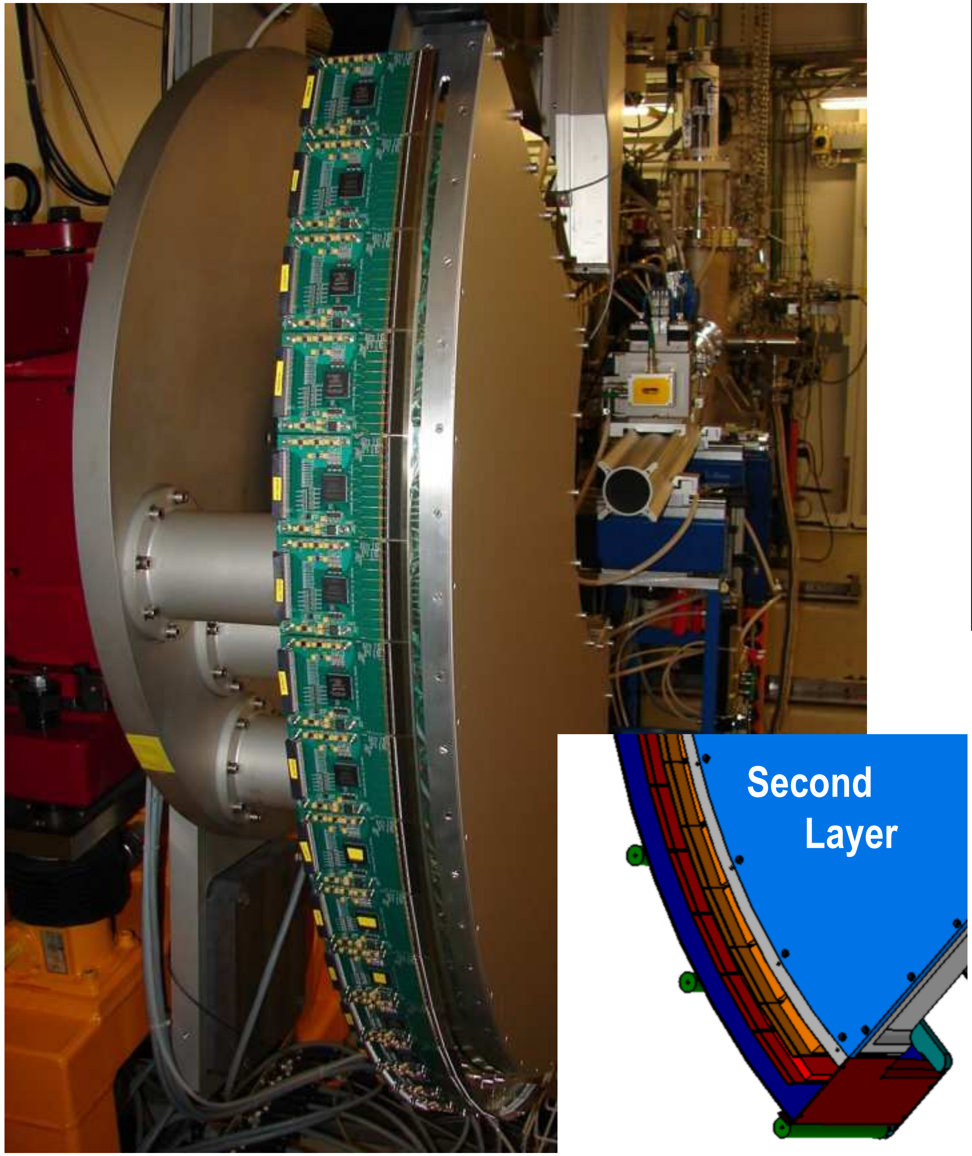
(MythenI: 2002-2007)

Silicon sensor with 1280 strips
8 mm long, 50 μm pitch, 300 μm thick

Read out chip:

- 0.25 μm readout chip, 128 channels
- low noise preamp: 190-240 e^- ENC
- 6 bit DAC for threshold fine tuning
  - 1.4keV without trimming and 140eV Trimmed
  - Minimum threshold: 3keV
- 24 bit binary counter
- Readout Time: variable length (4-24bits)

Mythen II full detector



120º Mythen system at the Powder diffraction end station, MS beamline

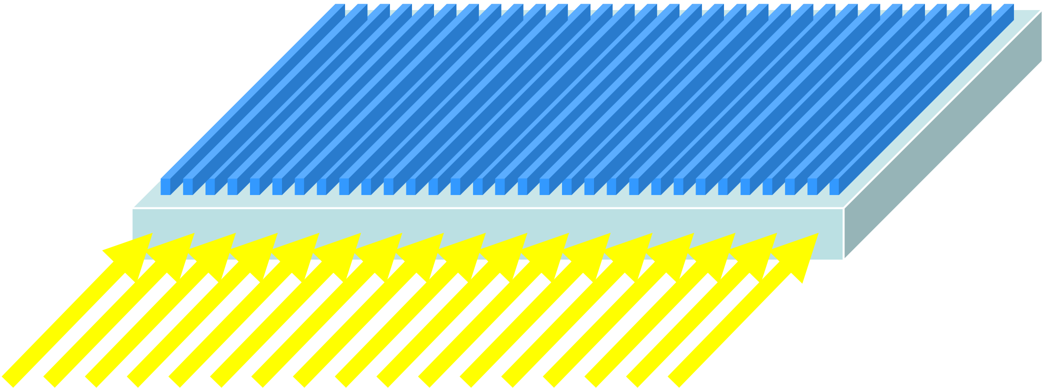
- full 120º spectrum taken in less than a second
- makes measurements 5000-15000 times faster
- solves problem of radiation damage in organics

- unique tool for time resolved 1D experiments (powder diffraction)

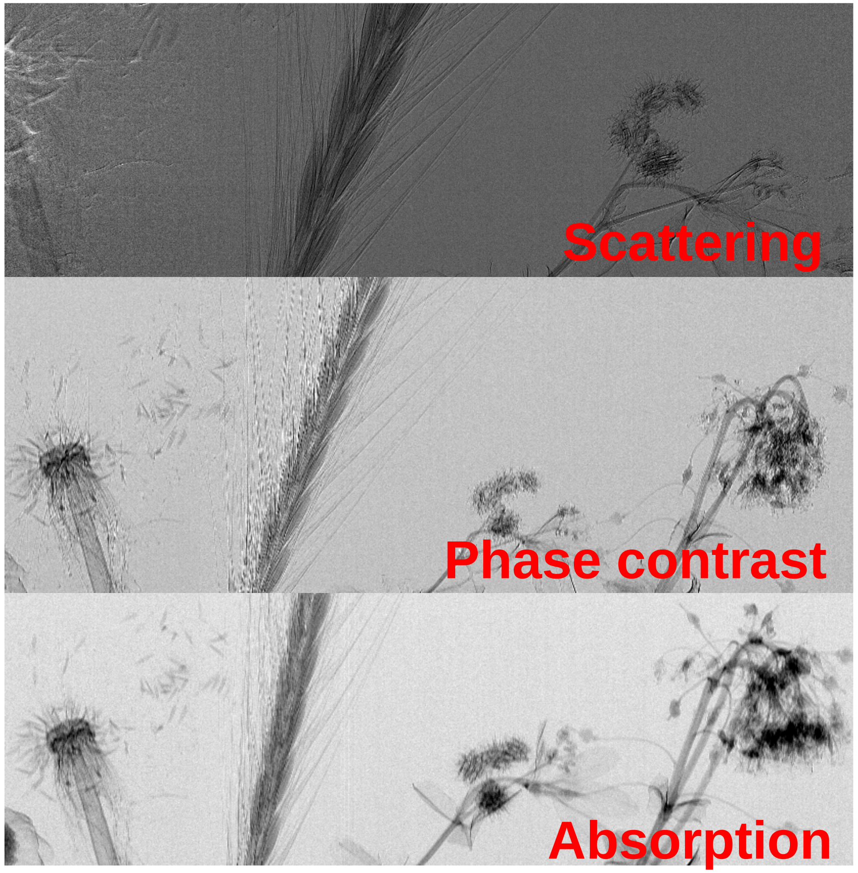
Imaging tests at Syrmep beamline

Sensor oriented with the strips parallel to the beam

- Custom sensor to improve the efficiency at 20 keV

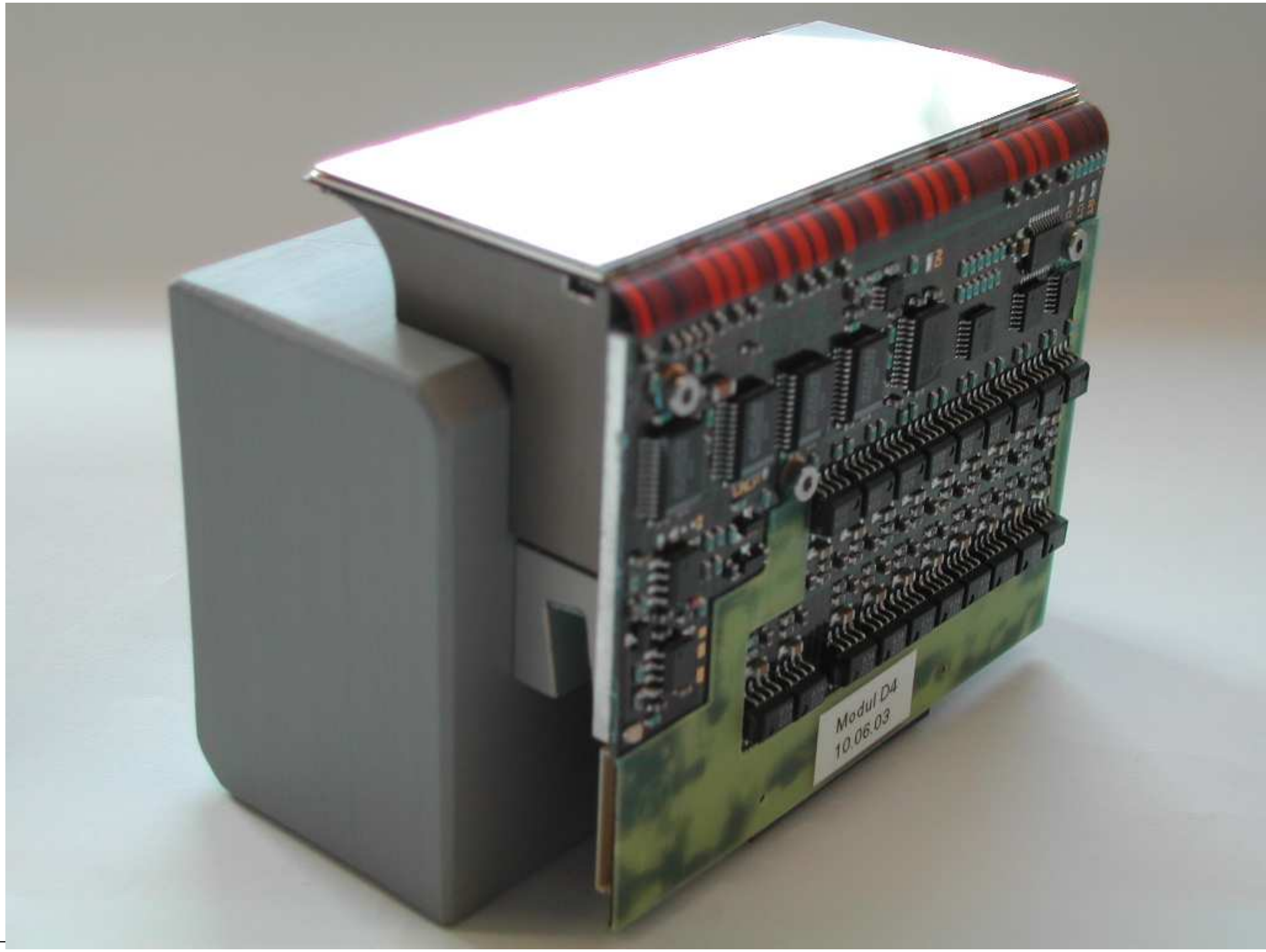


Measurements performed at the medical imaging beamline at Elettra (Italy)



PILATUS I

Demonstrate feasibility of large area hybrid pixel detectors for synchrotron radiation detection



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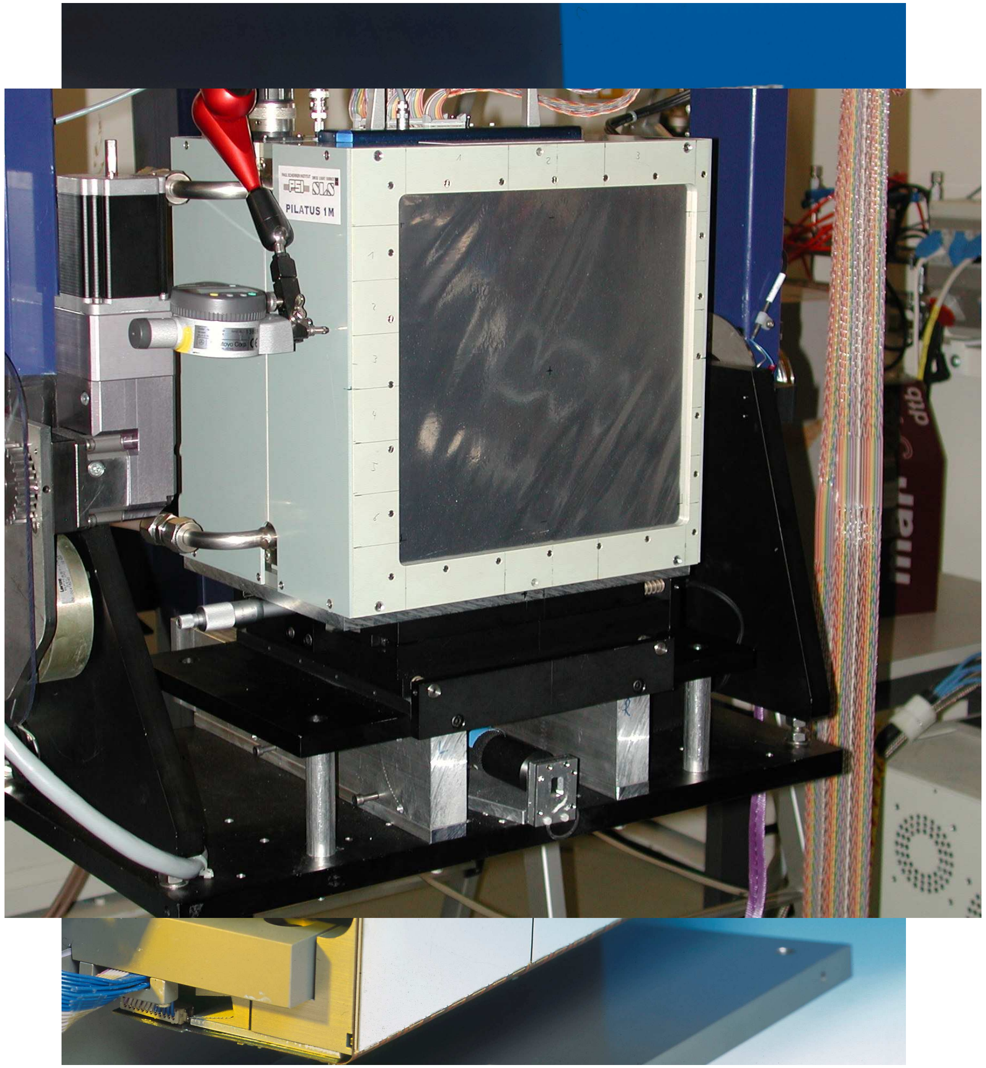
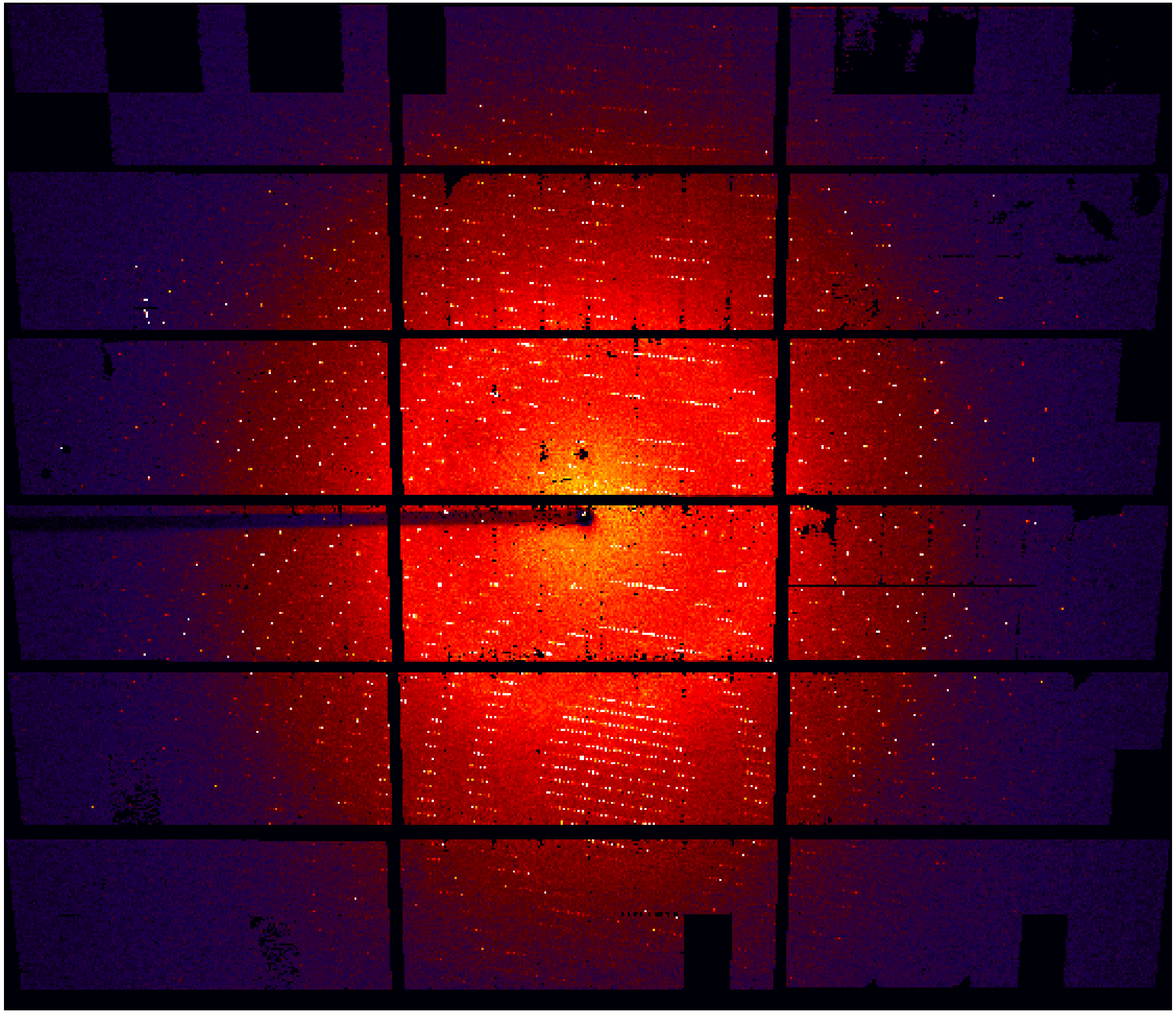
The PILATUS 1M Detector for Protein Crystallography

- DMILL rad-hard technology
- Pixel size: 217x217 μm^2
- Chip pixel array: 44 x 78
- Largest pixel detector array for SR
- 6 banks a 3 modules, 1120 x 967 pixels
- Area: 21 x 24 cm^2
- 288 chips->~300x10^6 transistors
- Readout time: 6.7ms
- 2 frames/ s
- Active area: 85%
- Moderate count rates (<10kHz/pixel)



Thaumathin crystal



Data Taking:

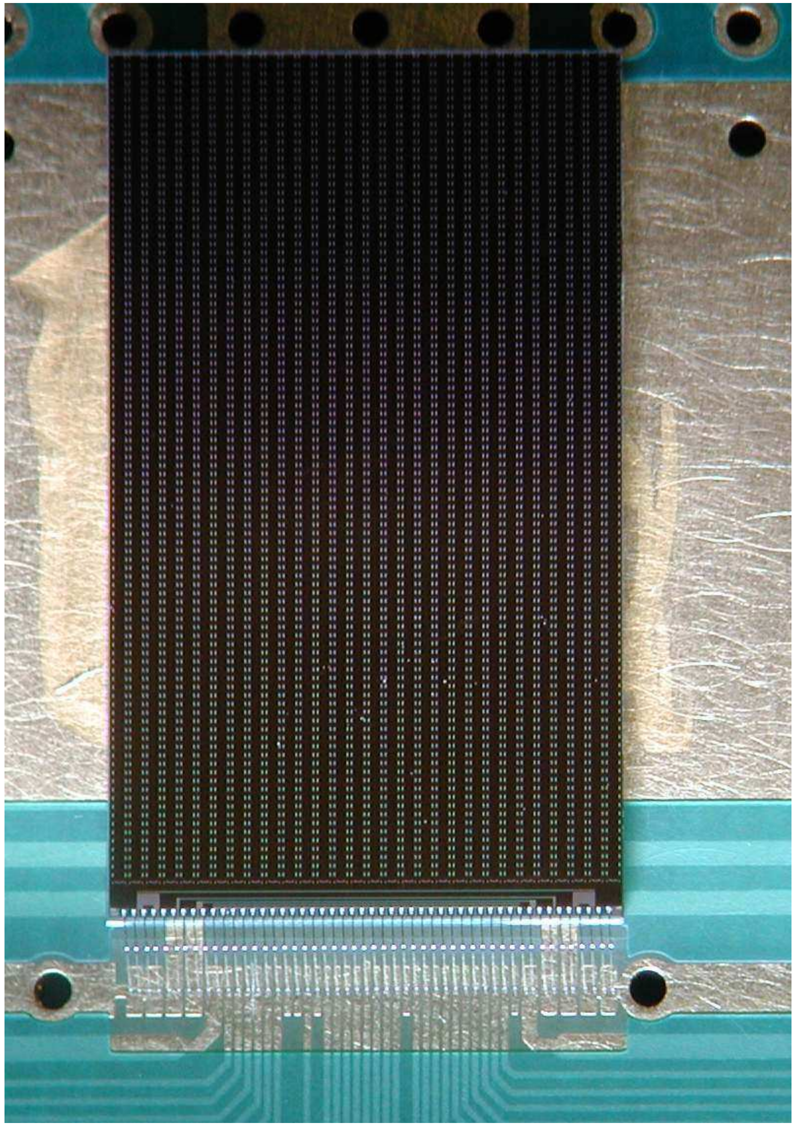
Data set: 120°
Exp Time: 4s
Integration: 1°
Beam energy: 11.9 keV
Beam intensity: 13.5%
D Sample-Det: 128 mm
Resolution: 1.4 Å

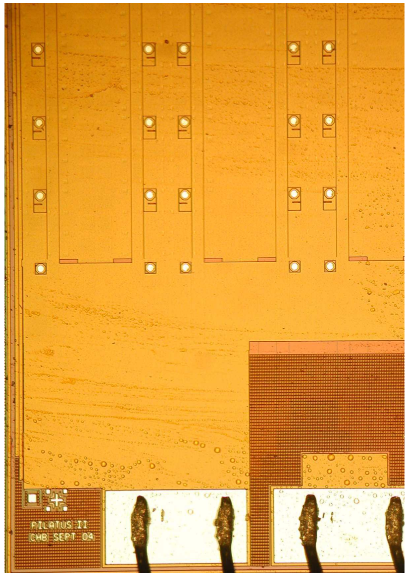
Analysis:

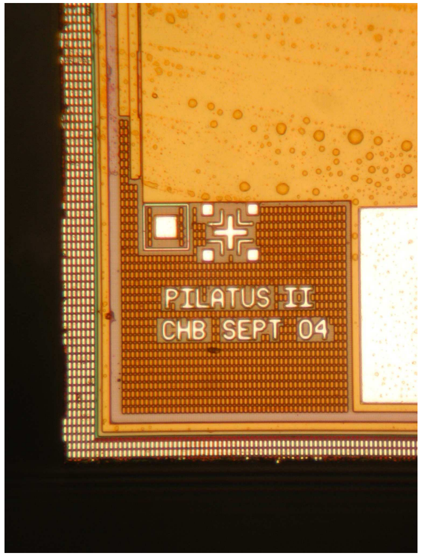
3 data sets merged
full geometrical correction
Processed with XDS

R_{obs}: 8.9% (overall)
Completeness: 90%
(98% up to 1.6 Å)

PILATUS II



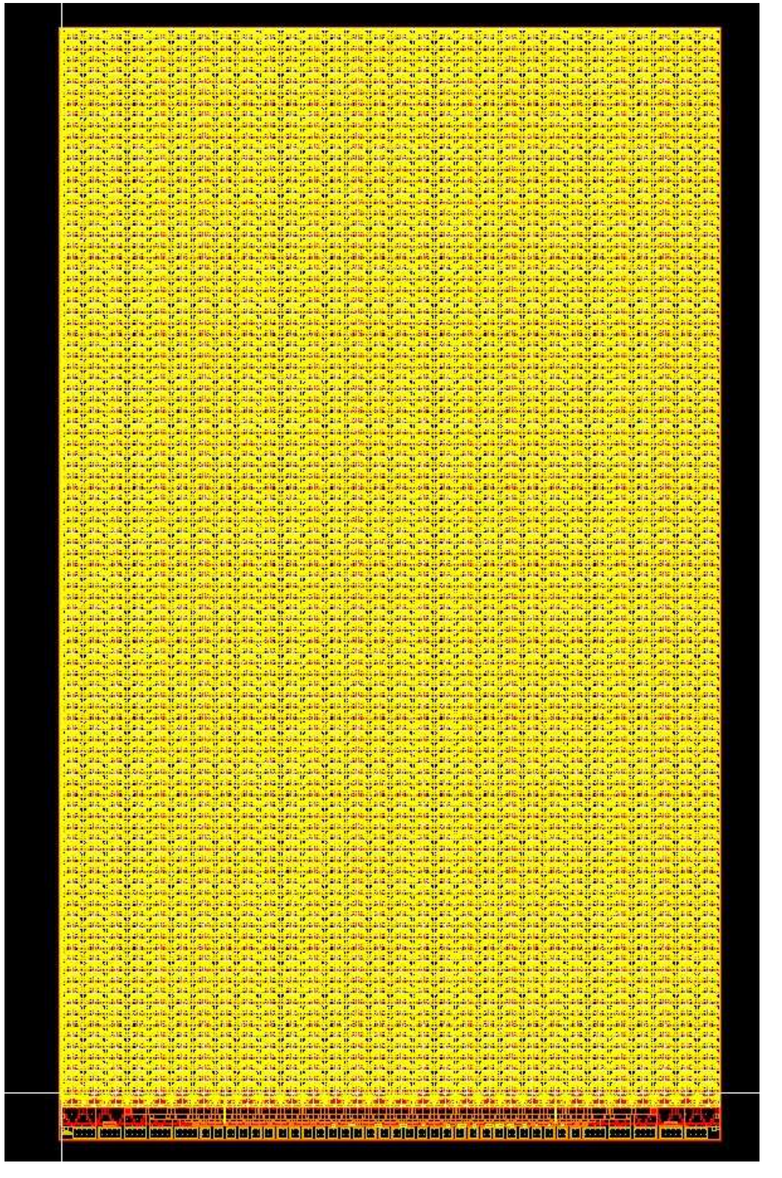




PILATUS II Chip

- UMC_25_MMC process; Radiation hard design
- 60 x 97 pixels = 5820 pixels
- Pixel size 172 x 172 um^2
- 17.540 x 10.450 mm^2
- Count rate: 1MHz/pixel
- 20 bit counter
- Counting timer circuit
- 6 bit DAC for threshold adjustment
- XY-adressable
- Analog output
- 100 MHz LVDS readout (T_{ro} = 1.2 ms)
- Submitted 29.09.04
- Received 1.12.04

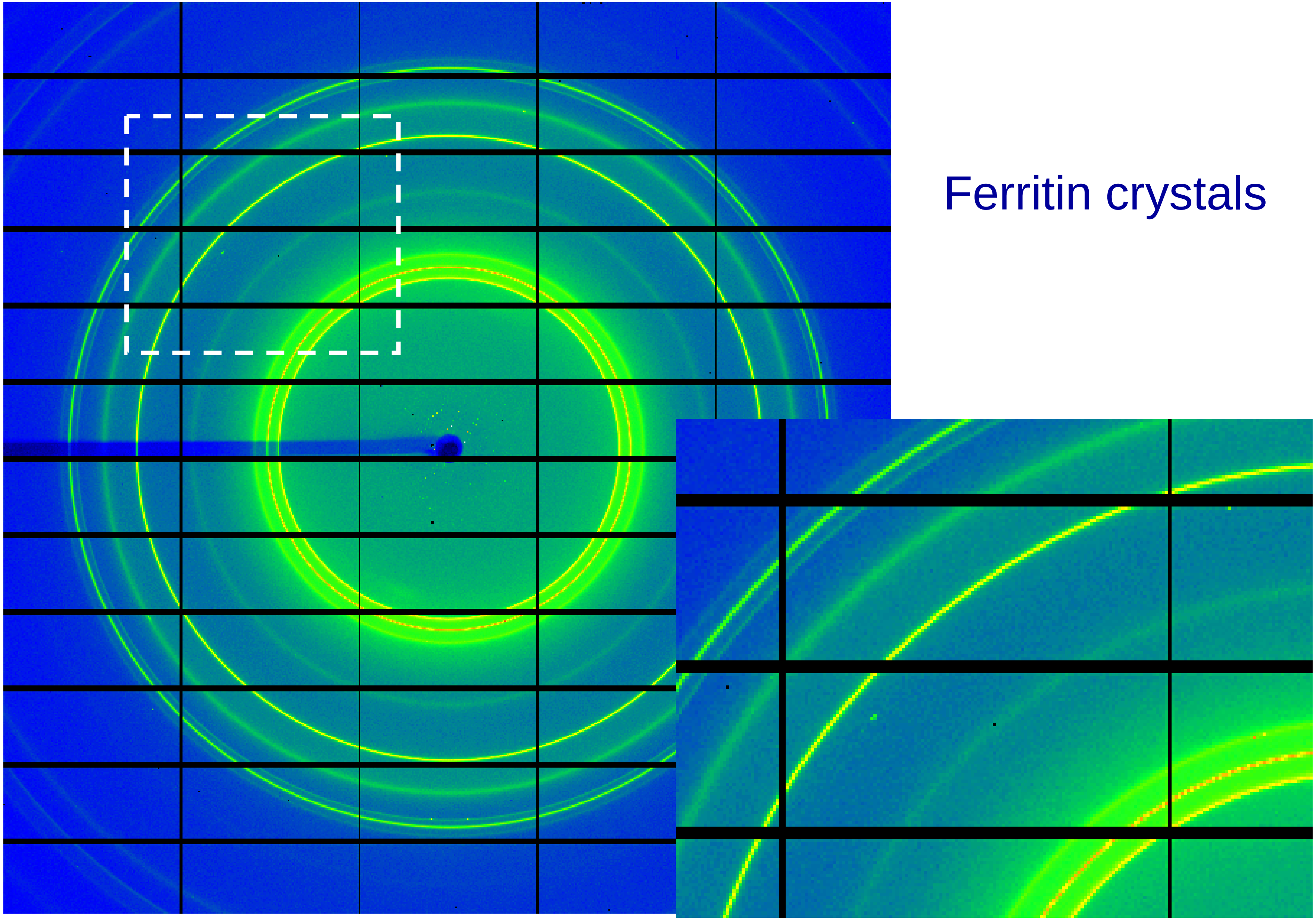
$4*10^6$ Transistors



The PILATUS 6M Detector

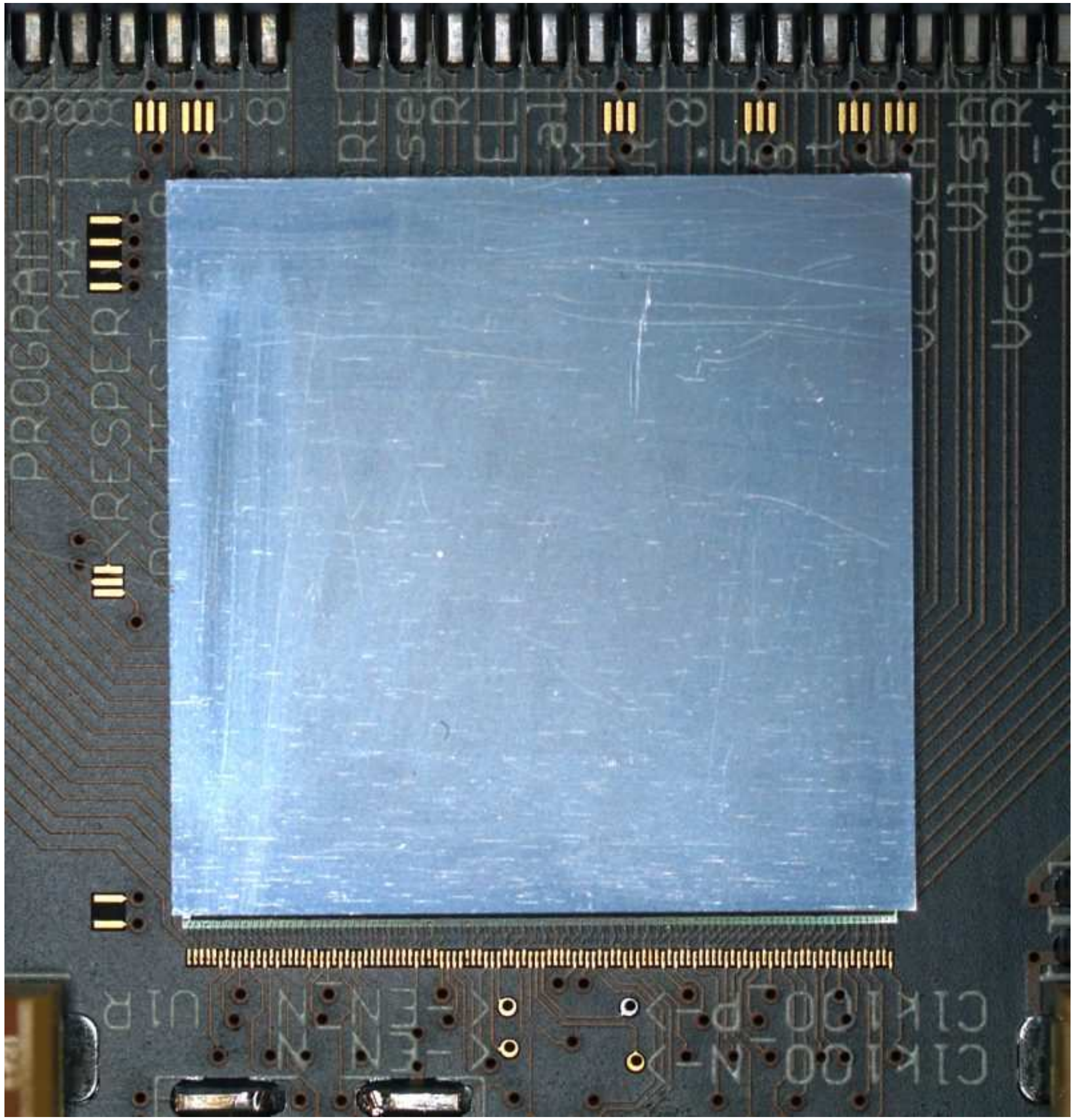
No of Modules	60
Module size	487 x 195 pixels (90k)
Detector Size	431 x 448 mm^2
No of Pixels	2527 x 2463 pixels
	(6.2 * 10^6 pixels)
Spatial resolution	0.172 x 0.172 mm^2
Dynamic range:	20bits
Readout time	~2ms
Frame rate	5-10 Hz
Rate	1 MHz/pixel
Spatial distortion	Flat geometry
Dead area	~8.4 %
	(7 pixels in x, 17 pixels y)
Operation mode	Fine ϕ-slicing

PX Data Collection at BL X06SA



Ferritin crystals

EIGER



Single photon counting pixel detectors

Requirements:

- X-ray sensitive
  - Energy range few keV to 25 keV
- Single photon sensitivity
  - Low noise
- Sufficient angular coverage
  - Large area
- Spatial resolution
  - Millions of small pixels
- High count rate capability
  - Count rates in the millions of counts/pixel/second
- High frame rates
  - Tens of kHz, parallel acquire/readout

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EIGER main features (I)

Technological process	**UMC 0.25 µm**
Radiation tolerance	**Full radiation tolerant design (>4Mrad)**
Analog Parameters	**30 ns peaking time** **~150 ns ret. Zero** **8.8 µW/pixel = 2.3 /** **Gain: 44.6 µV/e-**
Chip size	**19.3 x 20.1 mm^2 (active 19.2x19.2mm^2)** **> 2 x**
Pixel size	**75 x 75 μm^2** **= / 5.3**
Pixel array	**256 x 256 = 65536** **= 11.3 x**
Count rate	**3.4 x 10^9 x-rays/mm^2/s = 5.3 x** **(1-2 Mcounts/pixel/s)**
Transistors, Matrix: **Periphery:** **Transistors density:**	**28.44M = 9.5 x** **>120 000** **430/pixel, ~5 x**

In red: Improvement factor with respect to PILATUS

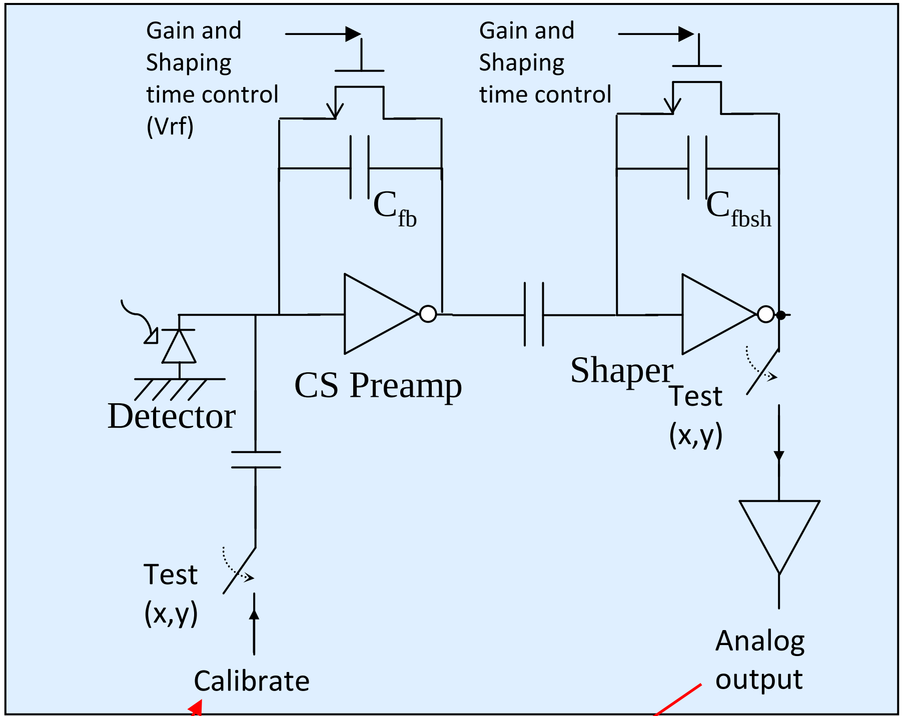
EIGER main features (II)

Nominal power supplies	1.1 V (analog), 2V (digital), 1.8V (I/O)
Counter	12 bits, binary, configurable (4,8,12 bit mode), double buffered
Continuous readout	yes
Detector readout speed	~11 KHz @ 8 bit mode, (22 @ 4 bit) Detector size doesn’t matter = up to ~2000 x (Clock=100 MHz DDR)
Threshold adjustment	6 bit DAC
XY-addressable analog out for testing	yes
Overflow control	yes

Both the chip and the readout electronics were totally redesigned, and almost all chip blocks are on silicon for the first time.

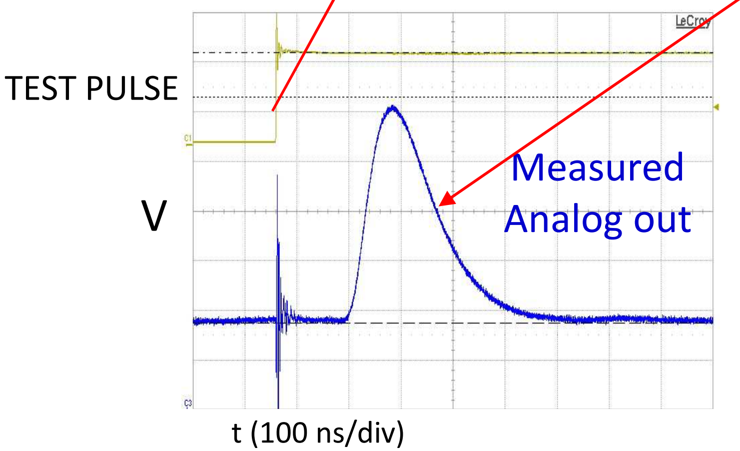
Project start: 02.2005, chip design as a one man project

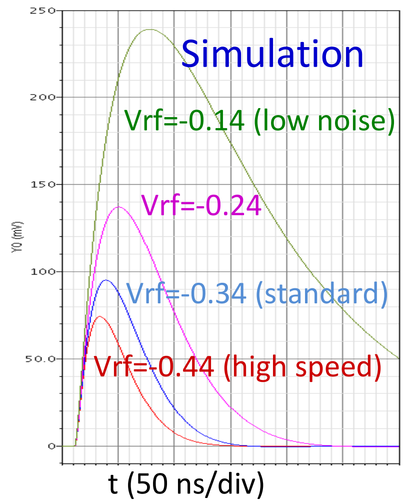
The EIGER pixel, analog part



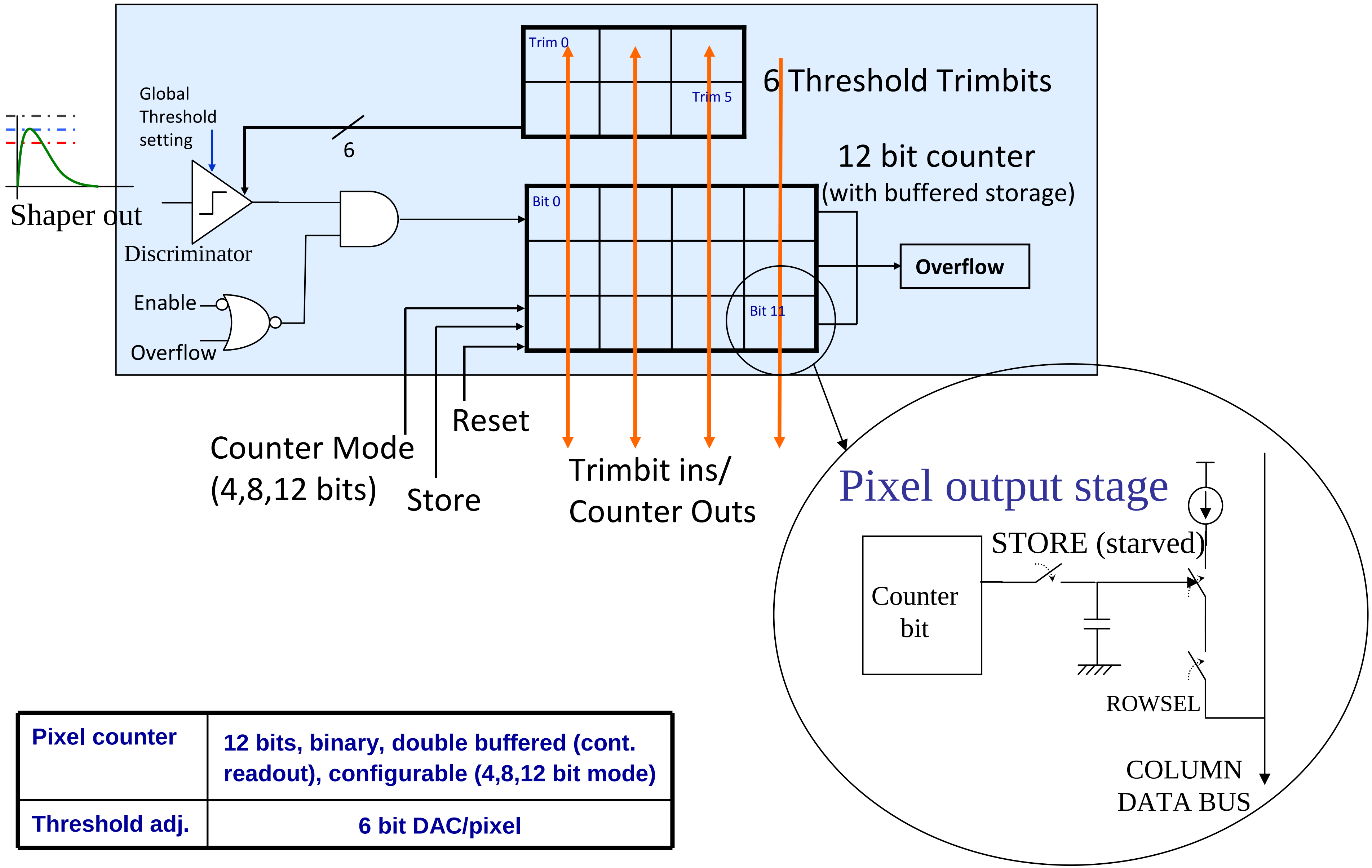
Simulated parameters with standard settings

Gain	**44.6 µV/e-**
Timing	**151 ns (Ret.to 0 @ 1%)**
Noise (simul.)	**135 e-rms**
Static power	**8.8 µW/pixel (~0.6W/chip)**



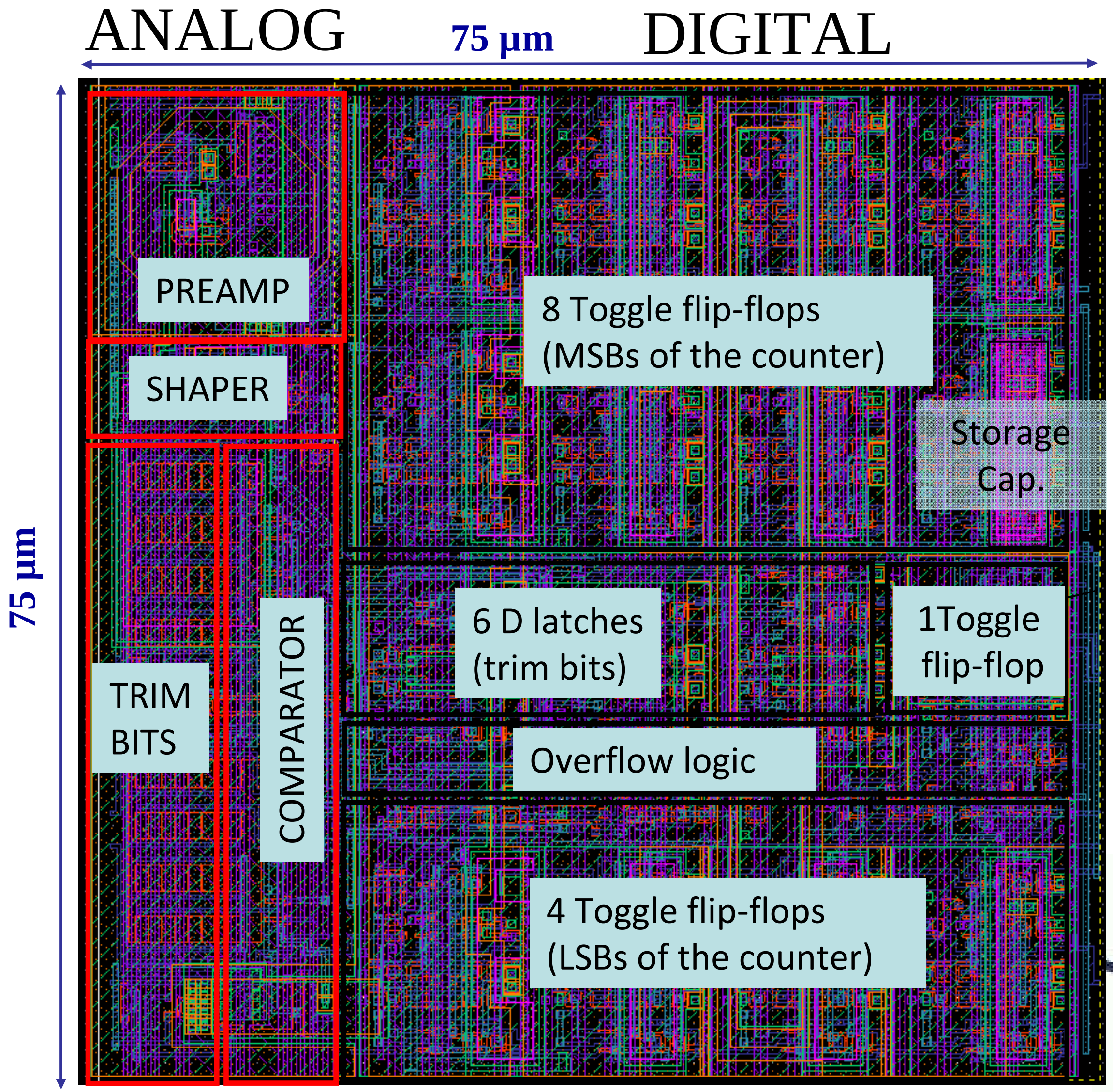


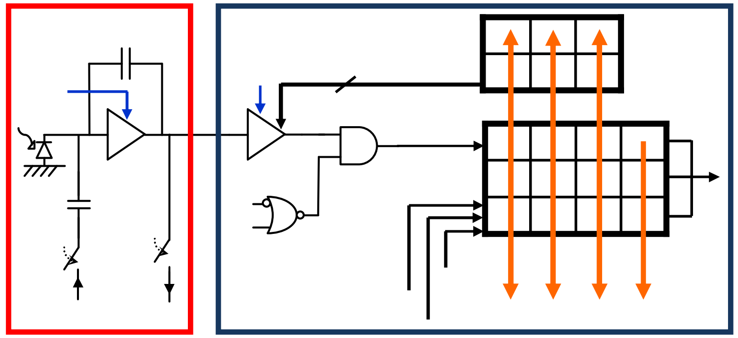
The EIGER pixel, digital part



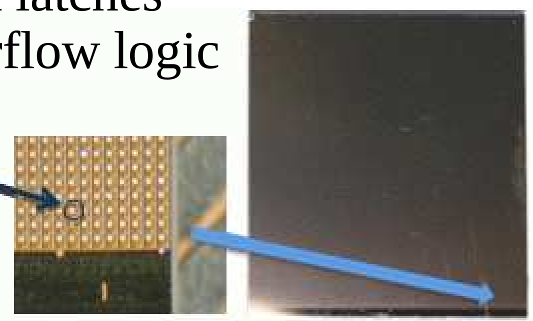
Pixel counter	**12 bits, binary, double buffered (cont. readout), configurable (4,8,12 bit mode)**
Threshold adj.	**6 bit DAC/pixel**

The EIGER pixel on silicon



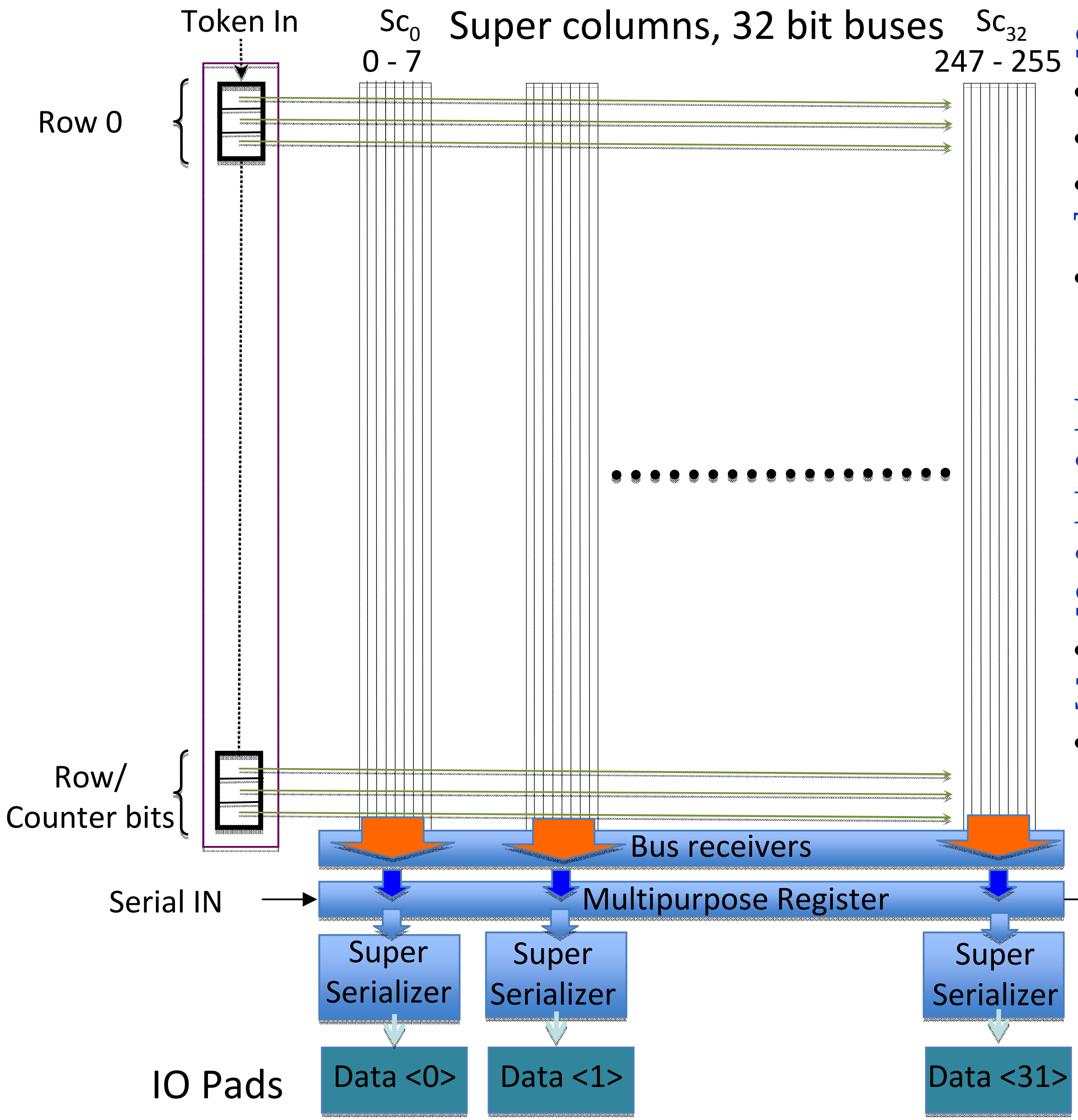


- Bump bond connection
- Preamp (TWELL)/shaper
- Comparator
  - Global threshold plus pixel trimming (6 bits)
- 12 bit counter
  - Counter logic
  - Buffered storage
  - Trim latches
  - Overflow logic



UMC 0.25 um Technology, full radiation tolerant layout; very high transistor density: 430 transistors/pixel, 5 metal layers only

EIGER readout architecture



Super column structure
- 8 columns/super column
- 32 super columns
- Current mode data buses

Token Shift Register
- Connects 4 bits of the counter storage cells or trimbits of a row to the bottom register

Bus receivers
- Perform I/V conversion

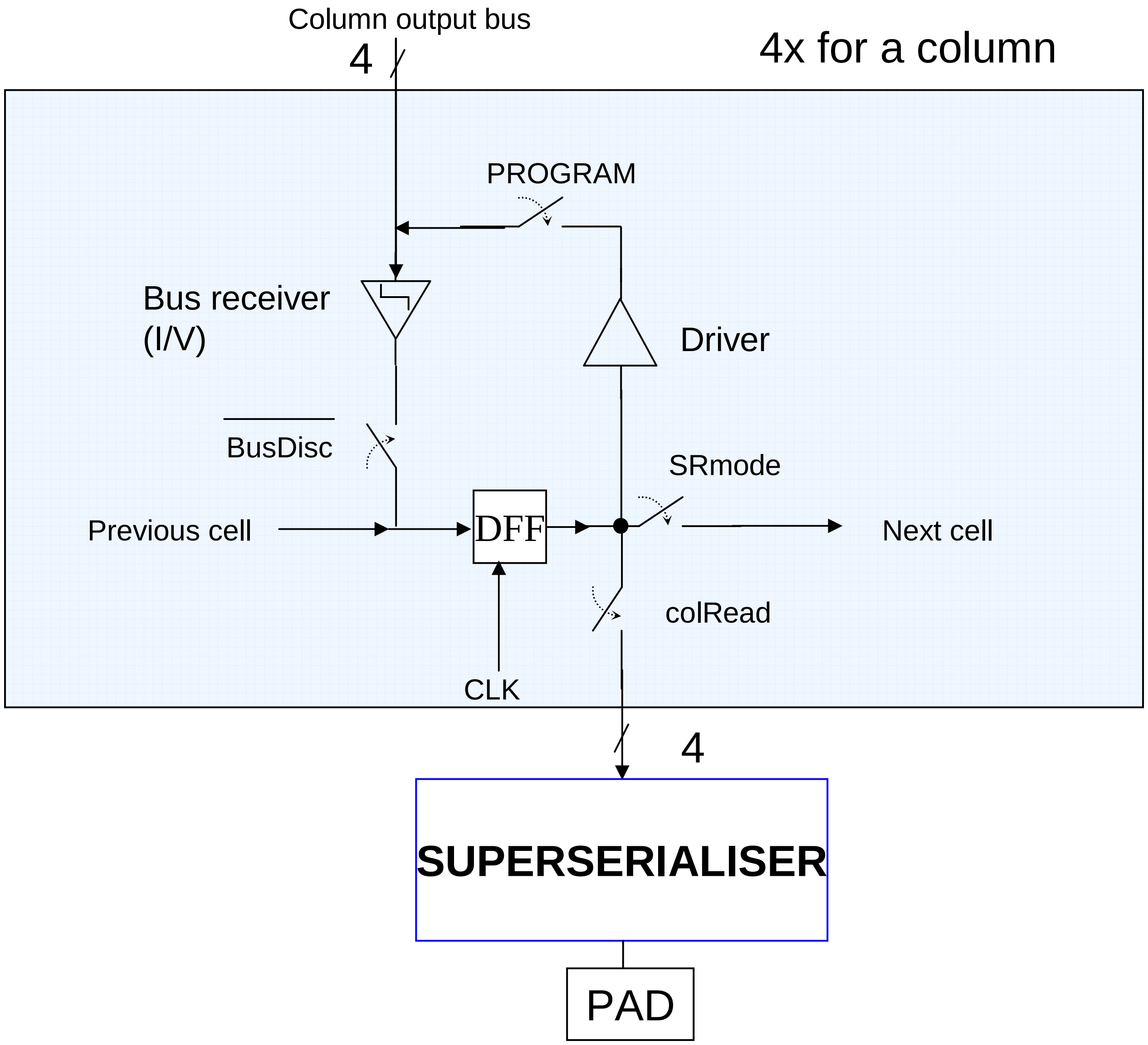
Multipurpose register
- Configurable serial/parellel I/O

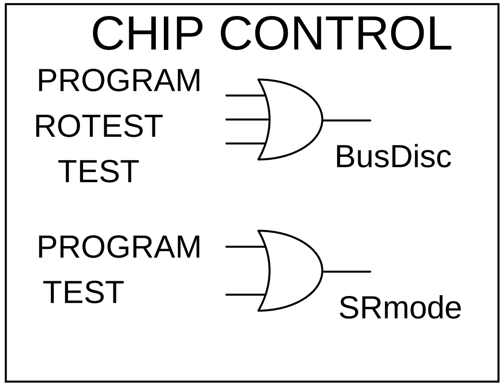
Super serializers
- Serialize data sent to the pad

32 Data pads
- 100 MHz DDR,TWELL

Basic cell of the multipurpose shift register

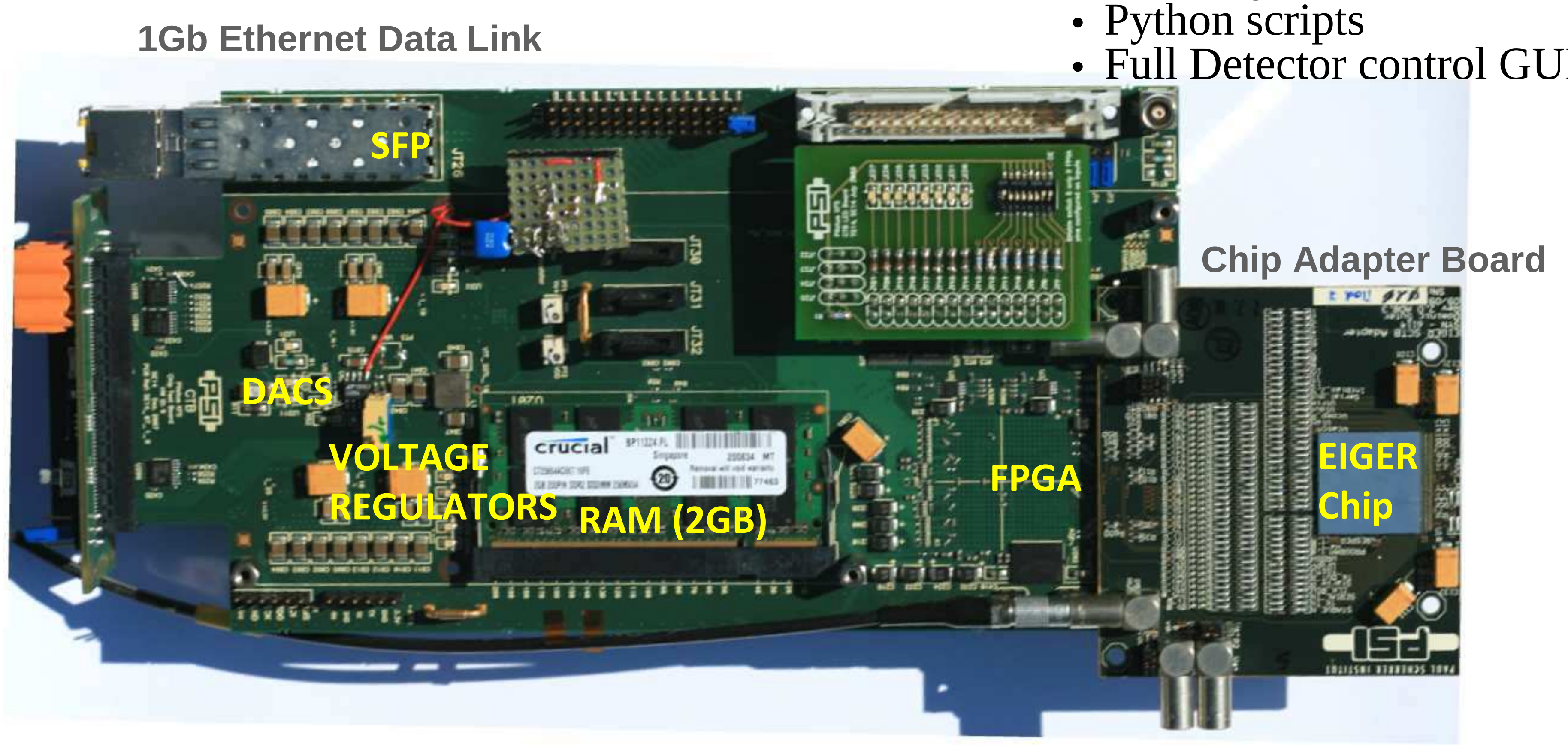
Modes of operation:
- Data taking
- Test
- RO test
- Program
- Serial readout





Single chip test setup

- Pattern generator
- Python scripts
- Full Detector control GUI



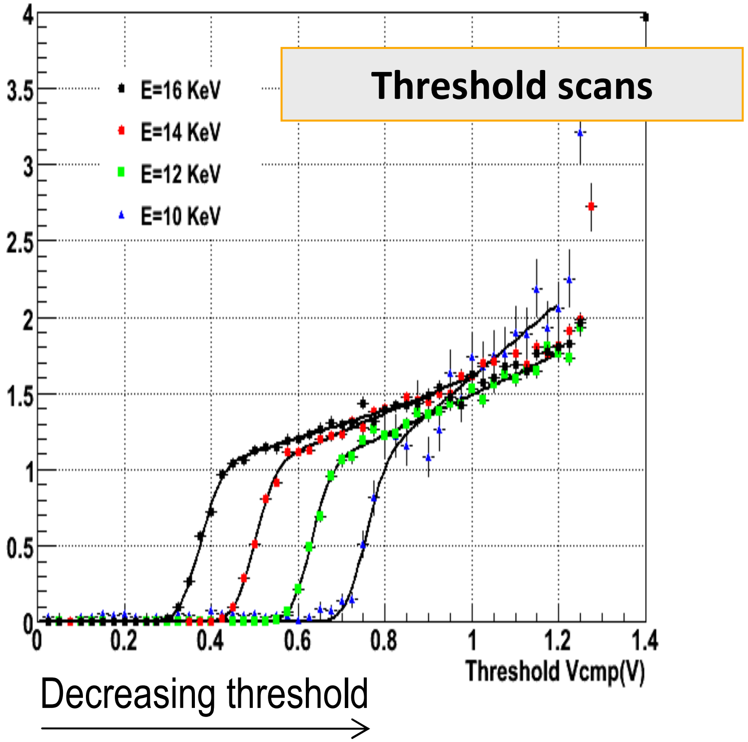
ALL WAFERS FROM FOUNDRY WERE OFF SPECS!

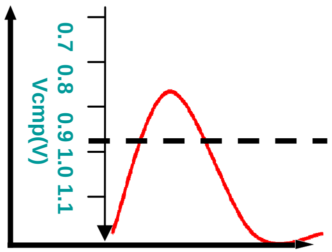
Testing a single photon counting detector

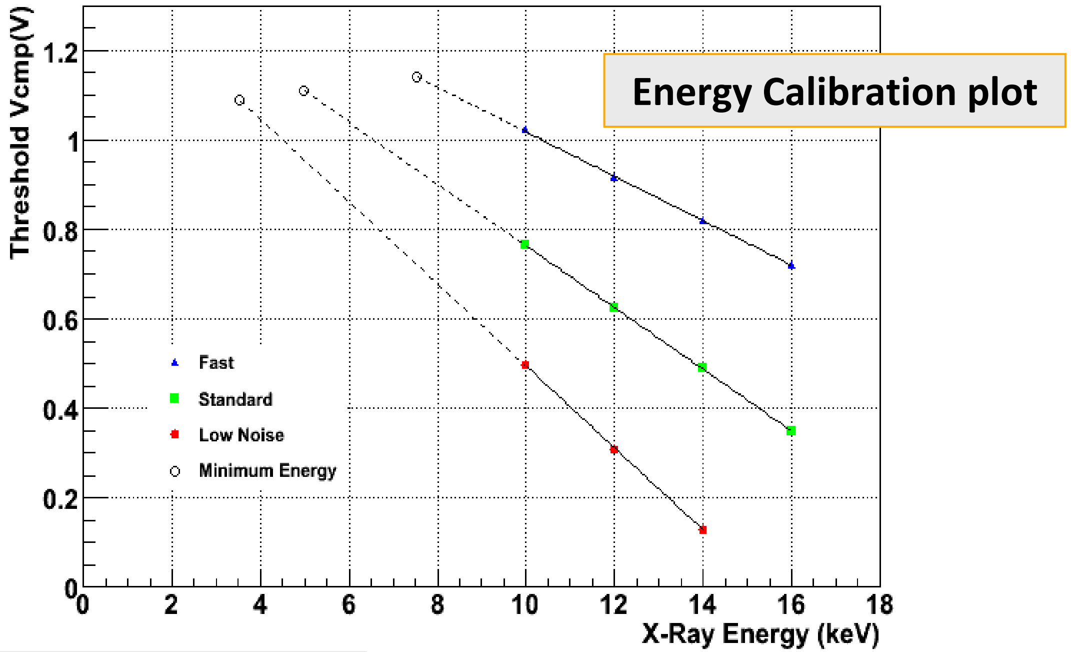
- Energy calibration
- Noise
- Trimming and threshold dispersion
- Rate capability
- Minimum energy
- Radiation tolerance

Energy Calibration

- **Energy Calibration:** Monochromatic beam of known energy
- **Threshold scans:** Number of counts in each pixel vs Threshold





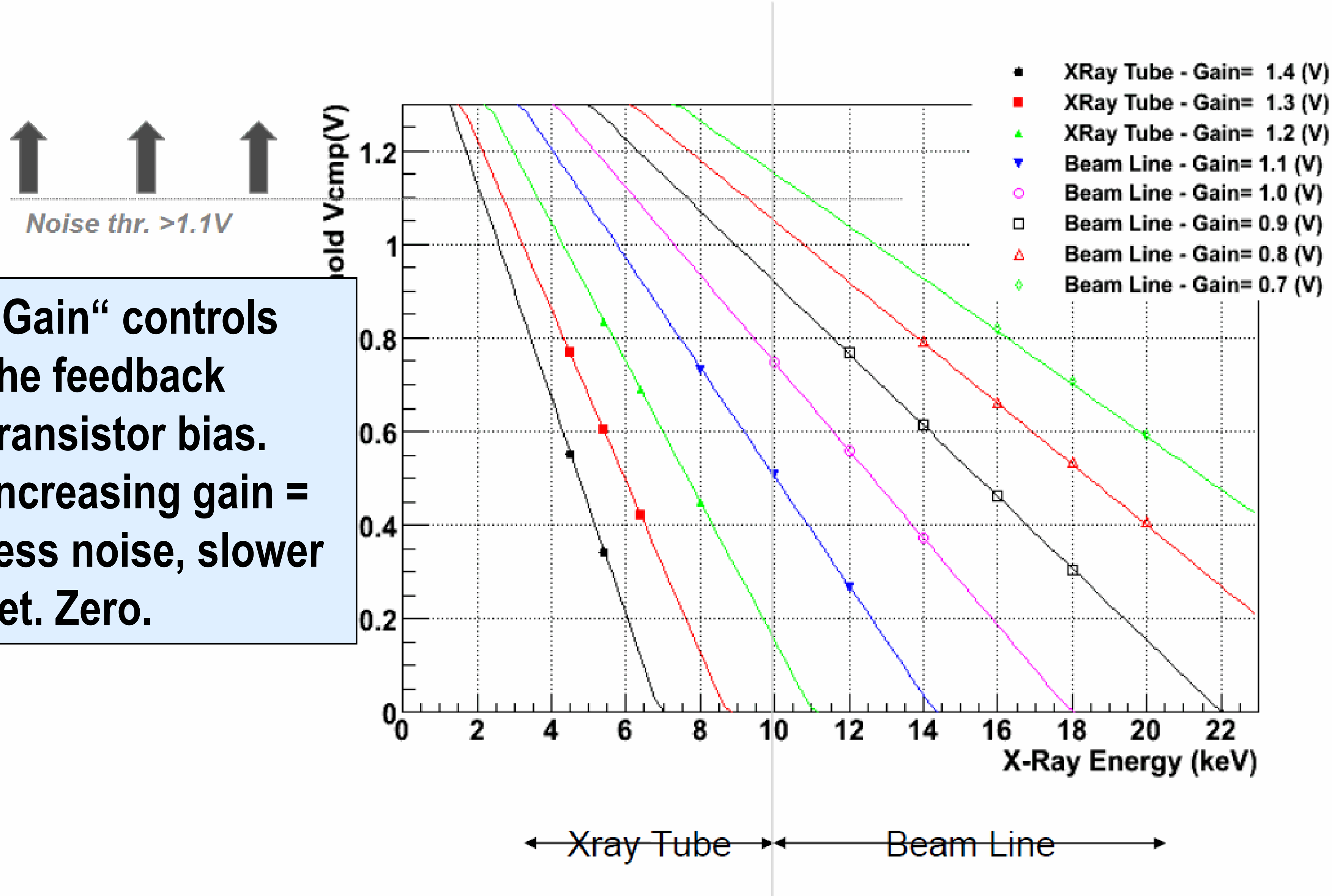


Fitting Function: Scurve·ChShar

$$n(V_{cmp}) = \frac{1}{2}\left(1 + erf\left(\frac{V_{cmp} - a_0}{\sqrt{2}a_1}\right)\right)\left(a_2 + a_3 V_{cmp}\right)$$

a_0 inflection point; a_1 noise
a_2 flux; a_3 charge sharing param.

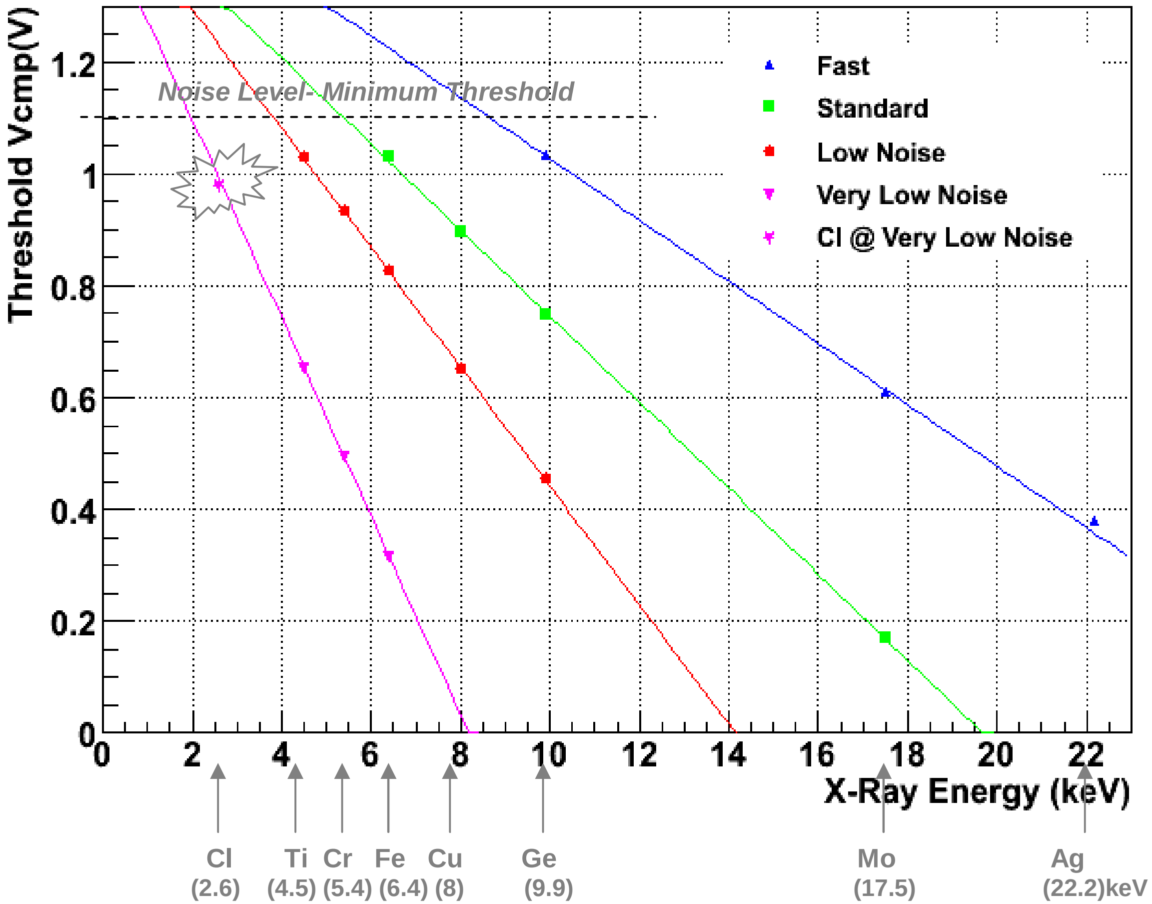
Eiger Calibration



„Gain“ controls the feedback transistor bias. Increasing gain = less noise, slower ret. Zero.

Low energy operation

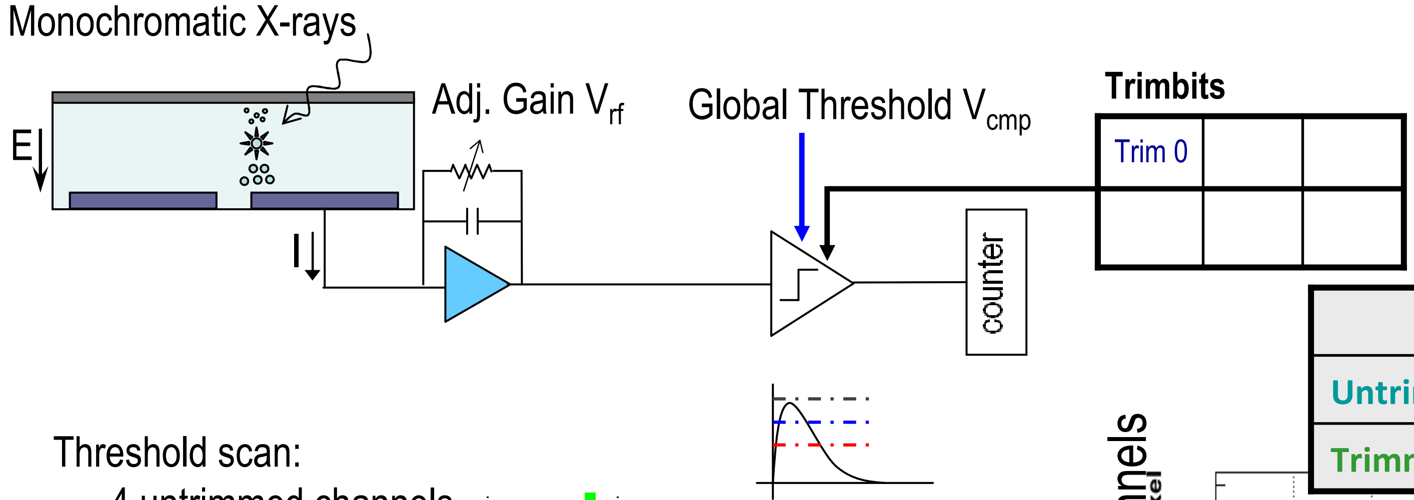
- **Energy Calibration**: XRay tube and Fluorescence samples: from Ag (22KeV) to Ti (4.5KeV) and Cl (2.6KeV)
- **One new mode operation (Fuchsia):** "Very Low Noise" i.e. "Very High Gain of the Preamp."



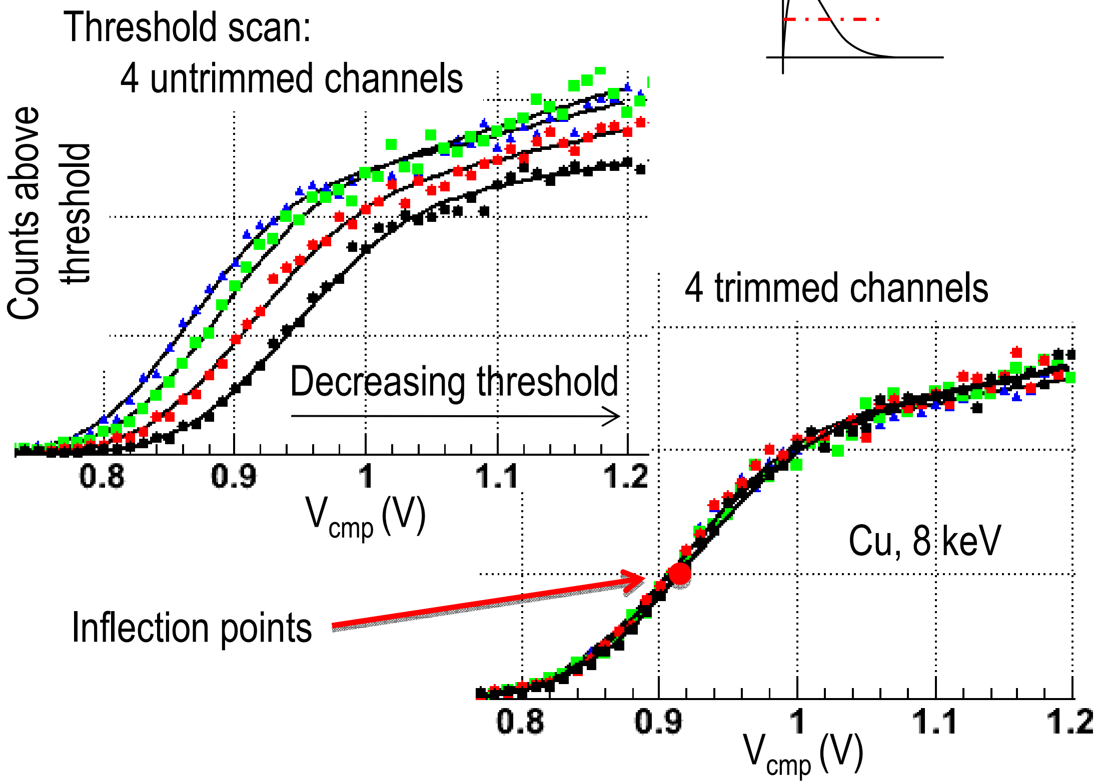
good performance of the chip at low energy:

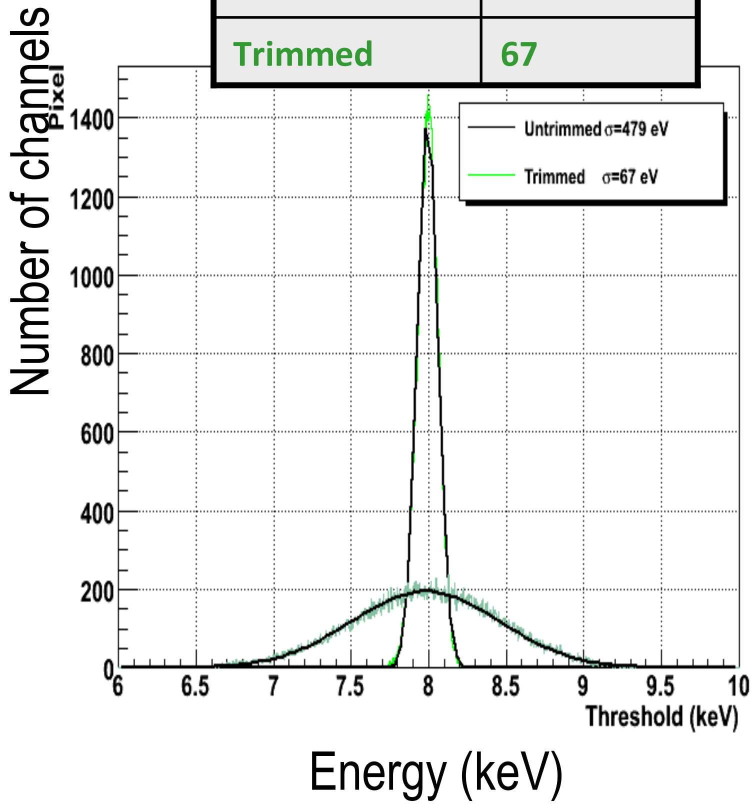
- comparator is linear down to low energies
- minimum threshold Vthr ~1.1V; safe operation of the comparator @ 1V
- threshold energy as low as 2.5keV can be set in the highest gain mode
- a further higher gain could also be investigated
- rate capability of "lower noise-higher gain" operation mode to be measured (good feedback from simulation)

Trimming and Threshold dispersion



	σ(eV)
Untrimmed	479
Trimmed	67

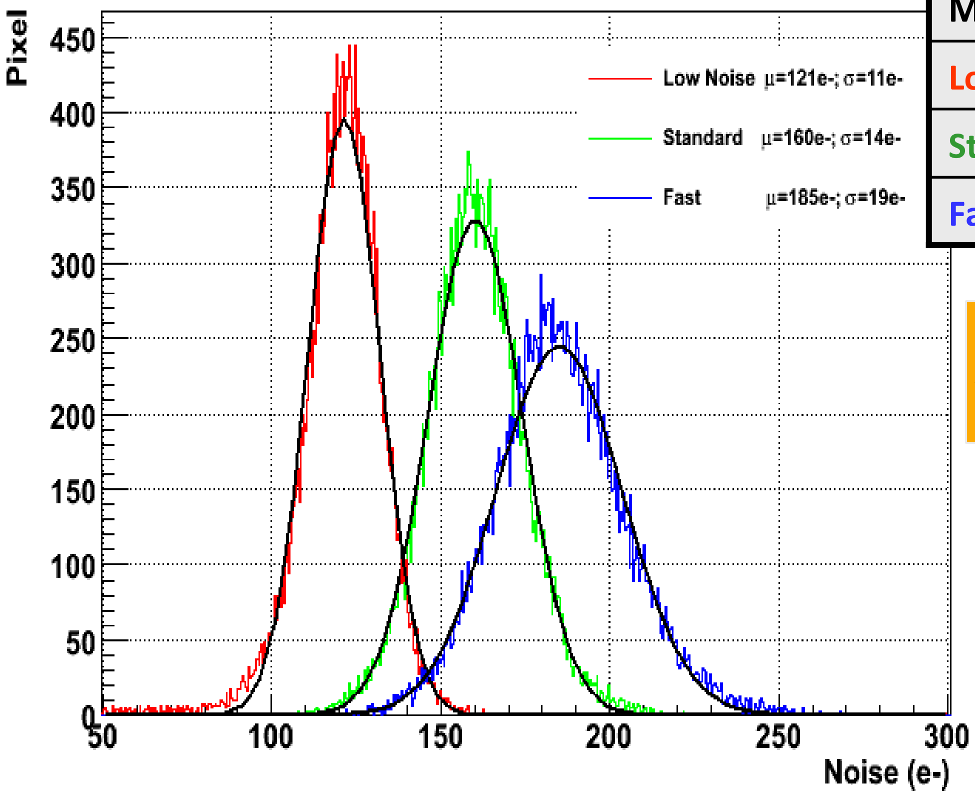




Noise

Noise distributions: monochromatic beam at the Beam line

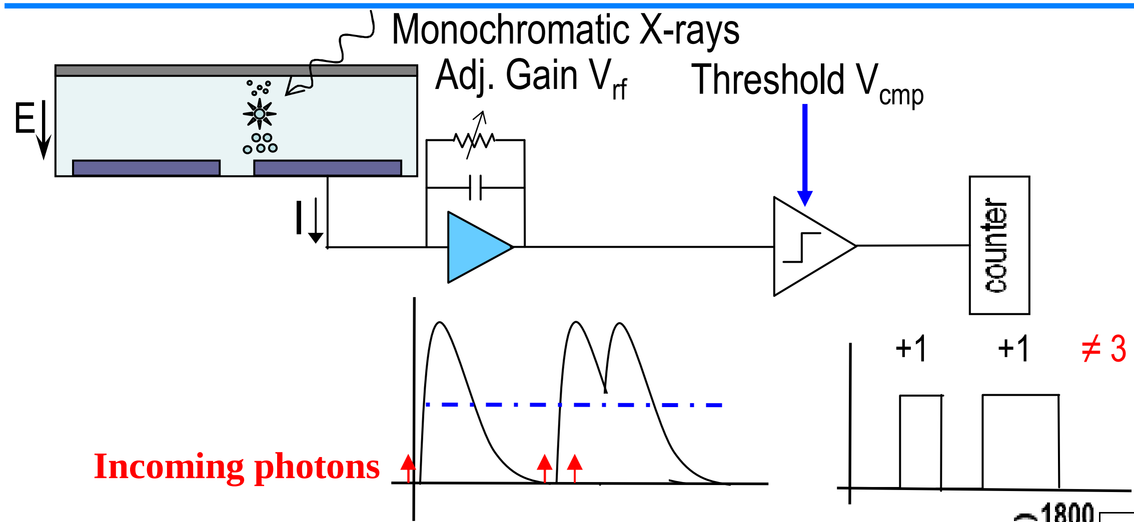
@14KeV



Operation Mode	Noise(e-)	Sigma (e-)
LowNoise	121.1±0.07	10.7±0.06
Standard	160.1±0.08	13.9±0.07
Fast	185.0±0.1	18.7±0.09

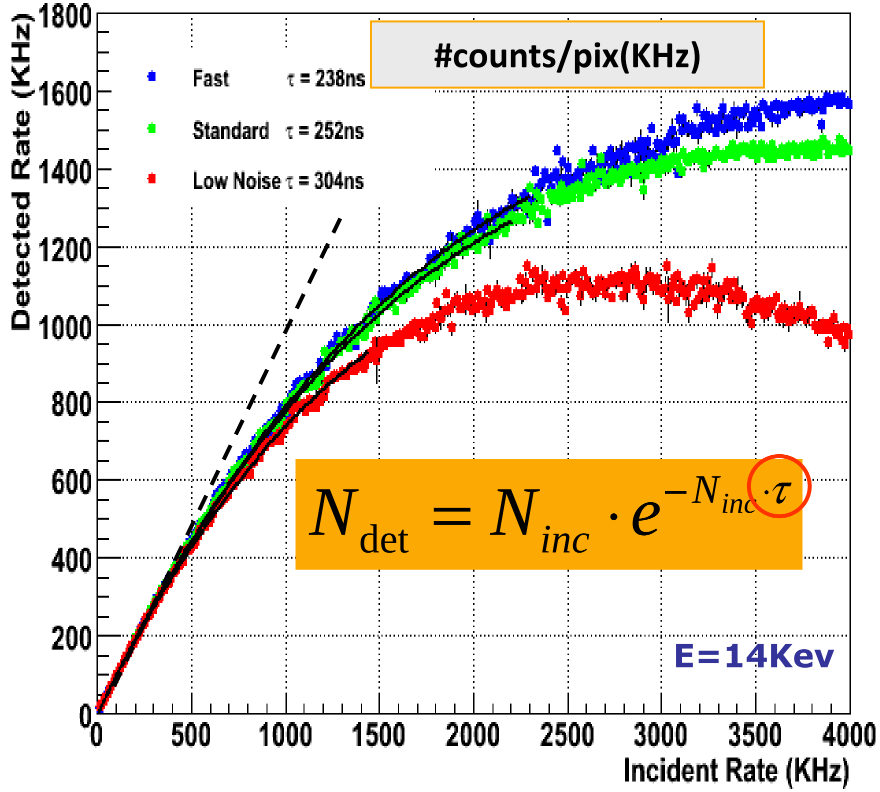
$$n(V_{cmp}) = \frac{1}{2}\left(1 + erf\left(\frac{V_{cmp} - a_0}{\sqrt{2a_1}}\right)\right)\left(a_2 + a_3 V_{cmp}\right)$$

Rate Capability



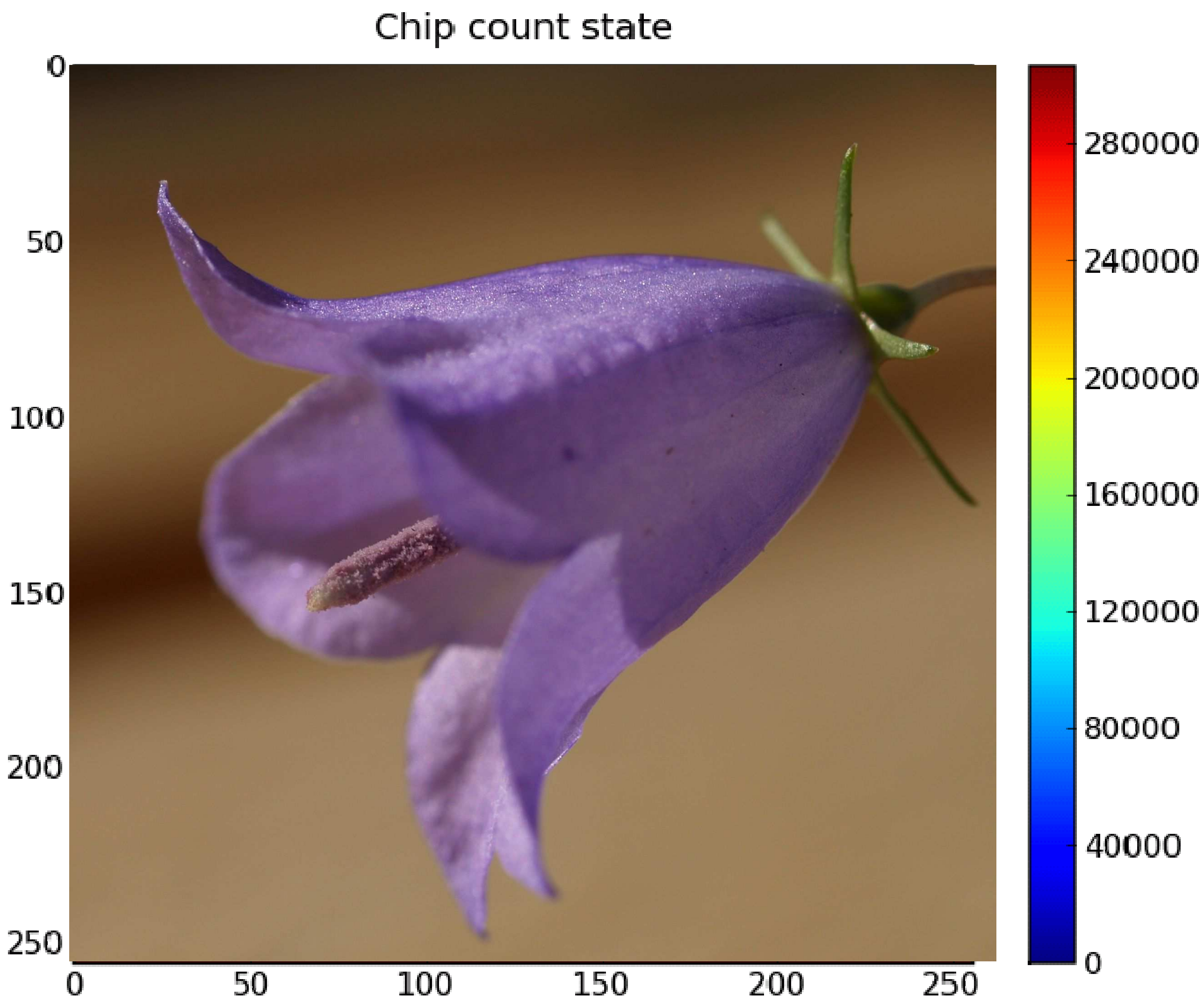
1)Measurement at low flux: use detector to calibrate source

2)Measurement at high flux: use source to calibrate detector

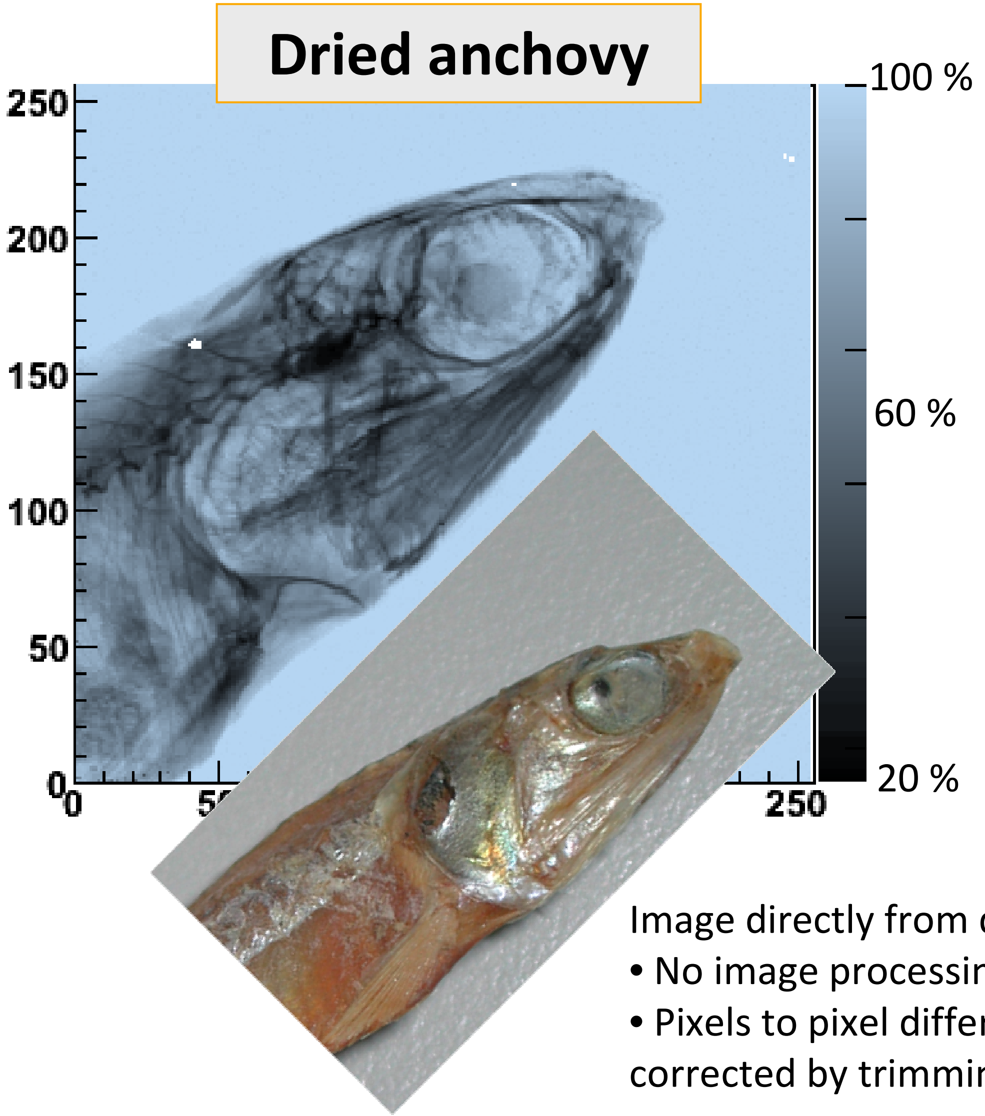


$$N_{det} = N_{inc} \cdot e^{-N_{inc} \cdot \tau}$$

EIGER absorption image



X-ray Images, single chip



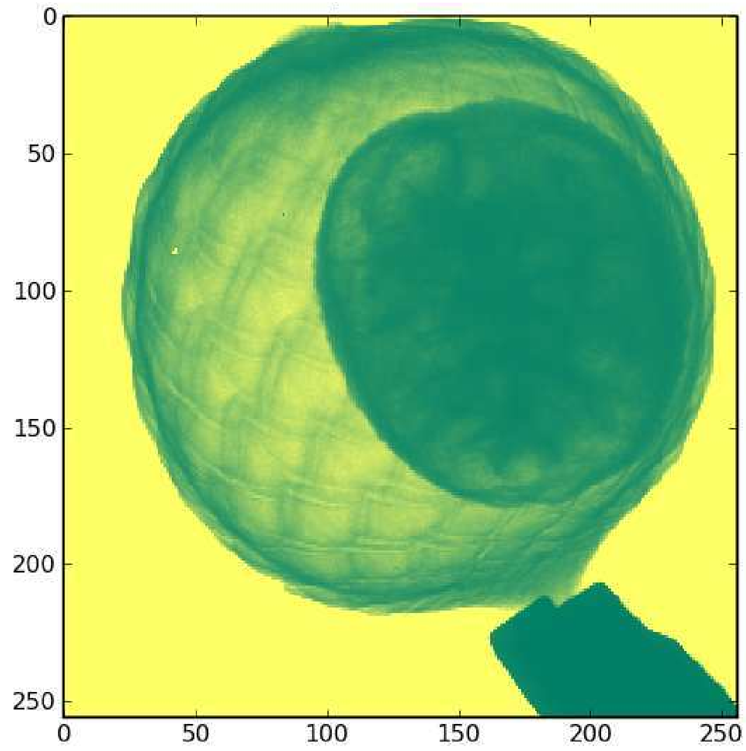
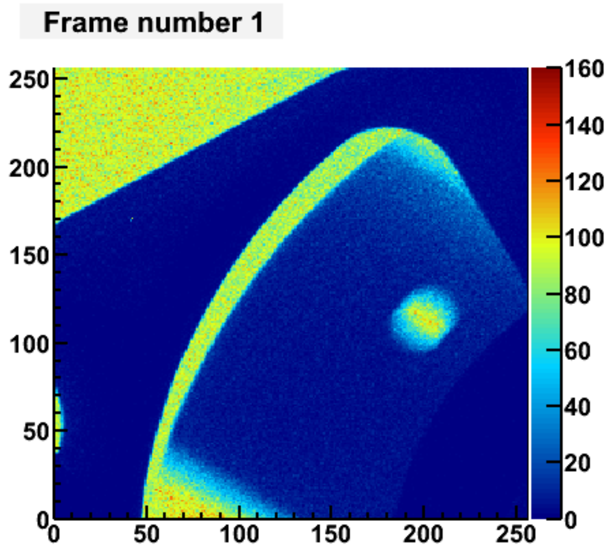


Image directly from detector
• No image processing
• Pixels to pixel differences corrected by trimming

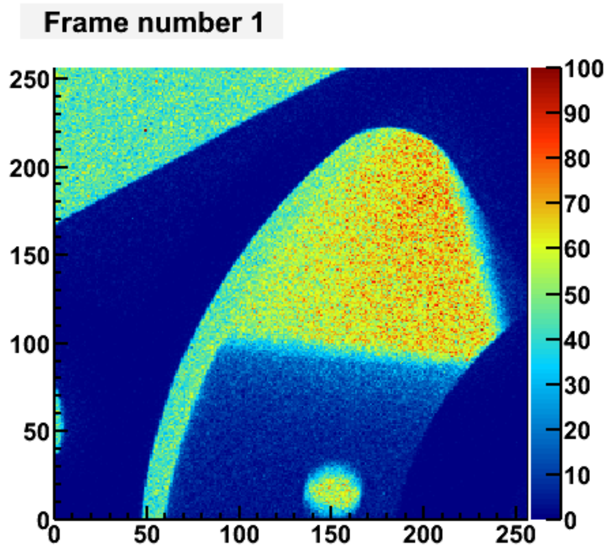
High Frame Rate Demo

V = 50KV, I = 0.4mA



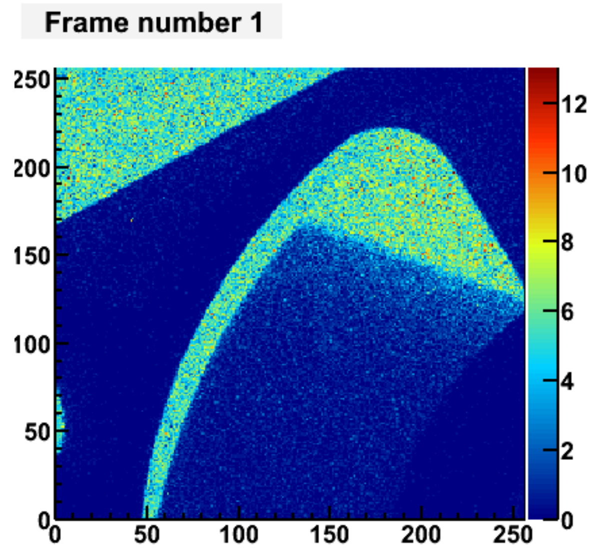
Chip in 12 bit Mode
Exposure time 125µs
Dead time 3µs
Frame rate 7.8 kHz

V = 50KV, I = 1 mA



Chip in 8 bit Mode
Exposure time 85µs
Dead time 3µs
Frame rate 11.4 kHz

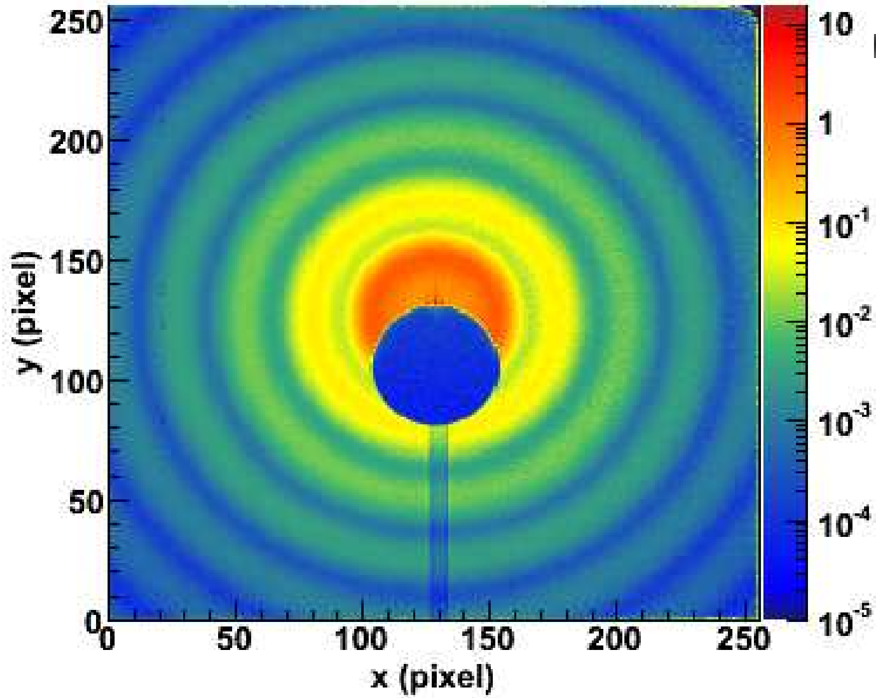
V = 50KV, I = 1 mA

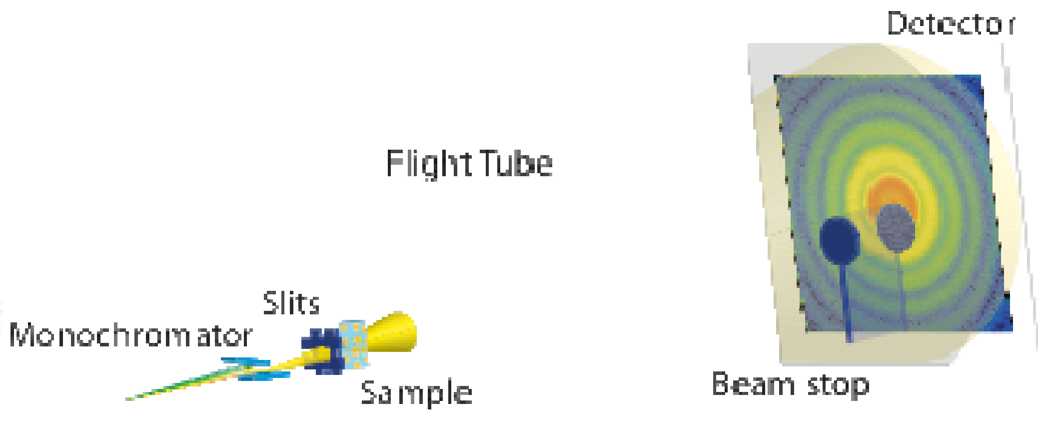


Chip in 4 bit Mode
Exposure time 45µs
Dead time 3µs
Frame reate 20.8 kHz

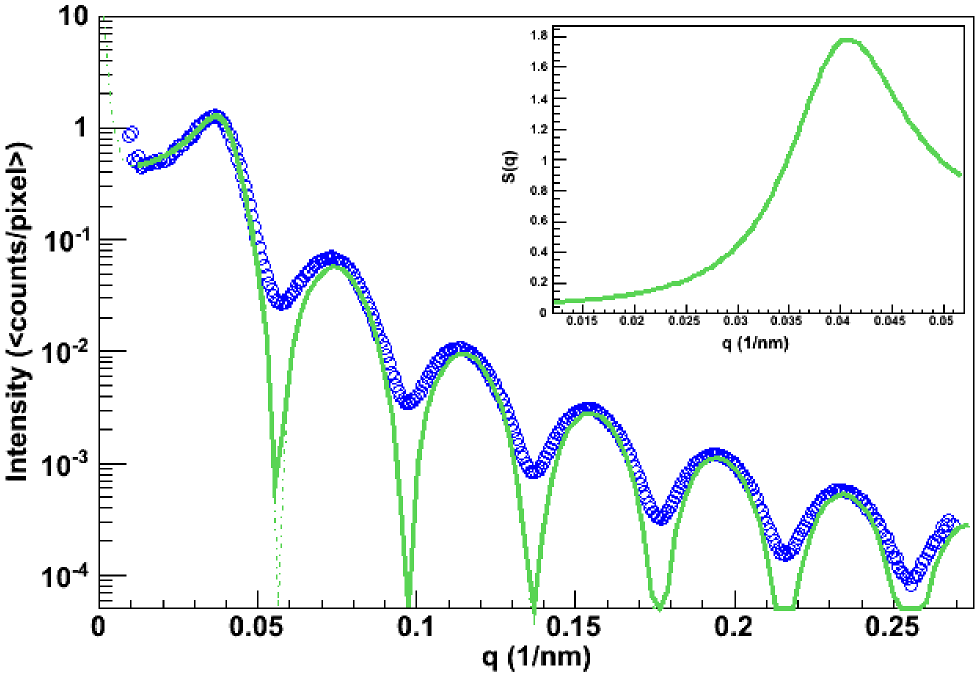
Investigating colloidal suspensions with Eiger

Average Diffraction Pattern
Thousands of 50 us exposures





Structure and Form factors



"Capturing dynamics with Eiger, a fast framing X-ray detector"
I. Johnson et al., J. Synchrotron Rad. (2012). 19, 1001

Analysis: Ian Johnson

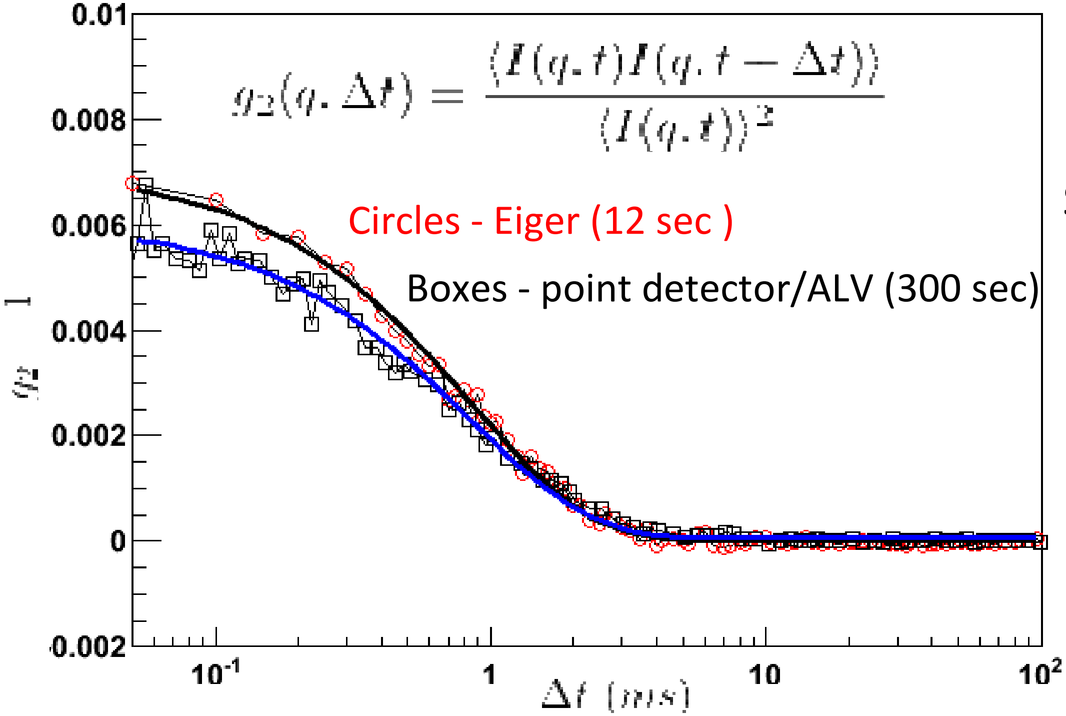
Probing the dynamics, Photon Correlation Spectroscopy

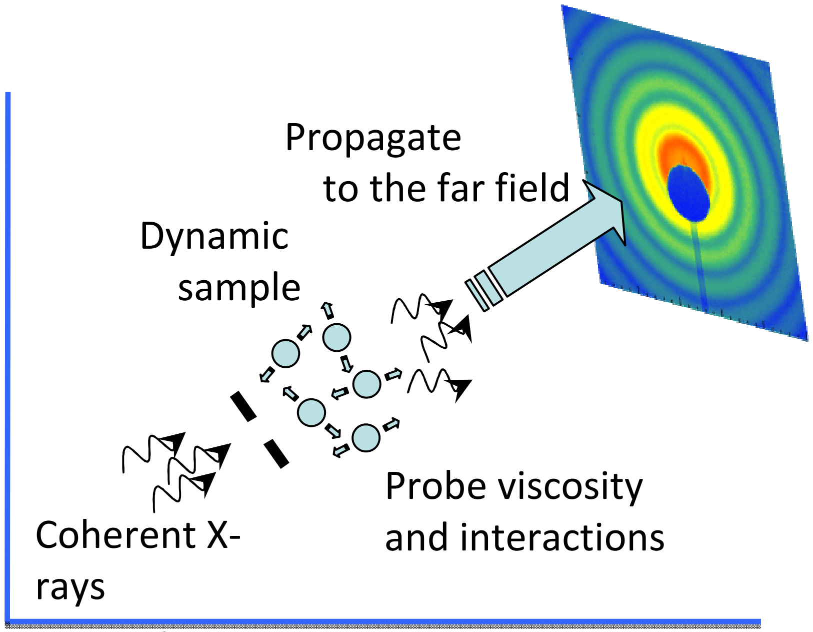
Eiger fast frame rate:

- Second long exposure series @ 20 kHz
- 45 us exposure and 5 us dead time between frames

Intensity Fluctuations to probe the dynamics

- Intensity-Intensity Auto Correlation Function





Siegert relation,

$$g_2(q,\Delta t) = 1 + \beta |g_1(q,\Delta t)|^2$$

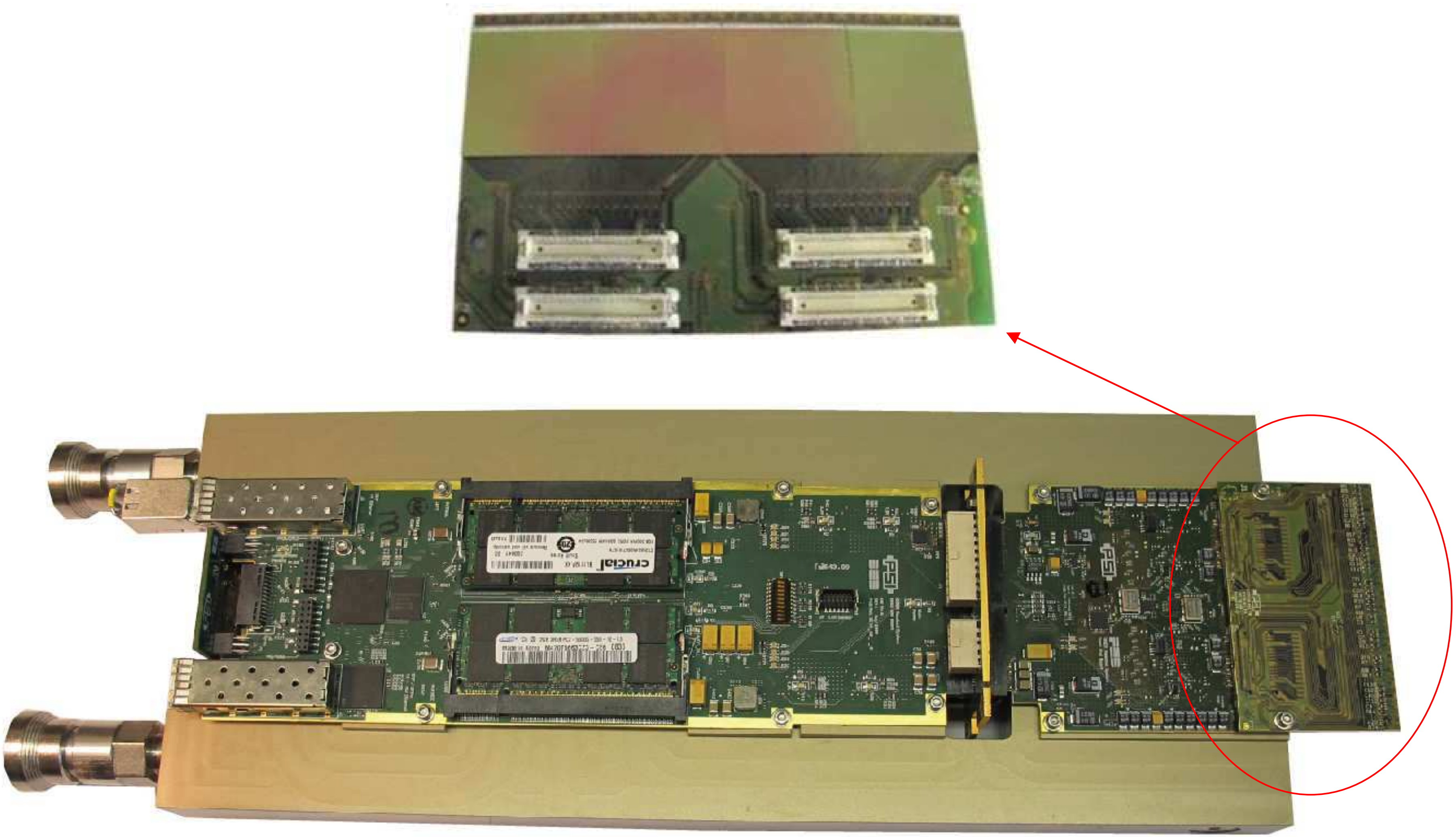
Normalized field correlation function

$$g_1(q,\Delta t) = e^{-Dq^2\Delta t}$$

Brownian motion,

$$D = D_0 = \frac{kT}{6\pi\eta r}$$

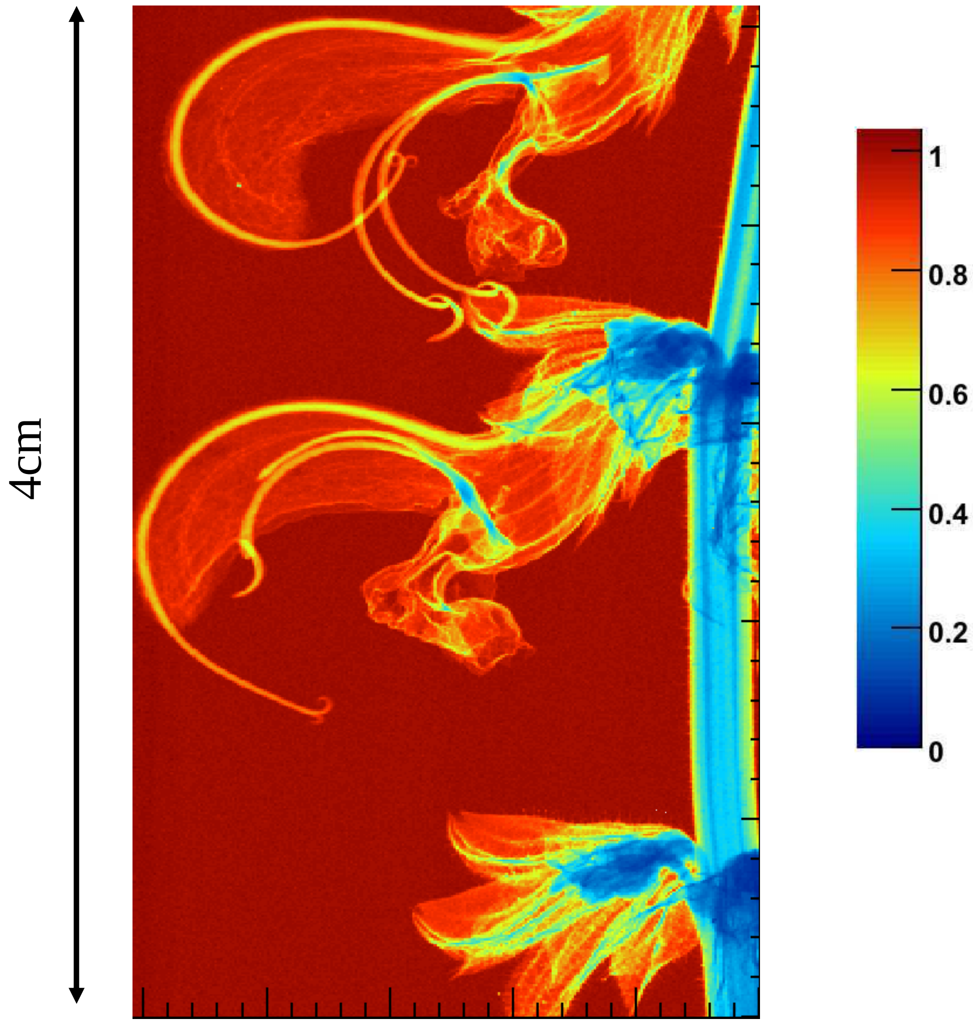
Half Module System



X-ray Images, two chips

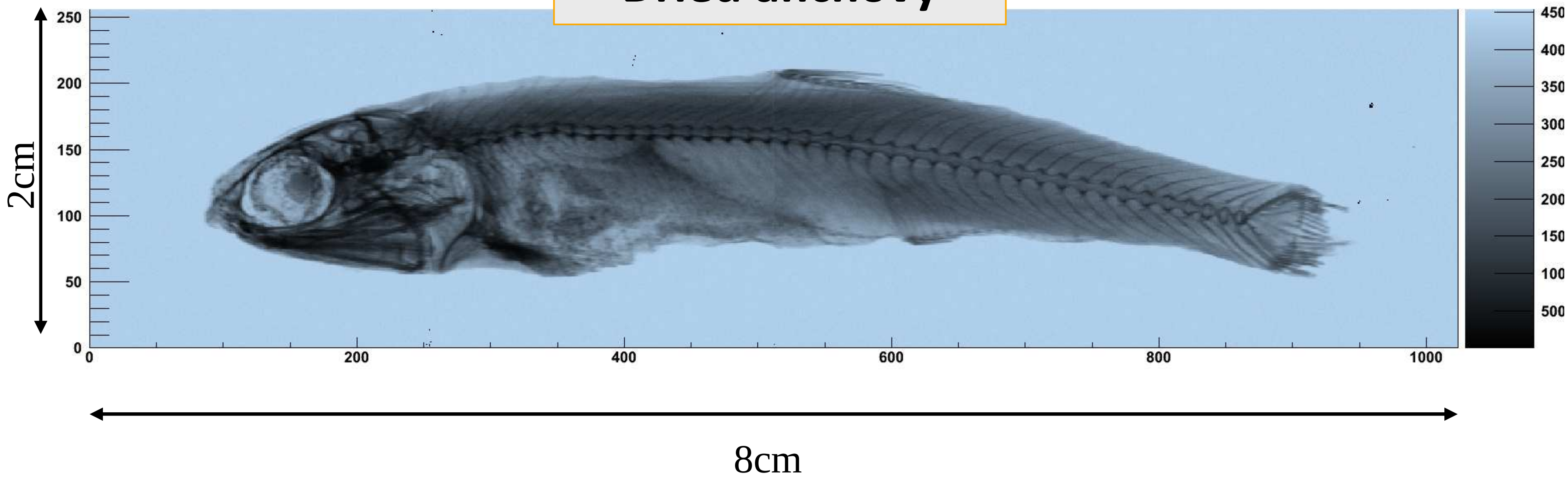
Wild flower

No stitching, no trimming, with background correction



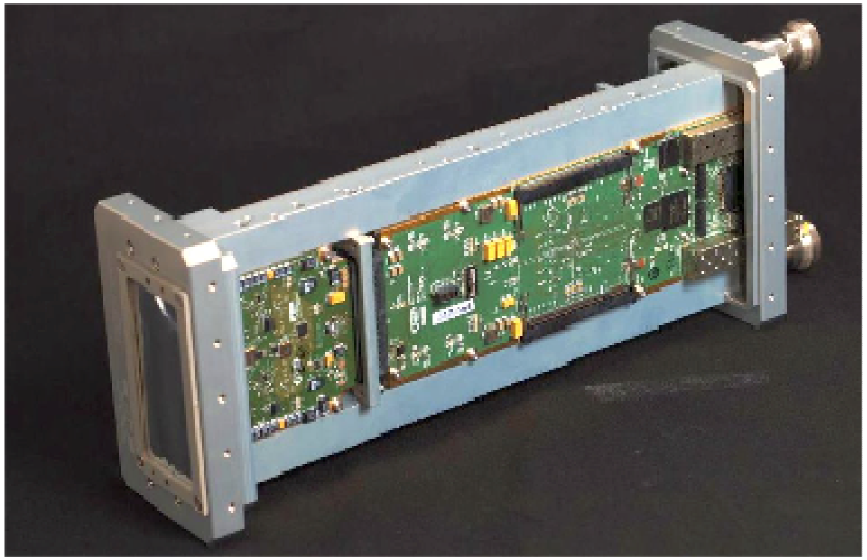
X-ray Images, half module

Dried anchovy



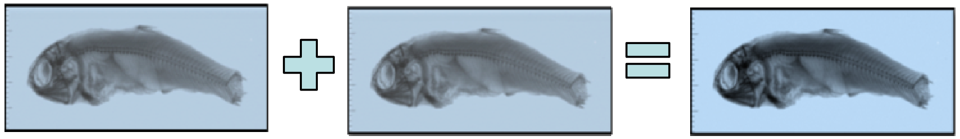
No stitching, no trimming, with background correction

The Eiger Module: Eiger 500k

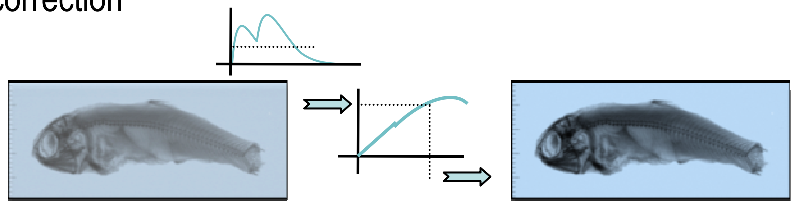


- 4x2 chips/module
- Electronics is separated for top and bottom halves
- Data buffering
  - 8 GB of on board memory per module
  - 32 k frames for 4 counter bits

Image summation



Rate correction

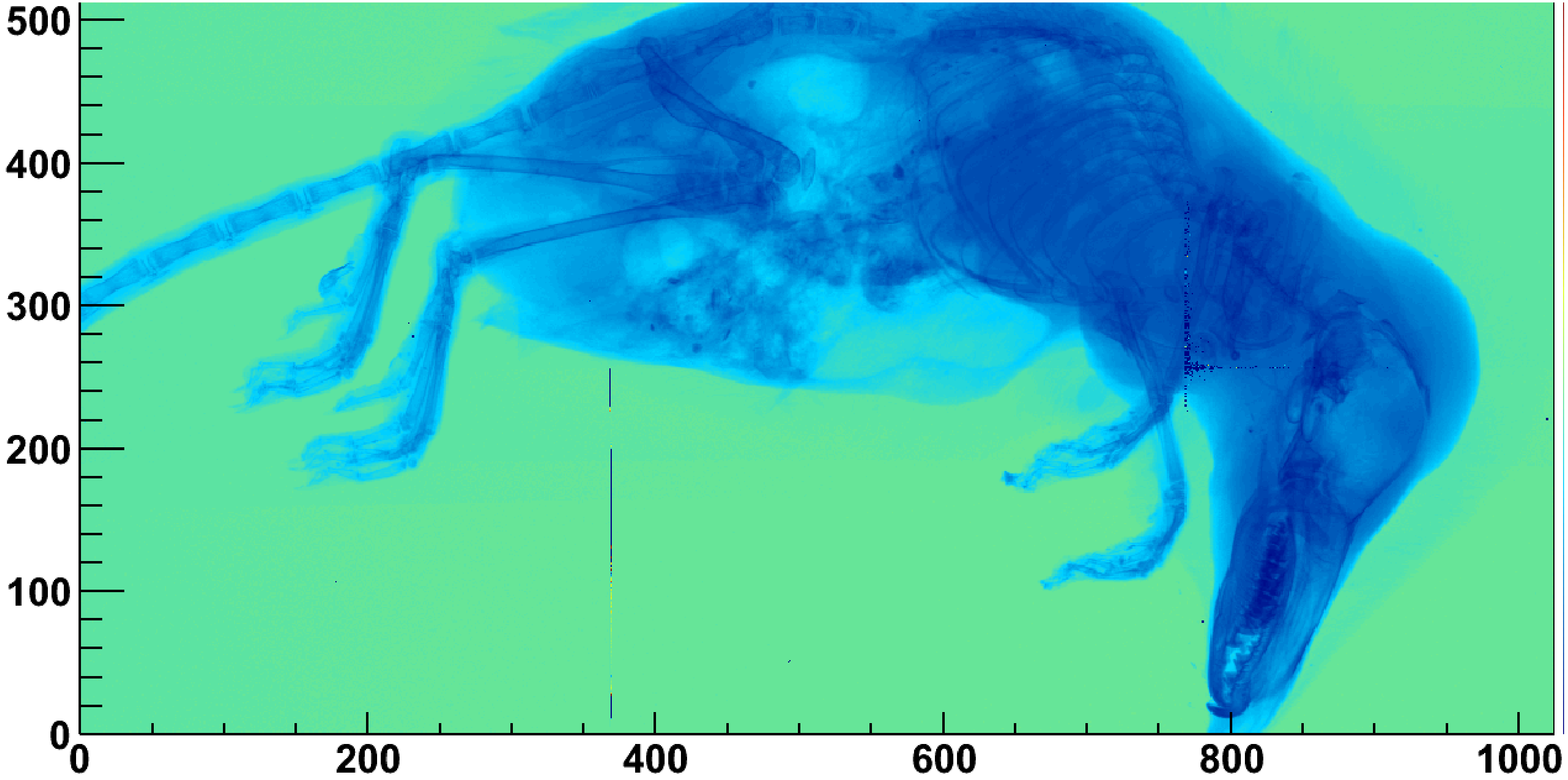


- Firmware data processing
  - Image summation
    - **extends the dynamic range from 4096 (12 bits) to 4x10^9 (32 bits)**
  - Rate correction
- Readout architecture
  - High speed data transfer: data is sent over 1 GbE or 10 GbE connections, one per half module
  - Online compression: HDF5 libraries

X-ray Images, full module

First working module after recovery from bump-bonding disaster.
No stitching, no trimming, no setup optimization, with background correction. New module.

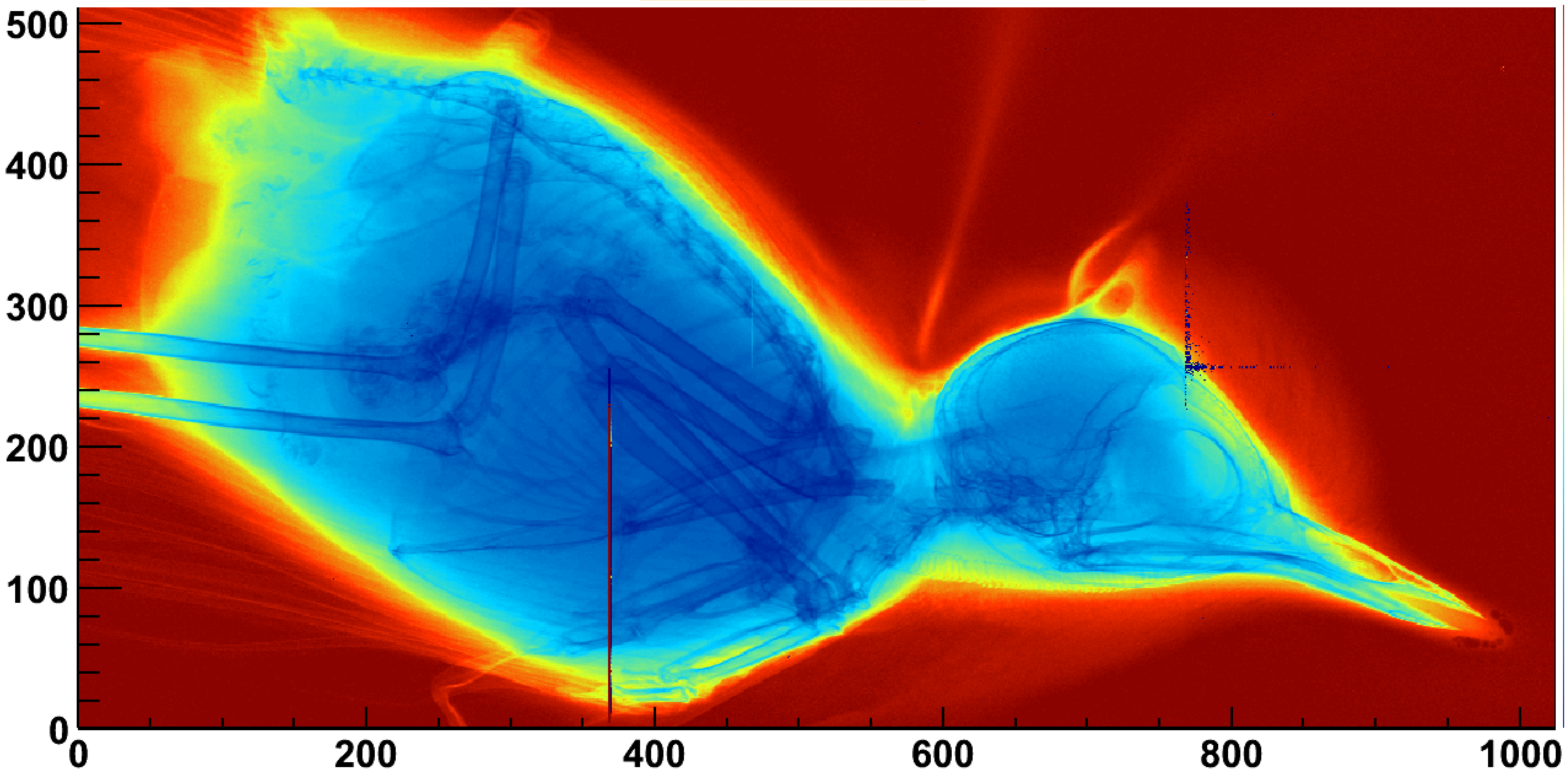
Shrew



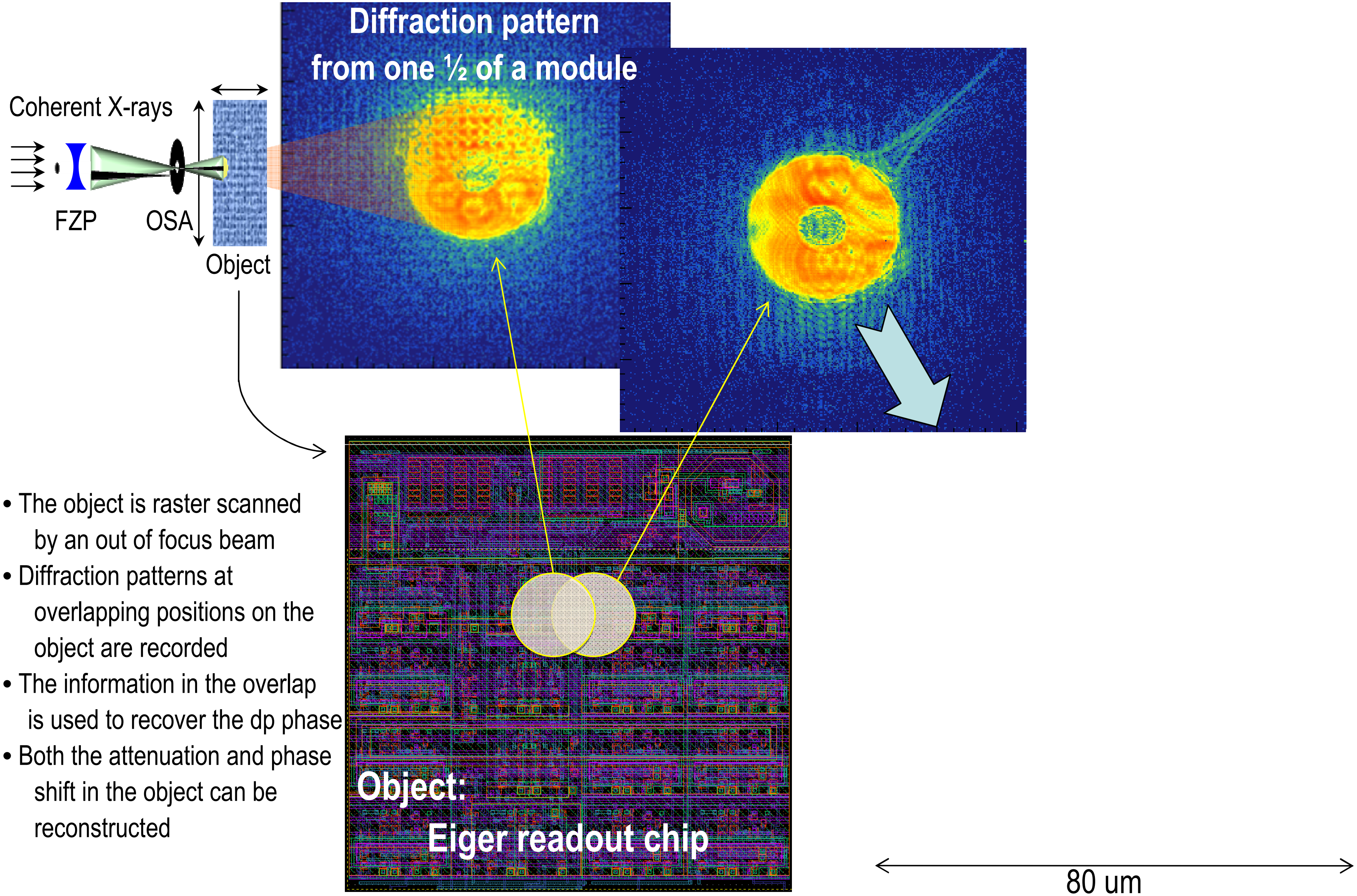
X-ray Images, full module

First working module after recovery from bump-bonding disaster.
No stitching, no trimming, no setup optimization, with background correction. New module.

Robin

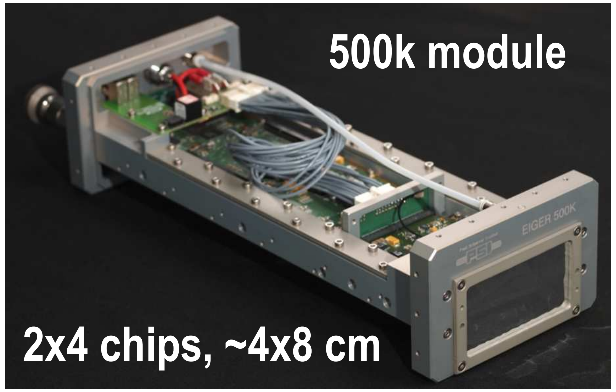


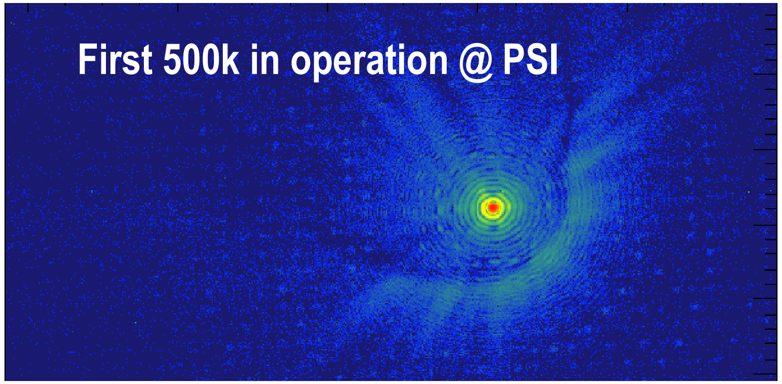
An Eiger self portrait (Ptychography)



- The object is raster scanned by an out of focus beam
- Diffraction patterns at overlapping positions on the object are recorded
- The information in the overlap is used to recover the dp phase
- Both the attenuation and phase shift in the object can be reconstructed

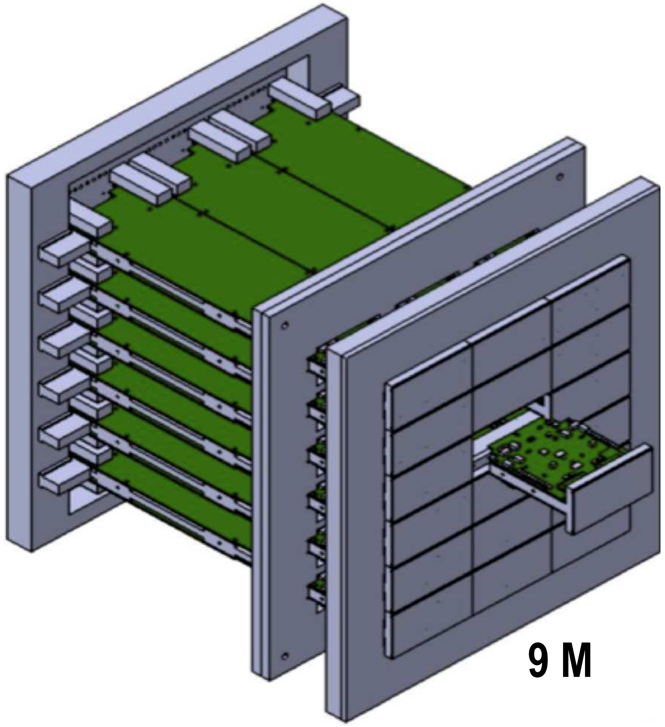
Eiger systems





Multi-module detectors

1.5 M



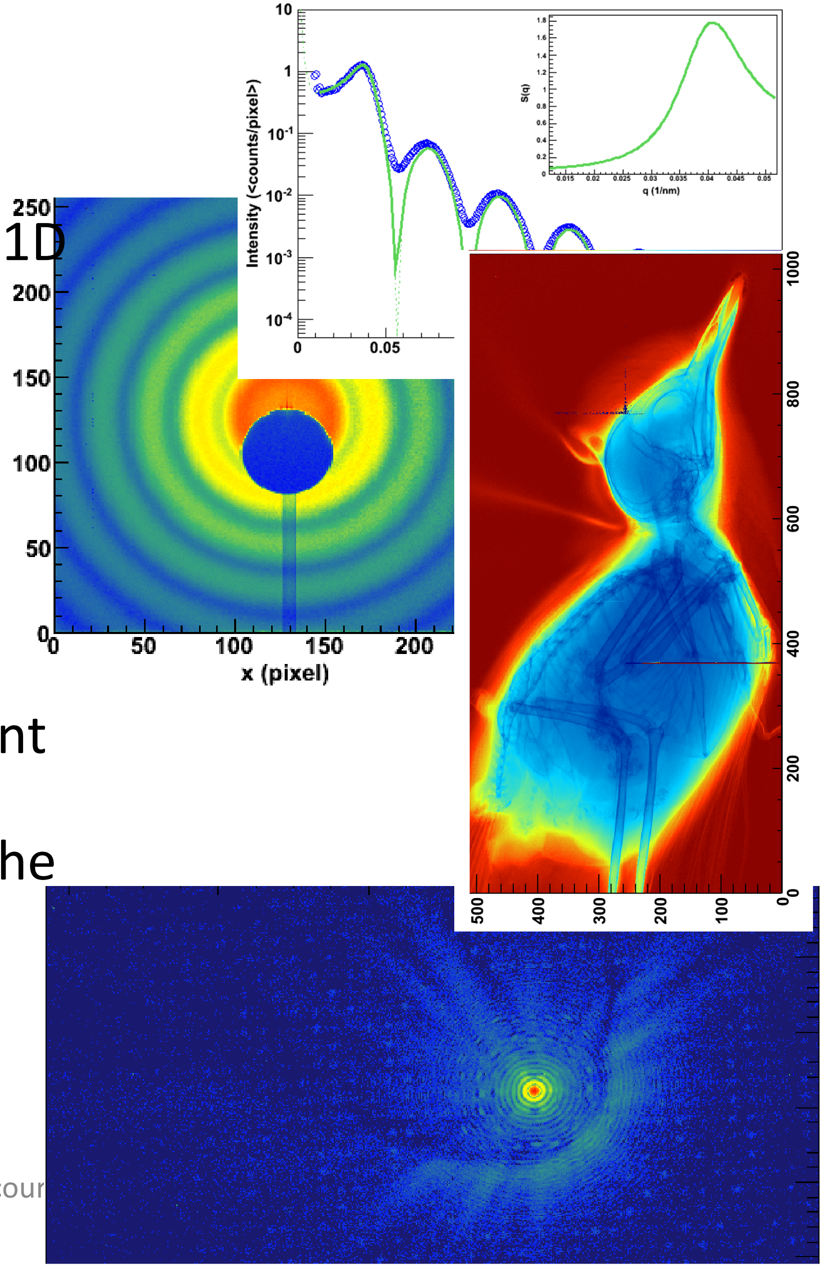
9 M

	Pixel array	Data rate[1] @ 12 kHz	Data rate[2] @ 1kH	Data rate[2] @ 100 Hz	Data rate[3] @ 10 Hz
Module	512 x 1024	50.3 Gb/s	8.39 Gb/s	839 Mb/s	168 Mb/s
1.5M	512 x 3072	150 Gb/s	25.2 Gb/s	2.52 Gb/s	503 Mb/s
9M	3072 x 3072	906 Gb/s	151 Gb/s	15.1 Gb/s	3.02 Gb/s

1) 8 bit, equivalent to ~4@23 kHz. 2) 16 bit. 3) 32 bit.

Conclusions

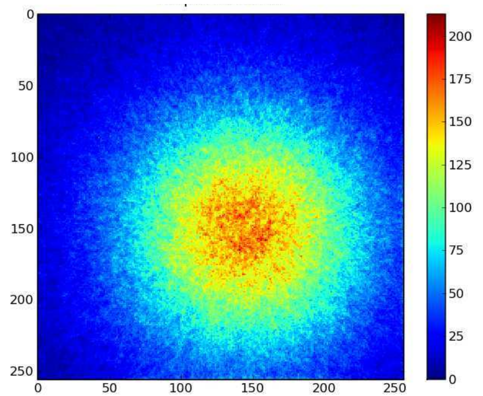
- PSI is active in chip design targeting many different applications but the main focus is detectors for X-ray appllications
- The SLS Detector group developed several 1D and 2D hybrid detectrors for synchrotron radiation applications
- The latest detector family is called EIGER.
- Relusts from extensive testing show that it fulfills the challenging requests from the beamlines in terms of noise and energy resolution
- The frame rate is up to ~24 kHz independent on the detector size.
- The first module is already operational at the cSAXS beamline at PSI
- We are working towards larger detector systems (1.5M, 9M)

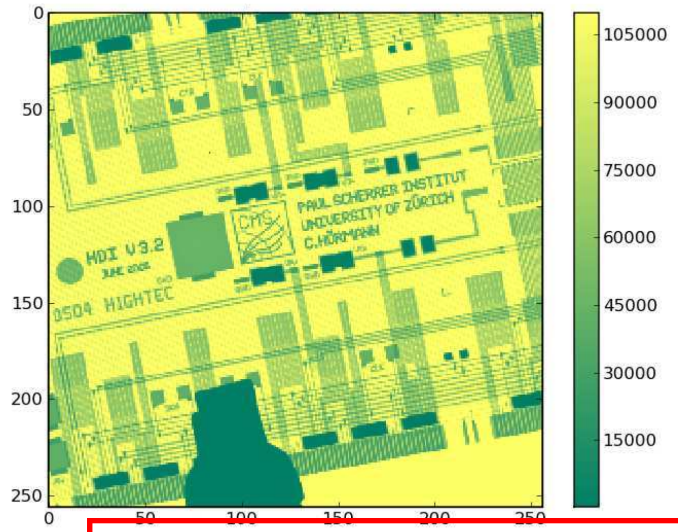


ACKNOWLEDGMENTS

Many thanks to:
Anna Bergamaschi, Heiner Billich, Beat Henrich, Dominic Greiffenberg, Roland Horisberger, Ian Johnson, Dhanya Maliakal, Beat Meier, Aldo Mozzanica, Peter Oberta, Lukas Schaedler, Nick Schlumpf, Elmar Schmid, Bernd Schmitt, Xintian Shi, Akos Schreiber, Anja Schubert, Silvan Streuli, Dominic Suter, Valeria Radicci, Gerd Theidel.

Not in the picture:
Julia Jungmann,
Davide Mezza

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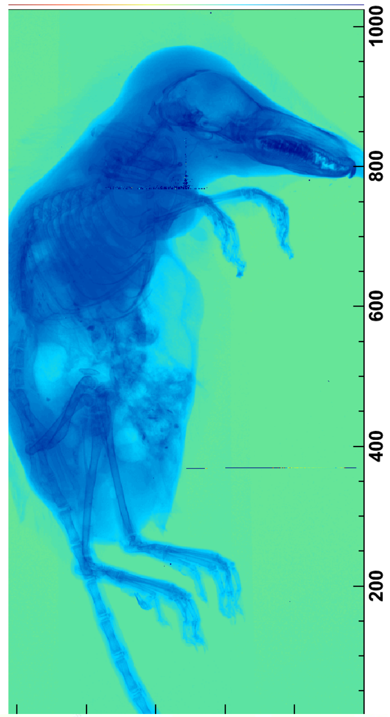
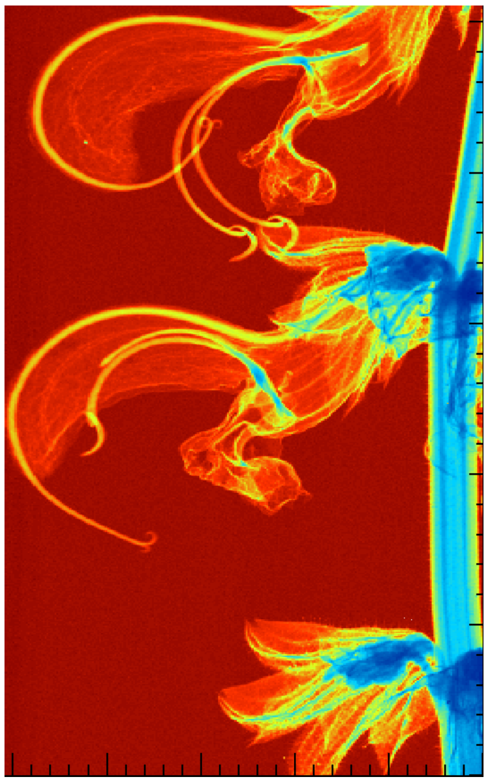
HDI V3.2
0504 HIGHTEC





THANKS!