# Detectors for Current and Future Synchrotron Light Sources

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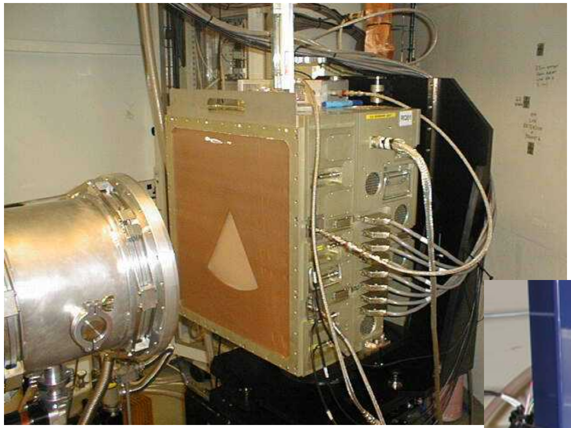
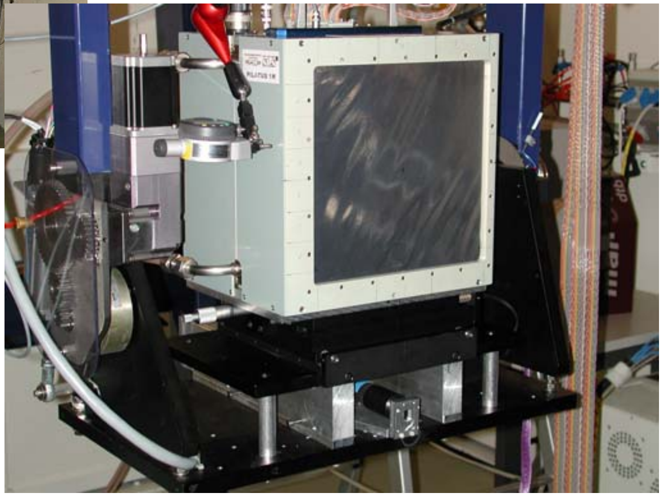
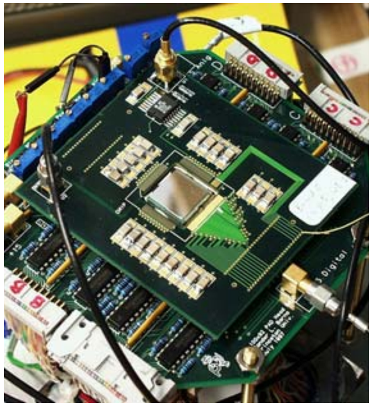
IWORID 7, 4.-7.7.05, ESRF







# Detectors for Current and Future Synchrotron Light Sources

1. Introduction
2. Existing Detector Systems
   Rapid
   Mythen
   Pilatus
3. Future Detector Systems
   Pilatus XFS
   APAD
   Analog Hybrid Pixels for FEL Apps
4. Conclusions

# Synchrotrons Worldwide

New Projects in Europe:

- Soleil, Fr (2006)
- Diamond, UK (2006)
- Petra upgrade, Ge (2009)
- Alba, Esp, (2010)
- Tesla FEL (2010)

- High demand for detectors in Europe
- Current and future science more limited by the detectors than the sources

->optimized detector systems for SR

# The Source - Detector Mismatch in the SR community

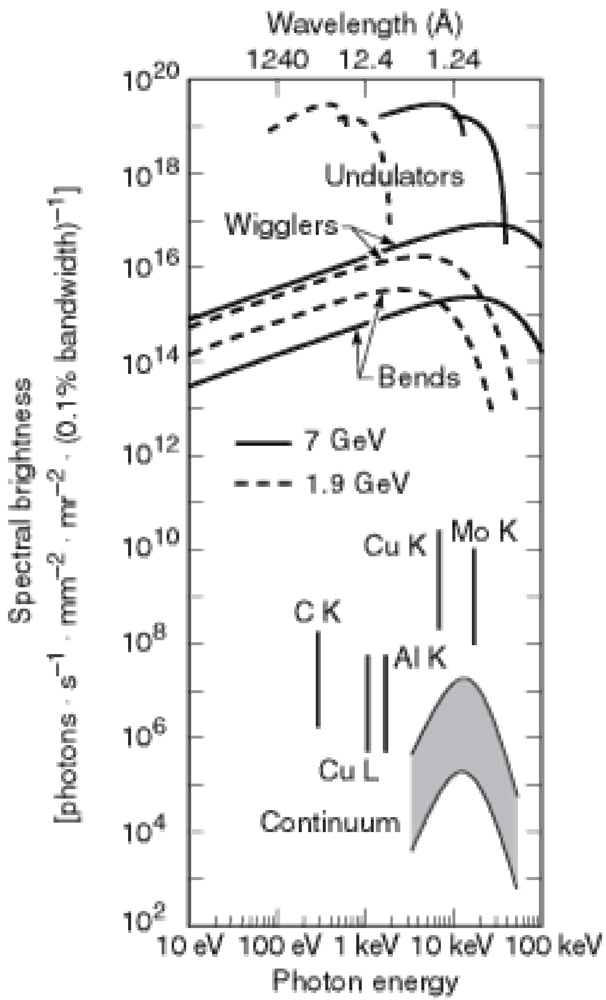
Detector development was systematically under-funded

Huge mismatch btw properties of the source and capabilities of the detectors:

- Count rate limitations
- Long readout times
- Solid angle coverage
- Detection efficiency

SR experiments are very diverse

We must deal more efficiently with the radiation delivered by the synchrotrons



# The Source - Detector Mismatch in the SR community

Examples:

## Count rate limitations

Pilatus I: 10 kHz/pixel/s -> 2.5*$10^7$ /$cm^2$/s

SLS X06SA PX I BL: Beam Intensity attenuated to 3%

Al-Filters in the beam to avoid saturation or damage of detector is a common situation

## Long readout times

Mar165 CCD at BL X06SA: $t_{exp}$=1s, $t_d$=3s

$$duty\ cycle = \frac{t_{exp}}{t_{exp} + t_d} = 25\%$$

## Radiation Hardness

3 years of operation: > 3 Mrad

Direct beam (SLS X04SA Wiggler Bl): 250krad/s/pixel

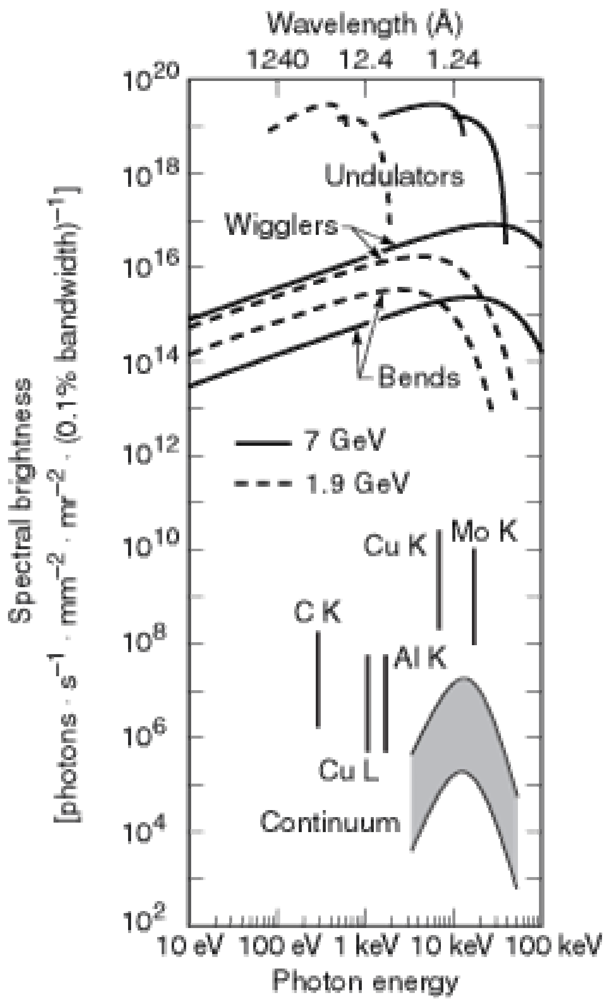
## Solid angle coverage

Analyzer crystals for Powder diffraction

Point detectors on diffractometers

## Detection efficiency

$E_{ph}$ > 20 keV



# Requirements for SR Detectors

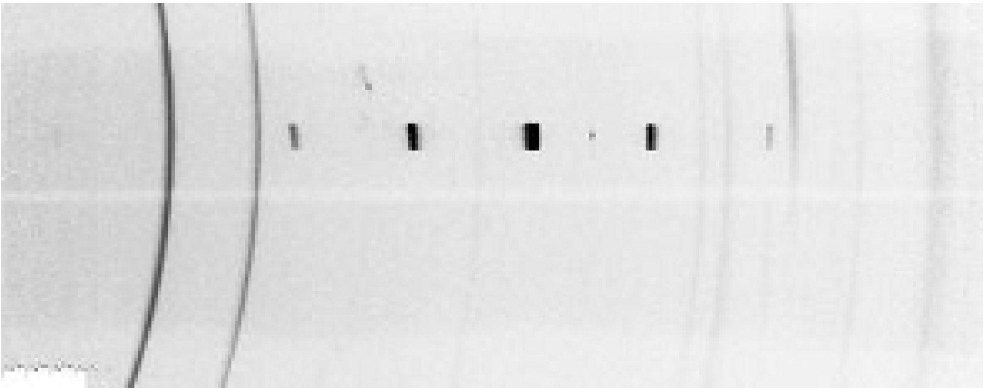
- High local and global count rate capability
- Short read-out time
- High spatial resolution
- High dynamic range
- High detection efficiency
- Large solid angle coverage
- Very good signal to noise ratio
- Precise calibration
- Radiation hardness
- (Software Integration ⇔ User operation)

Single Photon Counting Detectors (?)

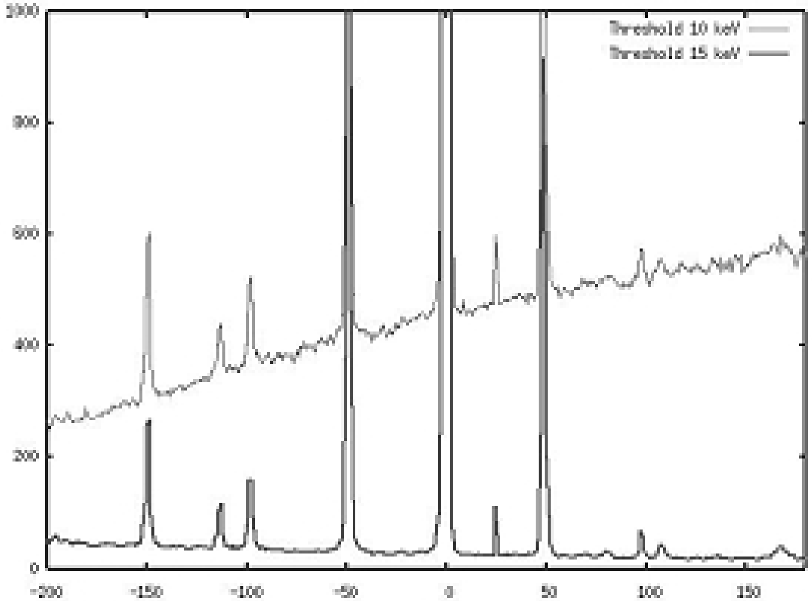
# Single Photon Counting vs Integrating Detectors for SR

| Property | Single Photon Counting | Integrating |
|---|---|---|
| Detection | Charge of Photon is amplified, counting above predefined threshold | Charge is integrated in Pixel |
| Count-Rate | Limited, dead time corrections for high rates, 1 MHz/pixel | Unlimited |
| Read-out | Digital highly parallel data transmission, Noisefree, 1 ms | Analog data transmission, ADC conversion, noise of few X-rays added, >100ms |
| Spatial resolution | > 55 x 55 $um^2$, PSF 1 pixel, | > 10 x 10 $um^2$, PSF type depending |
| Dynamic Range | $10^6$ | $10^4$ |
| Detection efficiency | 74% at 12 keV, low above 20keV | Depending on scintillator |
| Solid angle coverage | Modular detectors | CCD > 30 x 30 $cm^2$ |
| Signal to noise ratio | Fluorescent background suppression | Limited by dark current and readout noise |
| Calibration | Energy calibration with X-rays<br>Rate calibrations | Established corrections procedures |
| Radiation Hardness | Several Mrad required | Several Mrad required |

# Single Photon Counting: Fluorescent background suppression



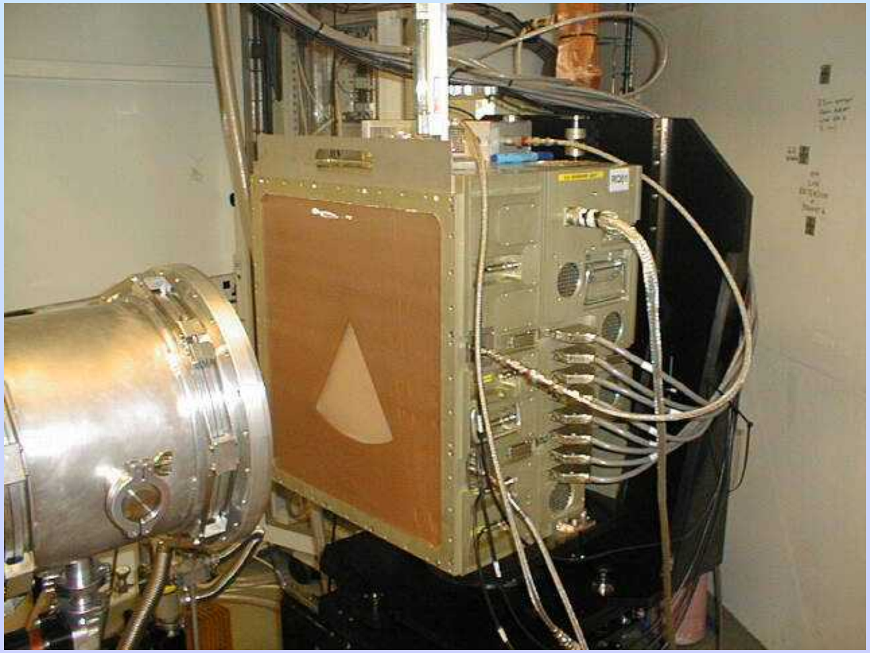
Diffraction pattern from GaAs/AlAs sample at the 18 keV X-ray beam

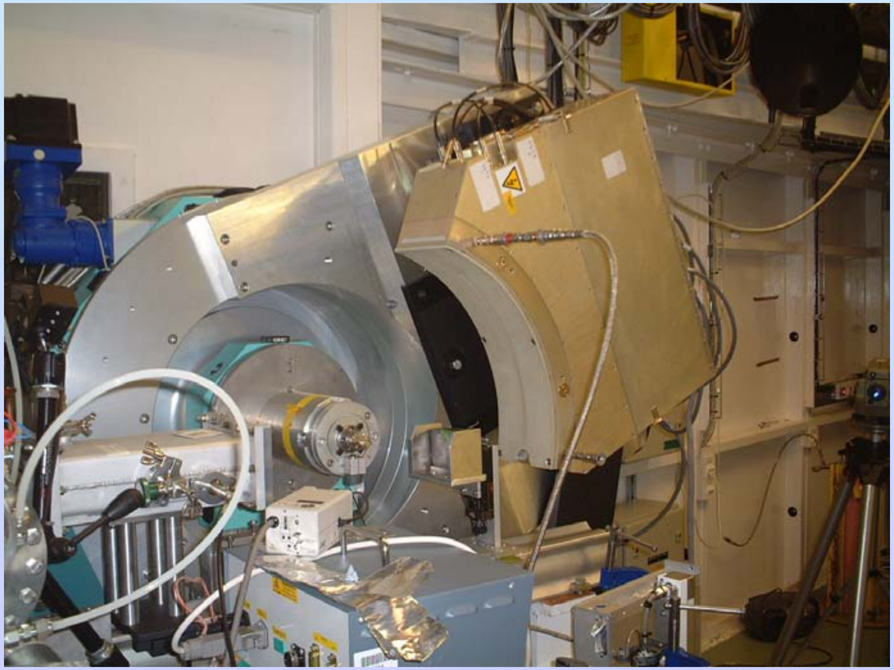



Results for 2 different threshold settings

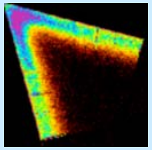
# Detectors for Current and Future Synchrotron Light Sources

# The Rapid2 SAXS/WAXS micro-gap detectors



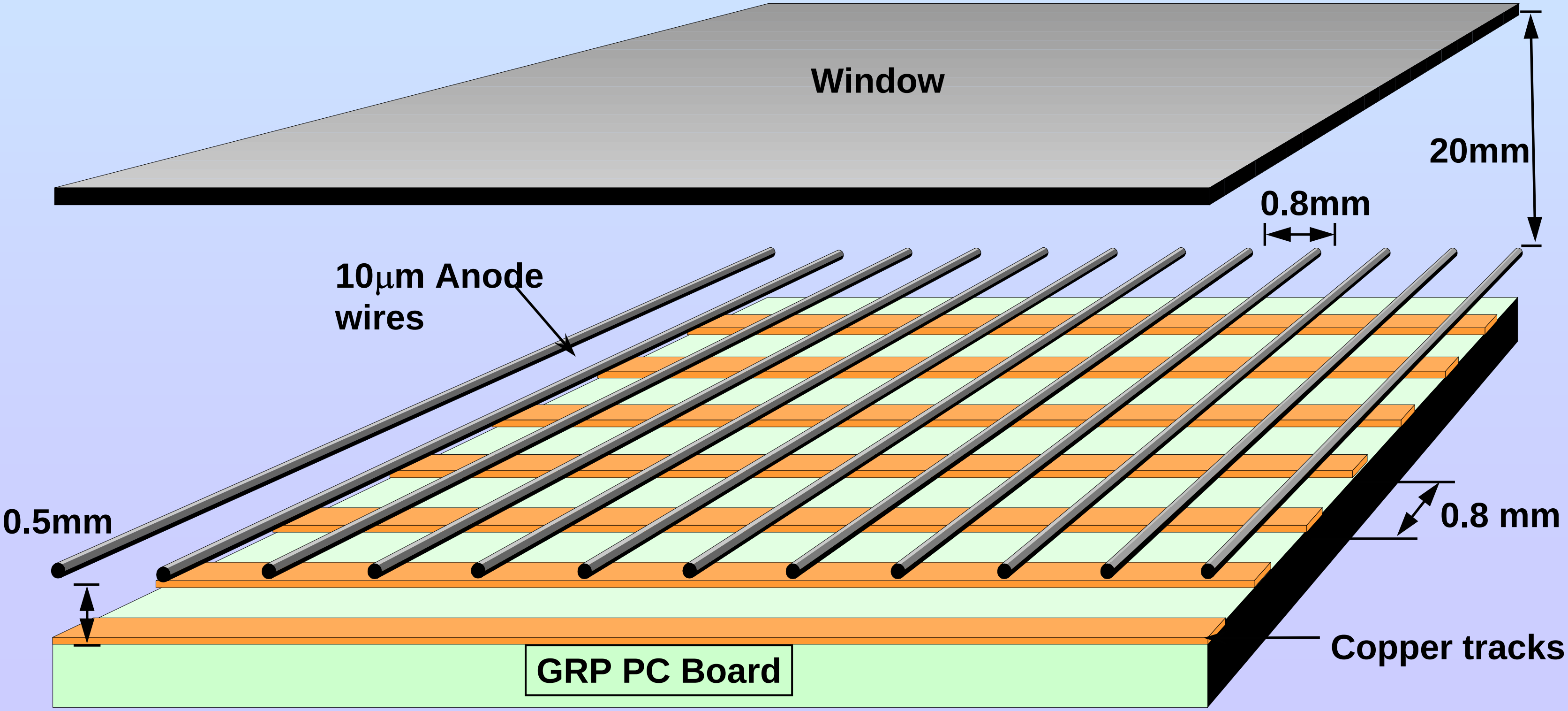


# Wire MicroGap Detector

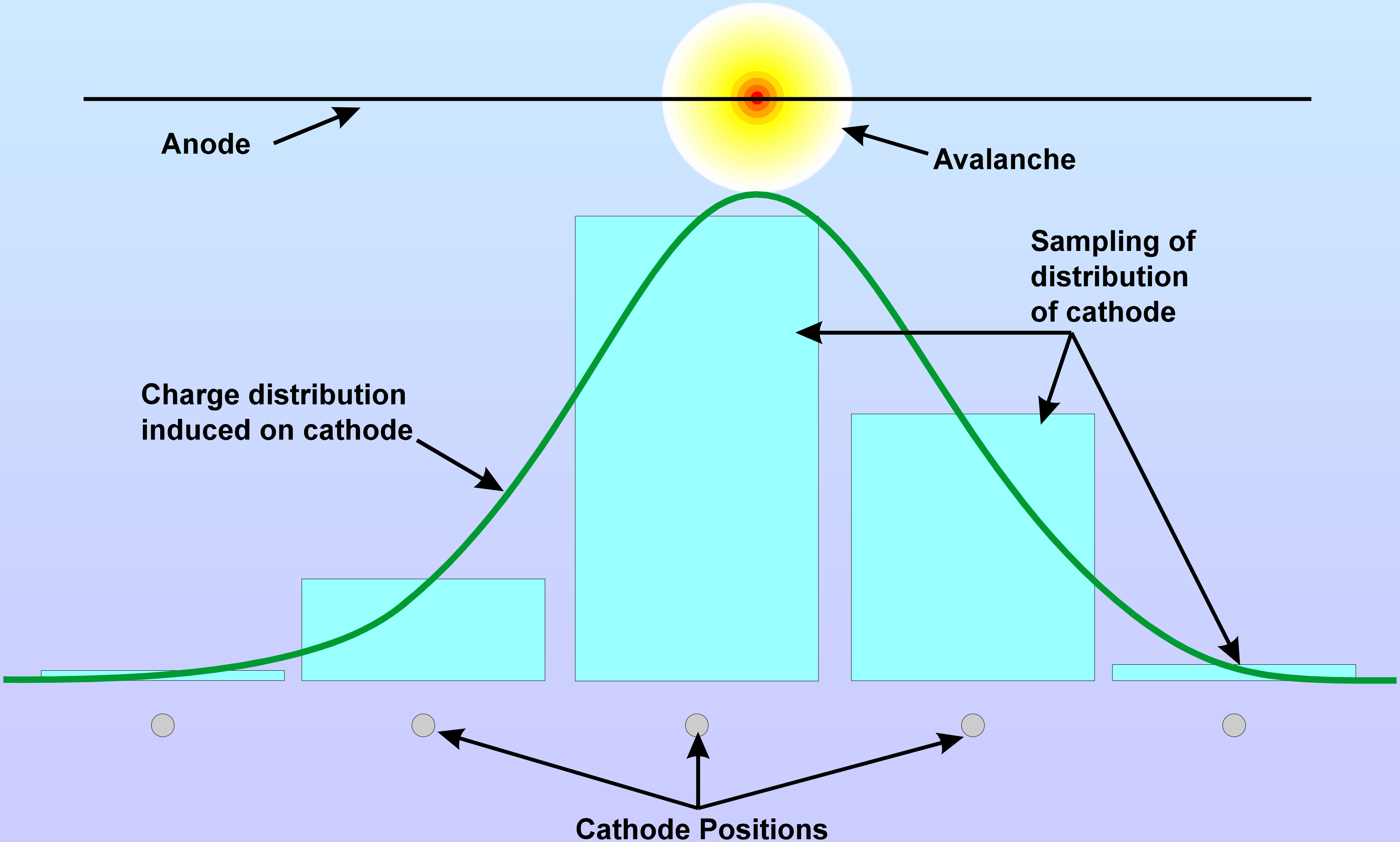


- Small Anode to Cathode gap (0.5 mm) gives good local count rate.
- Intrinsically 2D
- Difficult to maintain anode/cathode gap.

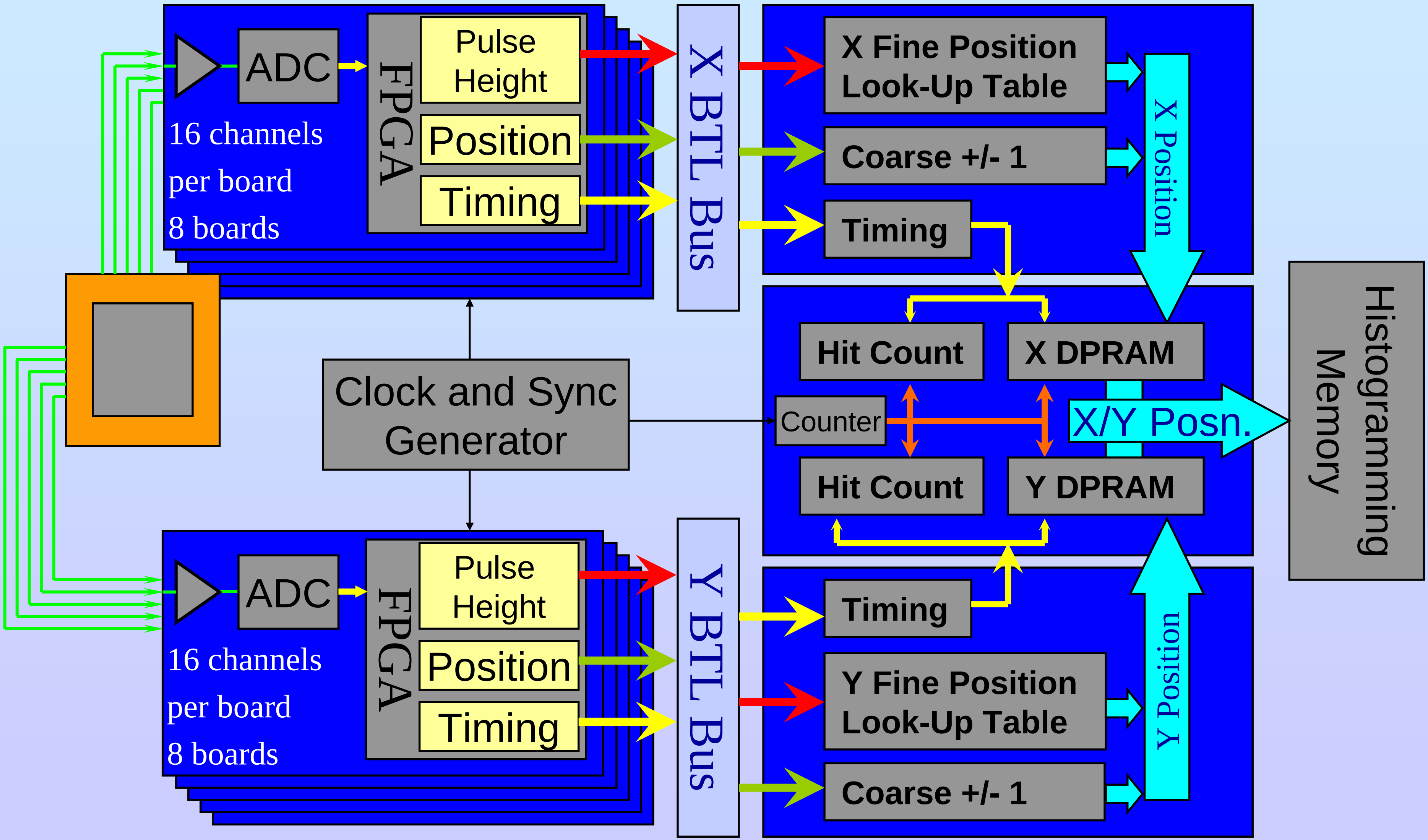
Careful control of wire tension and PCB flatness



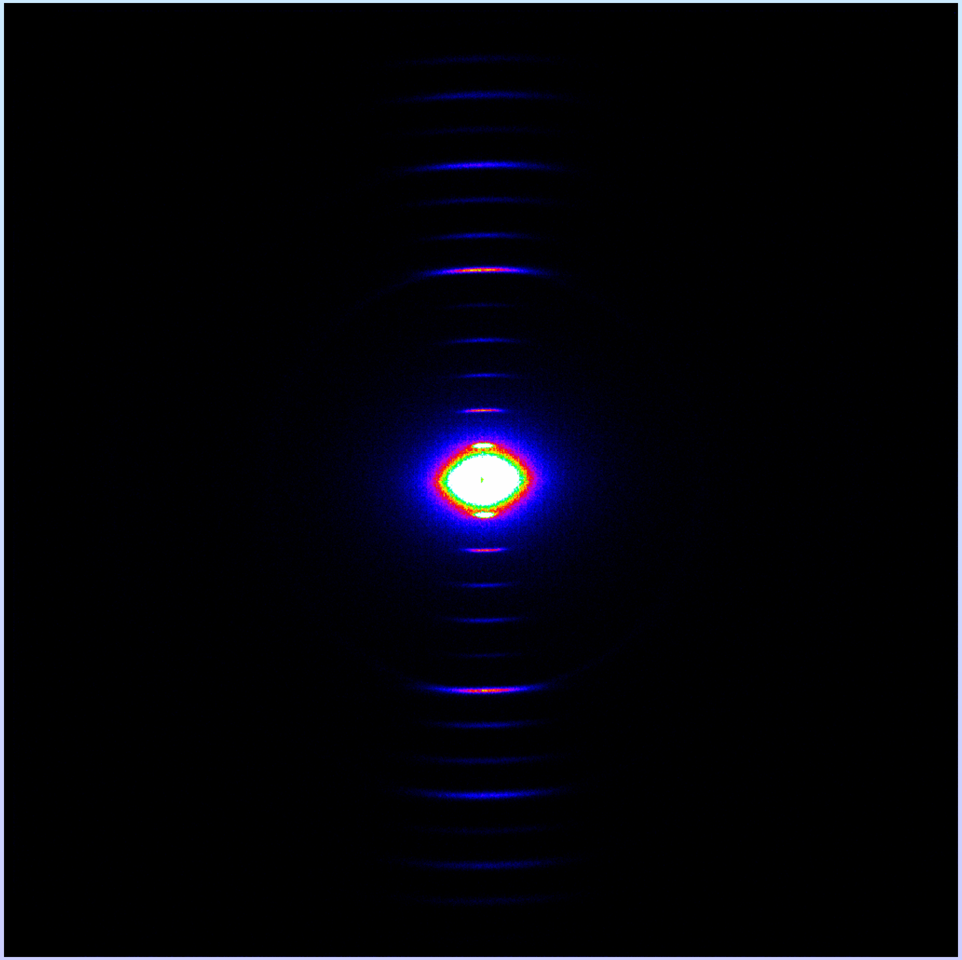
# Charge Distribution



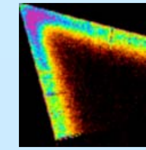
# RAPID 2 as 2D Data Acquisition System



# Collagen Collected at Spring-8 with 2D RAPID 2 2



# Rapid detector system



- **High parallel readout system for Multi Wire proportional counters.**
- **Can readout 1D and 2D detectors**
- **Uses ADC per channel to provide interpolation.**
  - **Gives spatial resolution of typically 512 to 4096 pixels from 128 channels**
- **Count rate performance**
  - **1D – Up to 40x$10^6$ Events/s**
  - **2D – Up to 15x$10^6$ Events/s**
  - **Maximum Frame rate > 1KHz**

# Powder Diffraction with Mythen Detector (SLS BL X04SA)

**Array of Microstrip Detectors**

**Angular coverage: 60º**

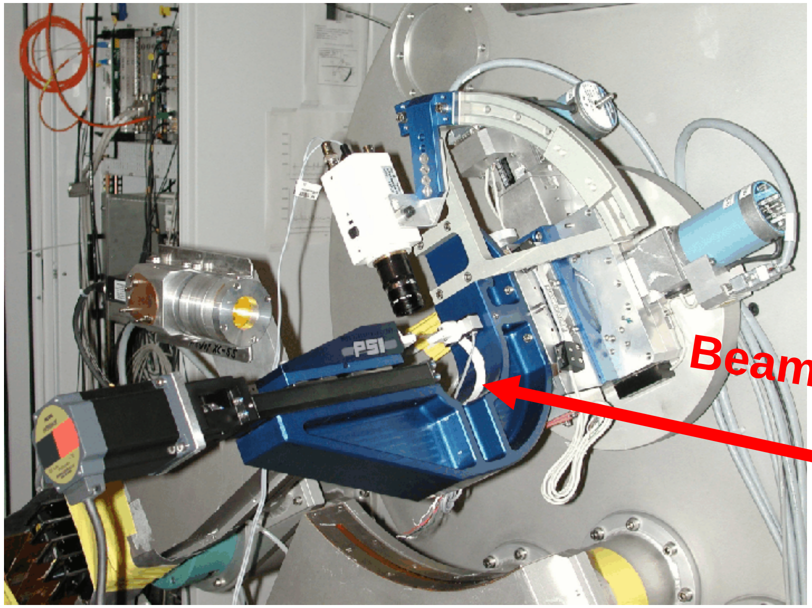
**No of channels: 15000**

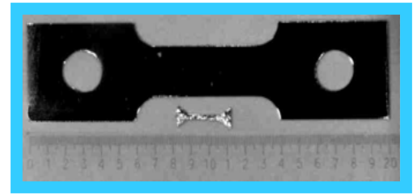
**Angular resolution : 0.004º**

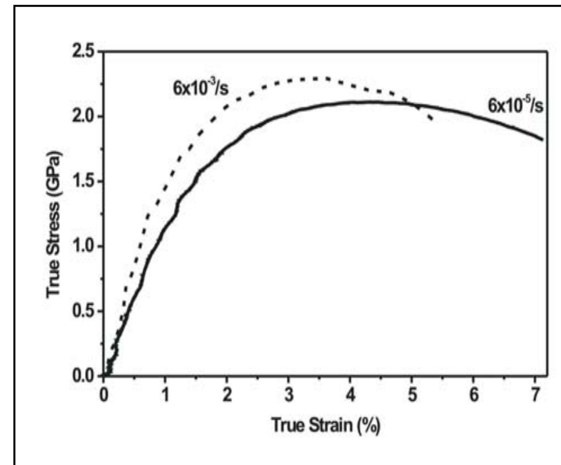
**Read-out time: 250 µs**

→ **time resolved powder diffraction**

# In-situ peak profile analysis of nanocrystalline Ni at SLS



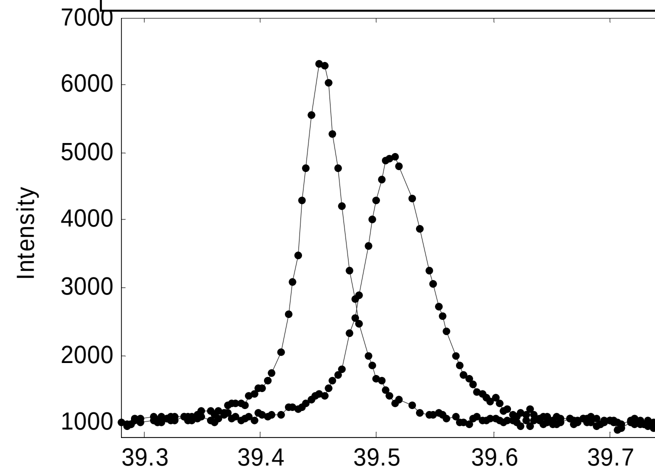




Microstrip-detector

In-Situ X-ray diffraction measurements
of deformation mechanisms

Full powder pattern recorded every 5 seconds

**Science, 304 (2004)**
**Nat. Mat., June (2004)**

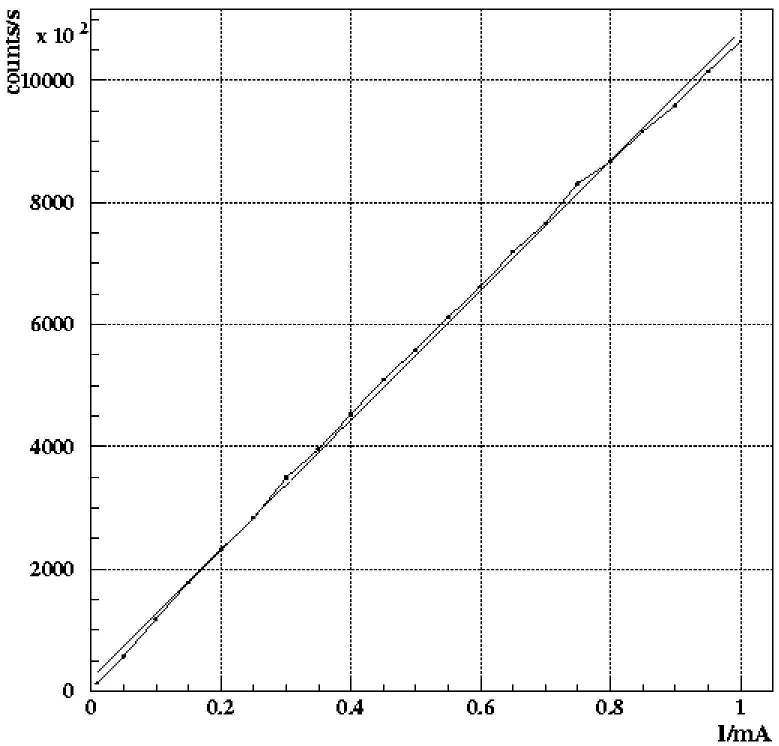


# Mythen V2 (B. Schmitt)

New 0.25 µm readout chip available

Features:
- 128 channels
- Low noise <240 e- ENC
- 6 trim bits High count rate: linear to >1MHz (measured with X-rays)
- 24 bit counter with variable length readout, readout time from 32 µs (4bit) to 64 µs (24bit) for entire chip/detector

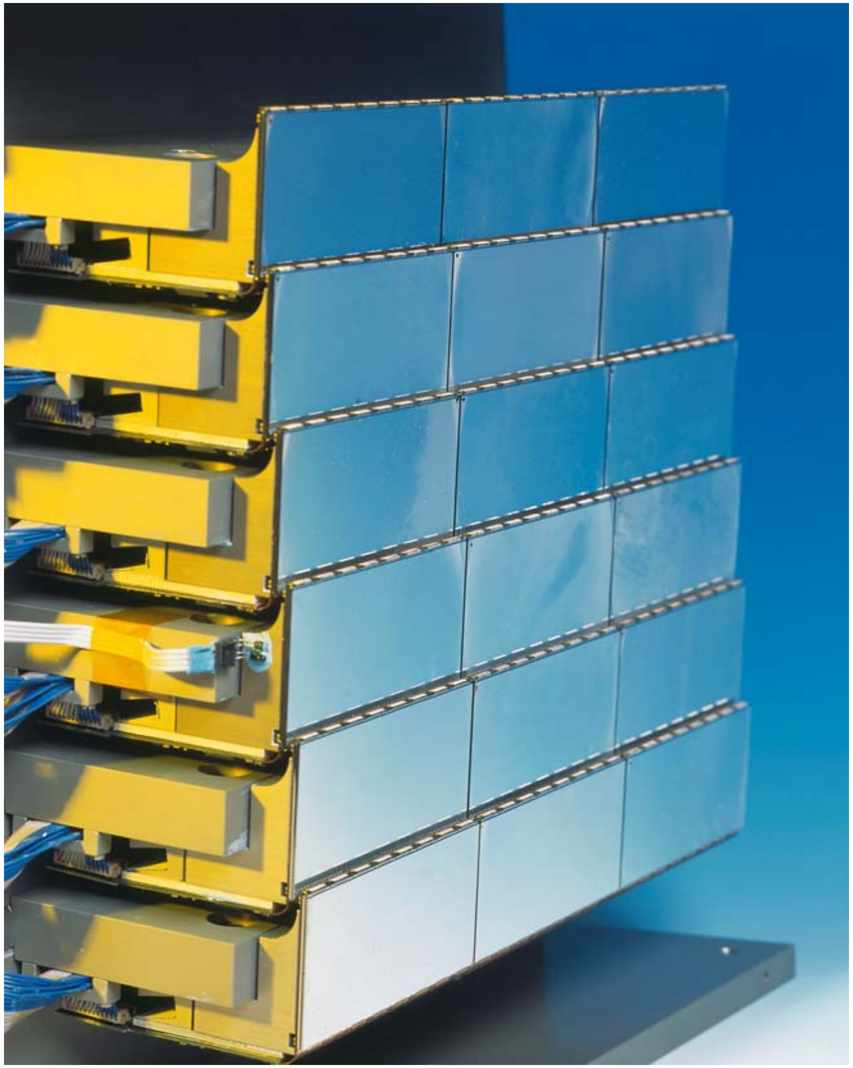
- Frame rates of 10kHz are planned

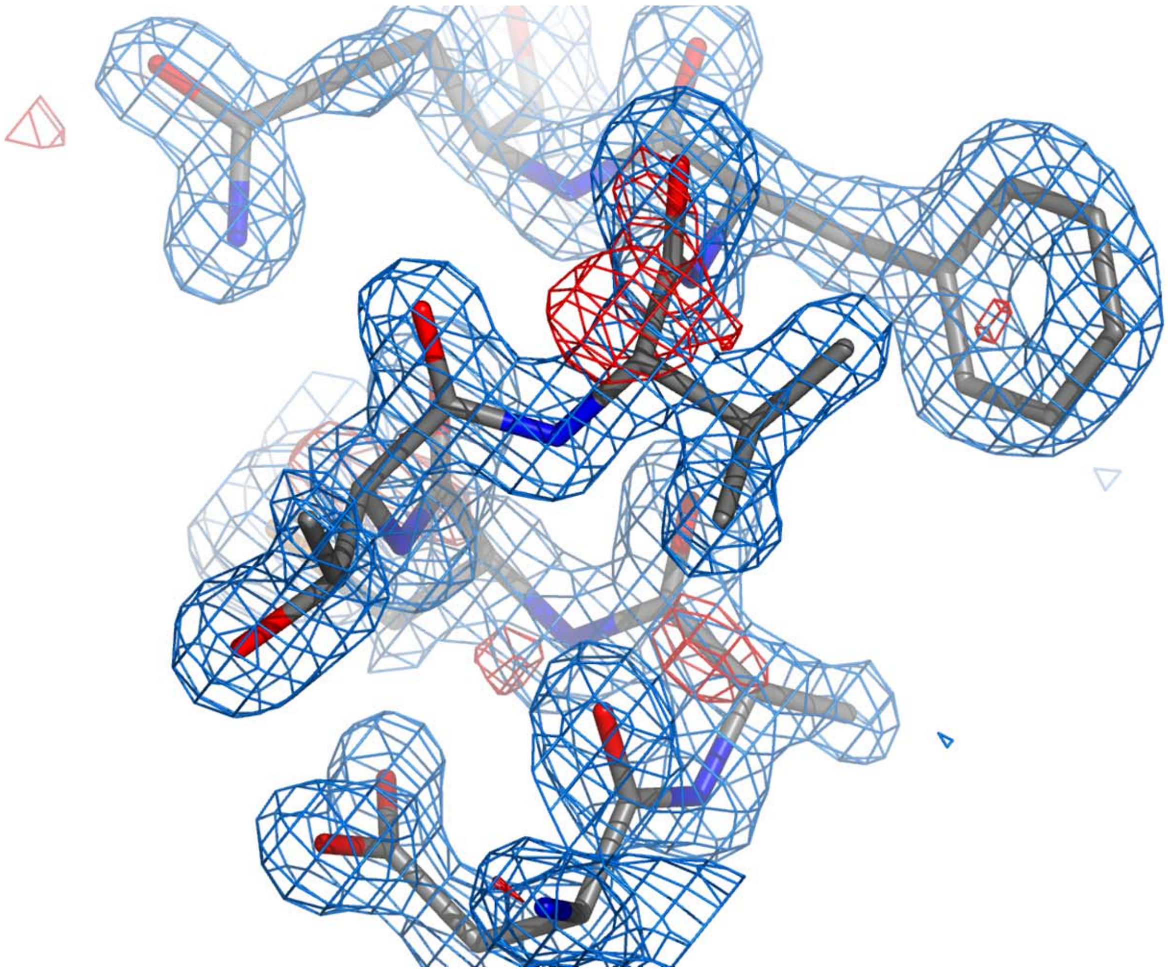



Current detector will be replaced by V2 in 2005

# The PILATUS 1M Detector for Protein Crystallography

- Largest pixel detector array for SR
- 6 banks a 3 modules, 1120 x 967 pixels
- Area: 21 x 24 $cm^2$
- 288 chips->~300x$10^6$ transistors
- Readout time: 6.7ms
- 2 frames/ s
- Active area: 85%
- Moderate count rates (<10kHz/pixel)
- PX Data processing difficult due to counting errors of PILATUS I chip





## Thaumatin electron density map

**Merging of 3 datasets at 3 positions**

**Processing with XDS**

**Refinement with SHELXL**

**Completeness: 90.3%**

**$R_{sym}$ 8.4%**

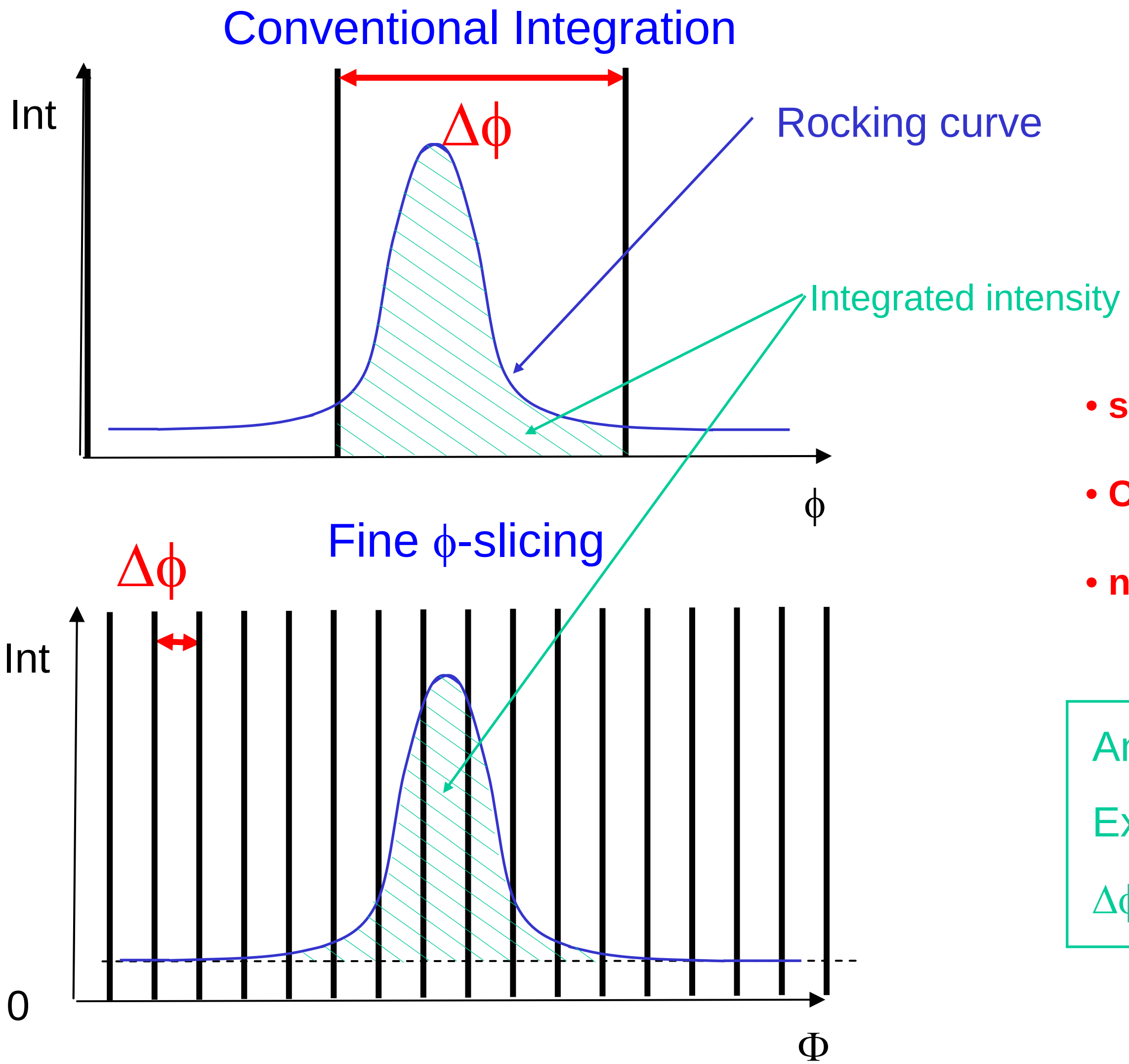
**Resolution: 1.4 Å**

**Refinement:
R-Factor 28%**

blue contours: 2*Fo-Fc (2sigma)
red contours: Fo-Fc (2sigma)

Ch. Broennimann et al, “The PILATUS 1M Detector”, submitted to J. Synchrotron Rad. (2005)
G. Huelsen et al.,”Distortion Calibration of the PILATUS 1M Detector”, accepted by NIM 2005

# Fine ϕ-slicing with the PILATUS Detector



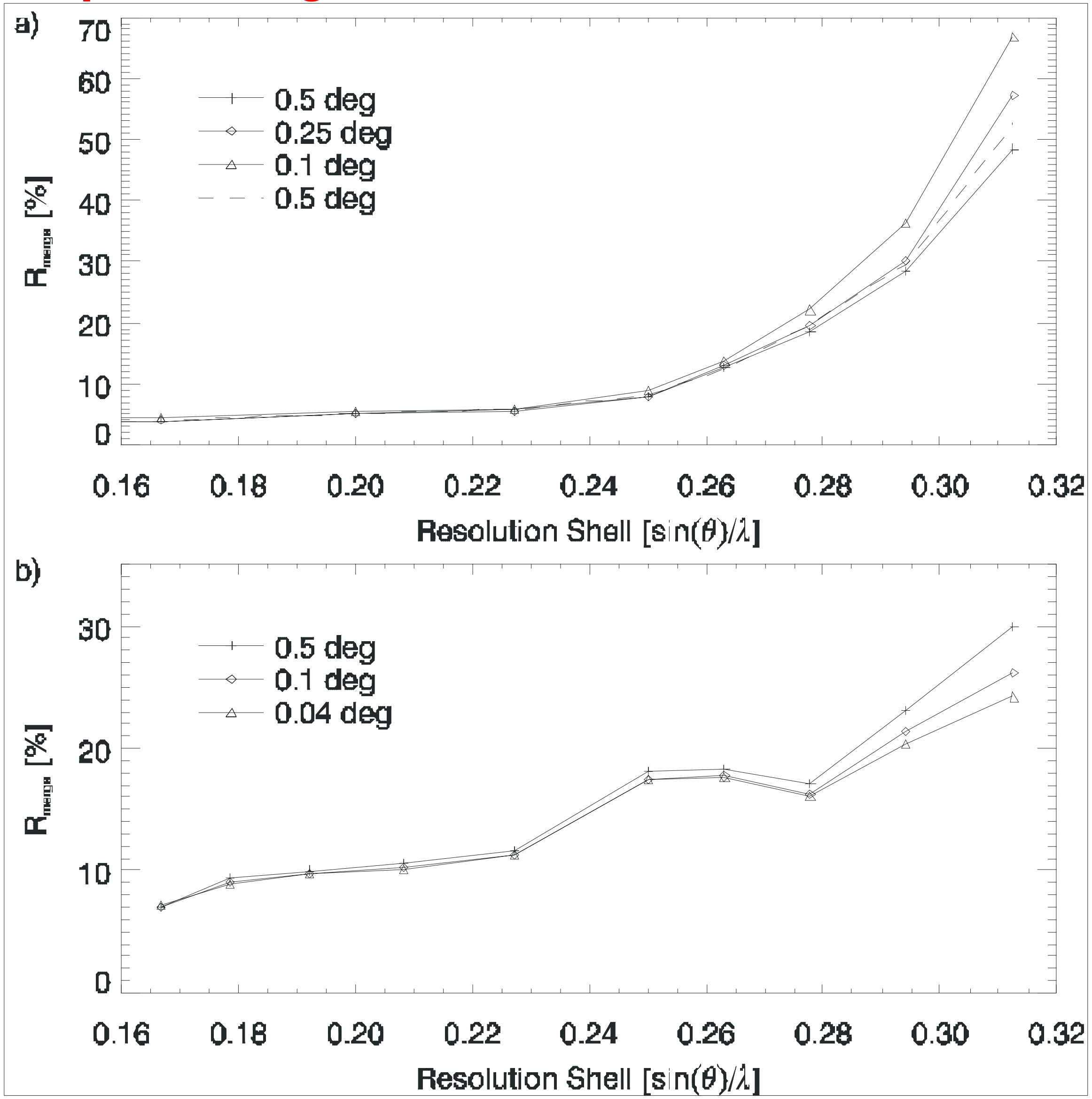

- short readout-time
- Continuous rotation -> no shutter
- no read-out noise

Angular speed $\omega$,

Exposure time t

$\Delta\phi = t*\omega$

# Results of Fine-phi slicing data-sets




CCD Data:

Finer slicing -> more readout noise, -> higher R-Factors

PILATUS 1M Data:

Finer slicing -> higher ϕ-resolution -> somewhat lower R-Factors

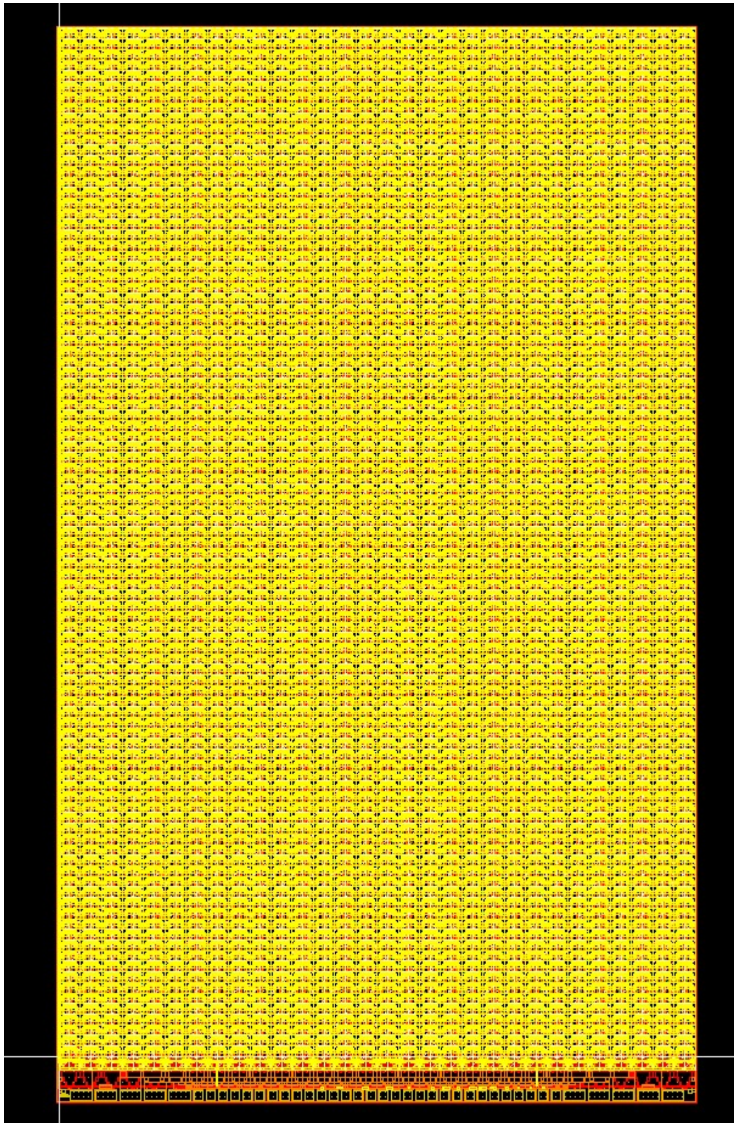
New version of XDS from W. Kabsch to process the 9000 frames a 0.02°/frame

G. Huelsen et al.," **Protein Crystallography with a Novel Large Area Pixel Detector**", in preparation

# PILATUS II Chip

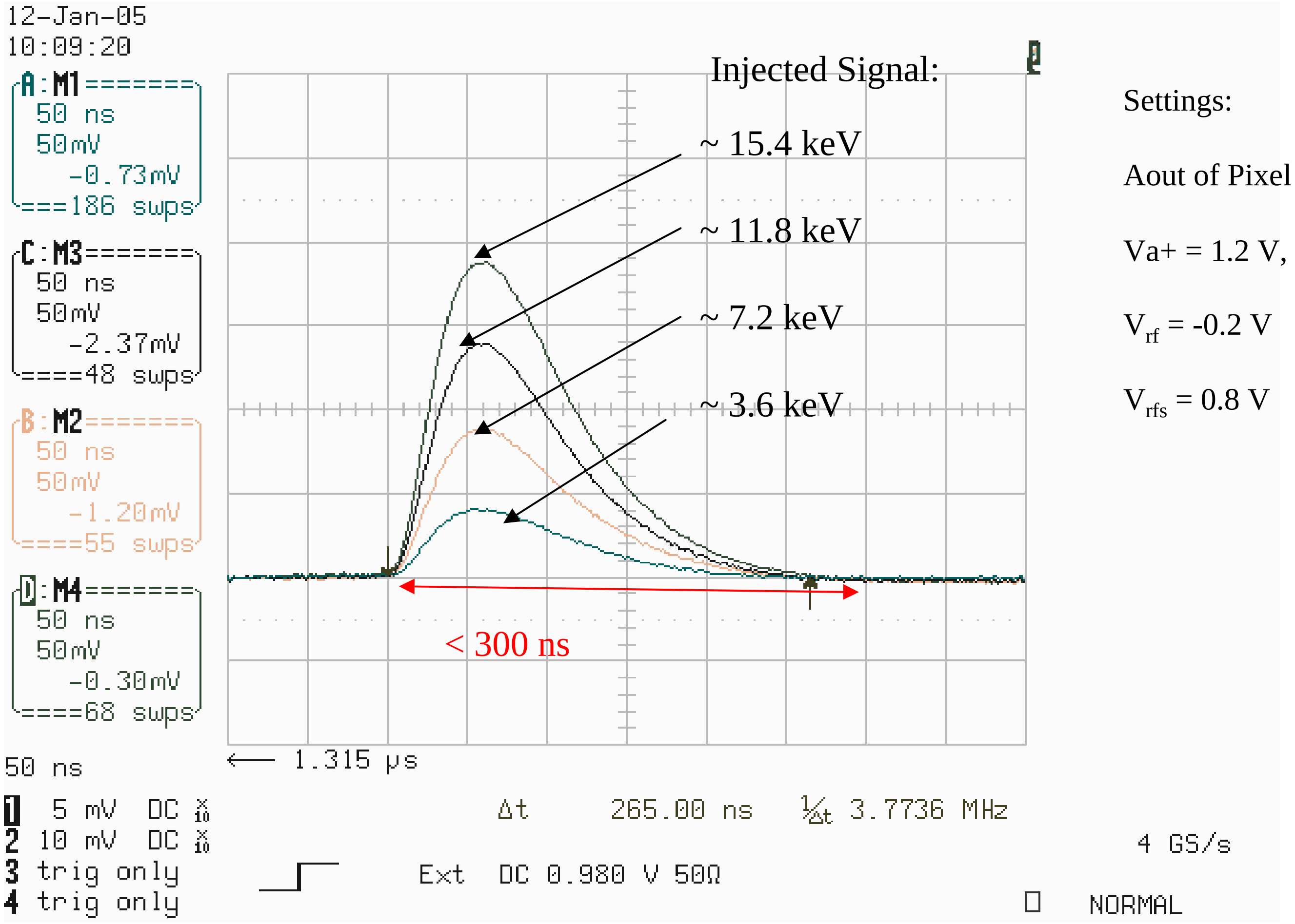
- UMC_25_MMC process; Radiation hard design
- 60 x 97 pixels = 5820 pixels
- Pixel size 172 x 172 $um^2$
- 17.540 x 10.450 $mm^2$
- Count rate: 1MHz/pixel
- 20 bit counter
- Counting timer circuit
- 6 bit DAC for threshold adjustment
- XY-adressable
- Analog output
- 75 MHz LVDS readout ($T_{ro}$ = 2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

$4*10^6$ Transistors



Philipp Kraft, Characterization of the Readout Chip for the PILATUS 6M Detector, ETHZ-IPP Internal Report 2005-03 (March 2003)
Available on-line soon

# PILATUS II: CS Amplifier




Settings:

Aout of Pixel 0,0 (bottom left)

Va+ = 1.2 V, ($I_{pix}$= 13 μA)

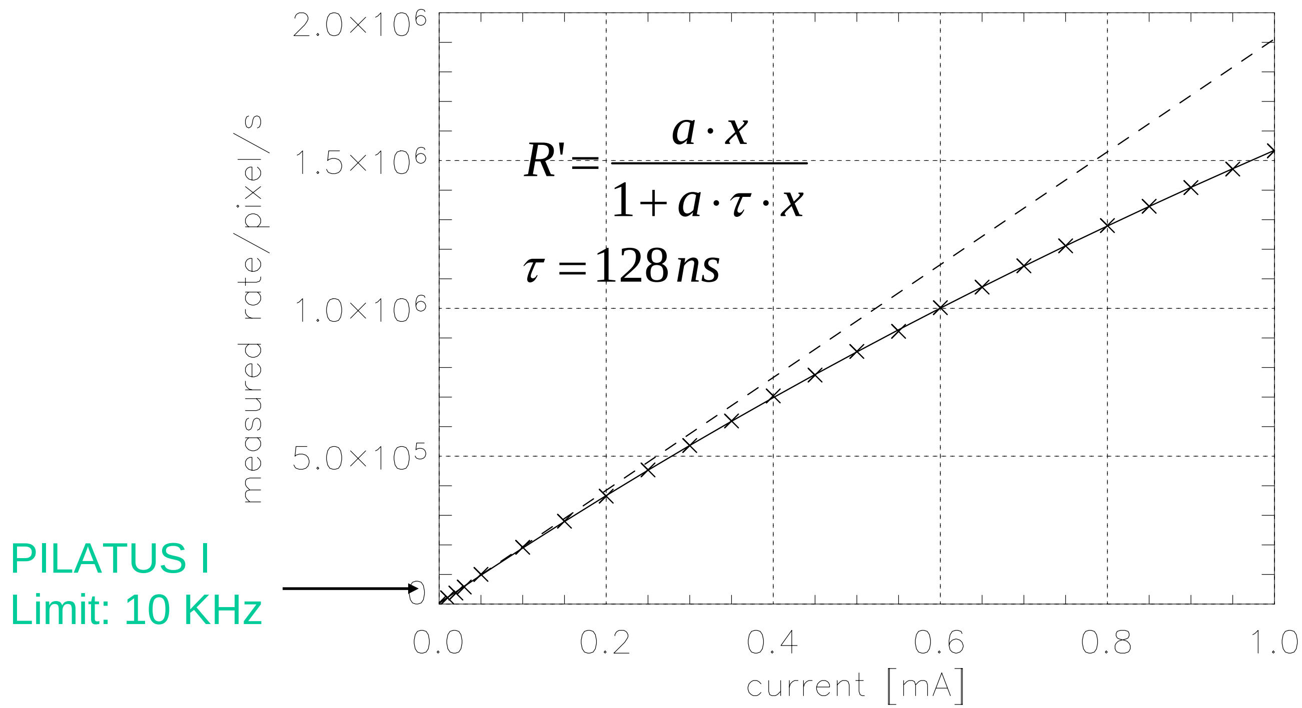
$V_{rf}$ = -0.2 V

$V_{rfs}$ = 0.8 V

$10^6$ photons/s/pixel with poisson distributed time-intervals should be possible

# PILATUS II Rate Tests

8keV X-rays, avg rate of 20 pixels



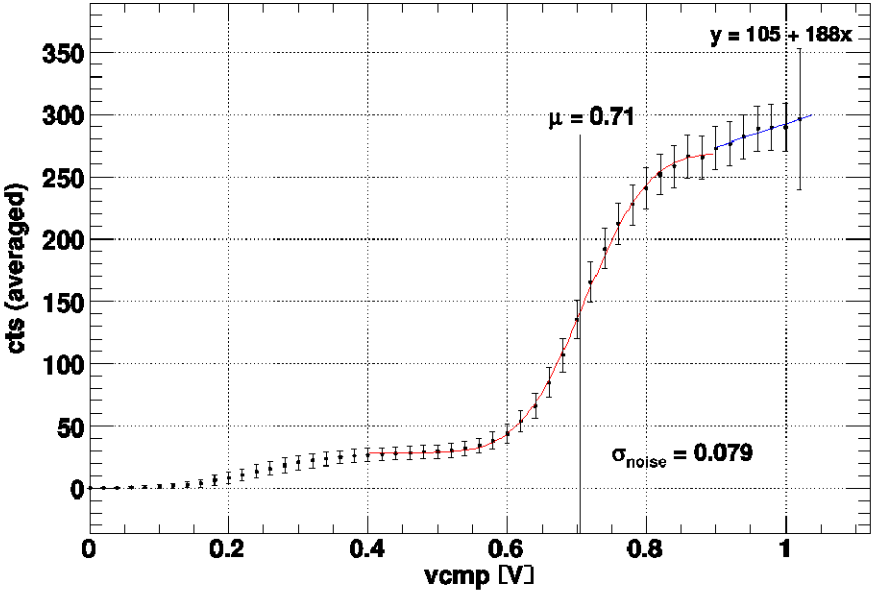

Count Rate capability:

- local $1.5 \cdot 10^6$ X-rays/s/pixel
- global $5 \cdot 10^7$ X-rays/s/$mm^2$

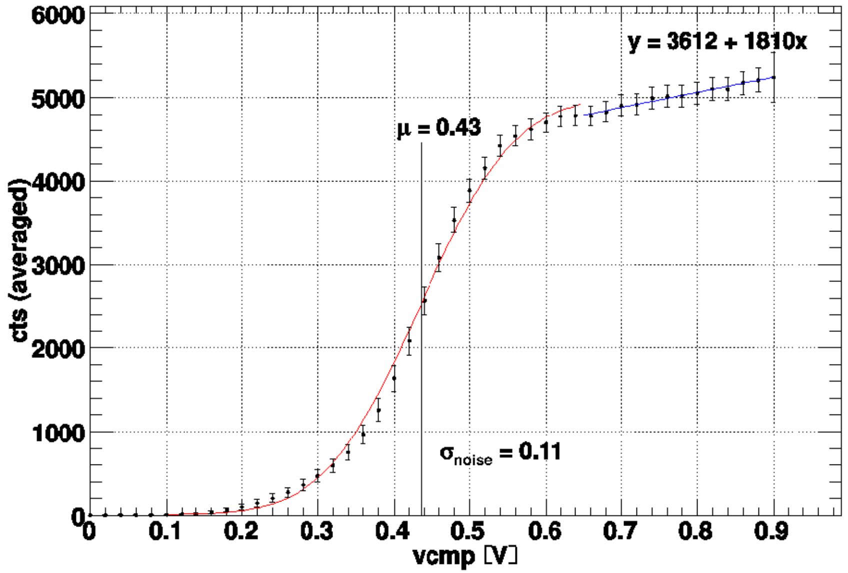
# PILATUS II Vcmp calibration

$V_{cmp}$ scans from flat-field illuminations, after trimming, averaged over all pixels

6 keV



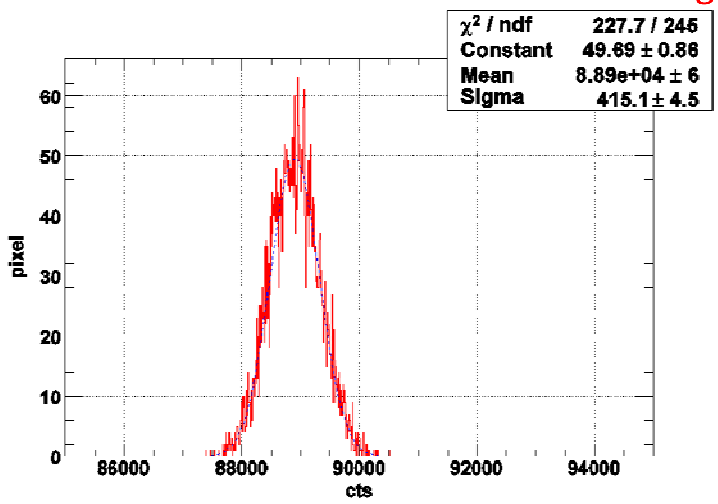

8 keV

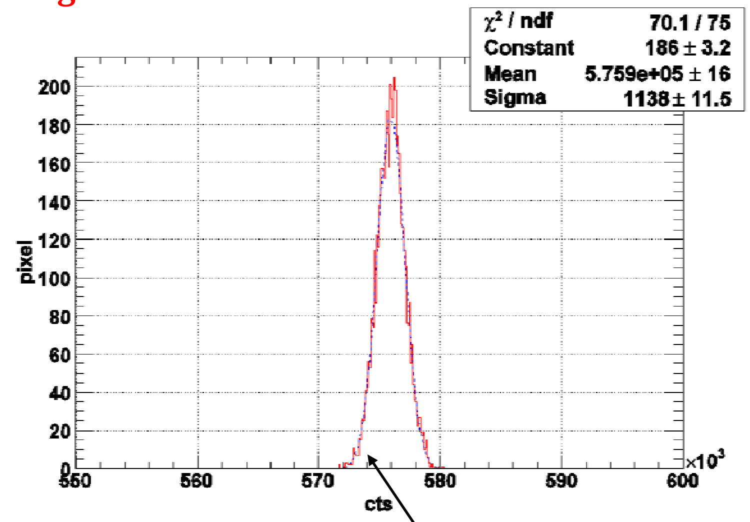


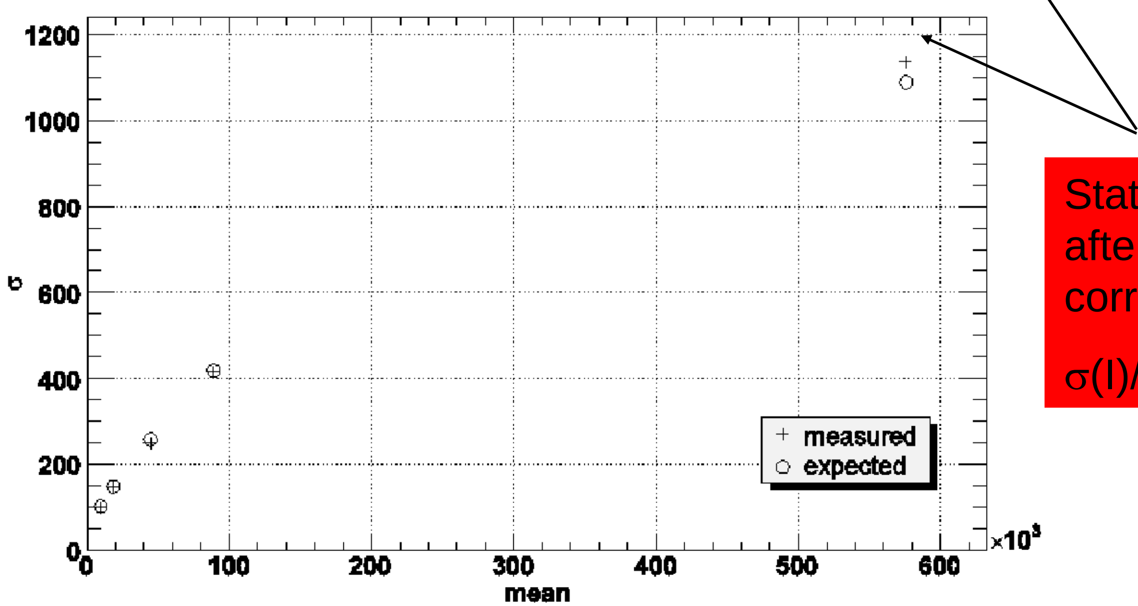

$\sigma$ = 158 $e^-$ (= 570 eV)

# Pilatus II Counting Statistics

## Flat-field Images after trimming at 12 keV




Statistical variation after flatfield correction:

$\sigma(I)/I = 0.2\%$

# Radiation Hardness (preliminary)

Counting detector delivers deposited dose directly:

$$D = \frac{N_x \cdot E_x}{m_p}, with$$

$$N_X = 10^6 / pix / s$$

$$E_X = 13.5 keV$$

$$m_p = 2 \cdot 10^{-5} g$$

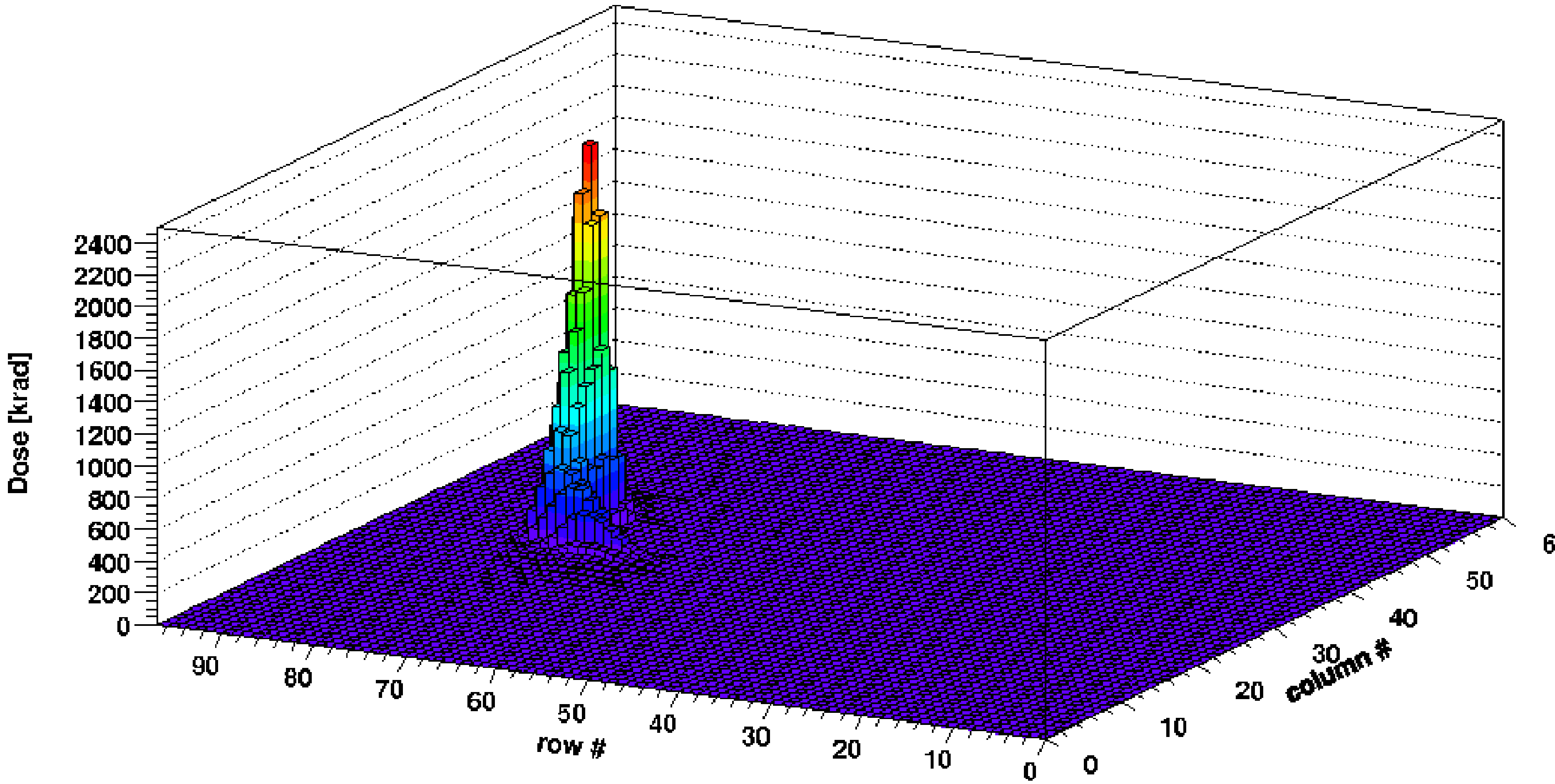
$$1\, rad = 6 \cdot 10^{10} keV / g$$

$$\Rightarrow D = 10\, rad / s$$

- Put Pilatus II chip in direct beam
- Adjusted beam intensity to obtain ~$10^6$ X-rays/pixel
- Increased beam intensity by 100 ->~ $10^8$ X-rays/pixel
- -> central pixels saturated
- Exposed for 3600s
- Peak doses ~2 – 3 Mrad (20- 30 Gy)
- Flat field illumination befor and after irradiation -> count rate variation < 1%

Pilatus II Chip + Sensor are radiation hard

# Distribution of Dose on Chip



# PILATUS II: Single Module


Module Parameters:

487 x 195 = 94’965 pixel

$T_{ro}$ = 2 ms

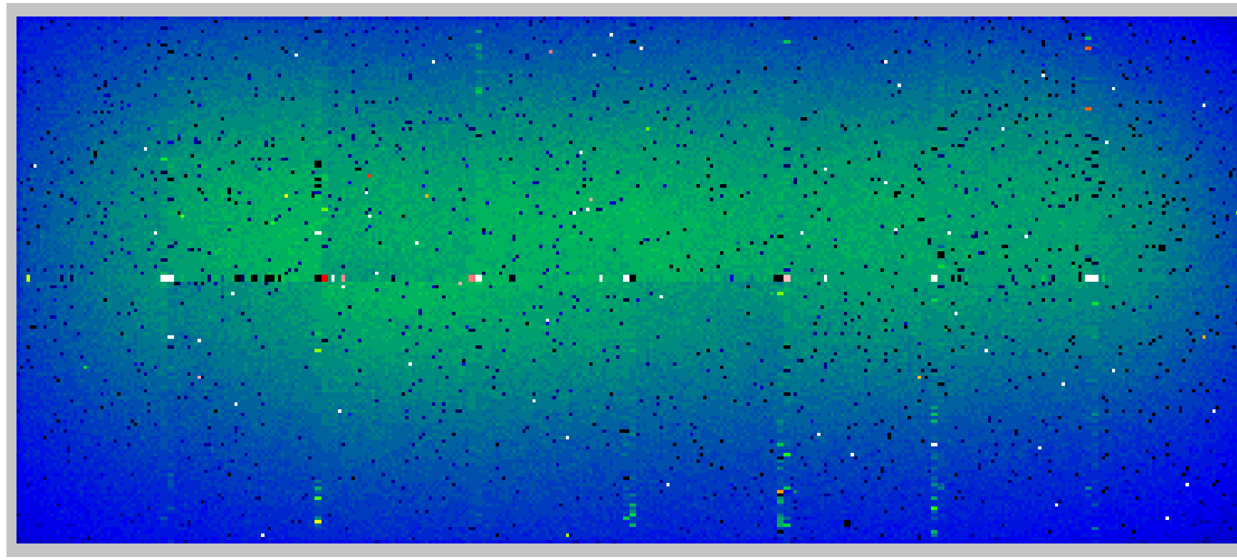
Maximum Frame Rate with Gigastar PCI Card: 150 Hz

# Quality

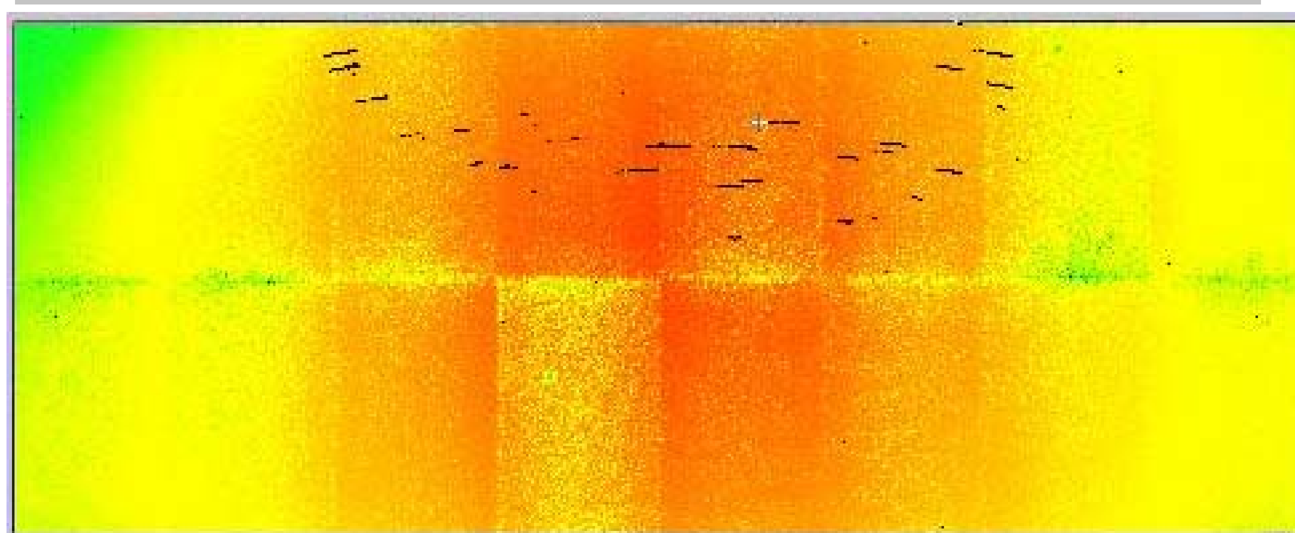
$^{55}Fe$ Irradiation (6keV):

(Very sensitive to high resistivity bumps)

PILATUS I:
54912 pixels
5% overall defects

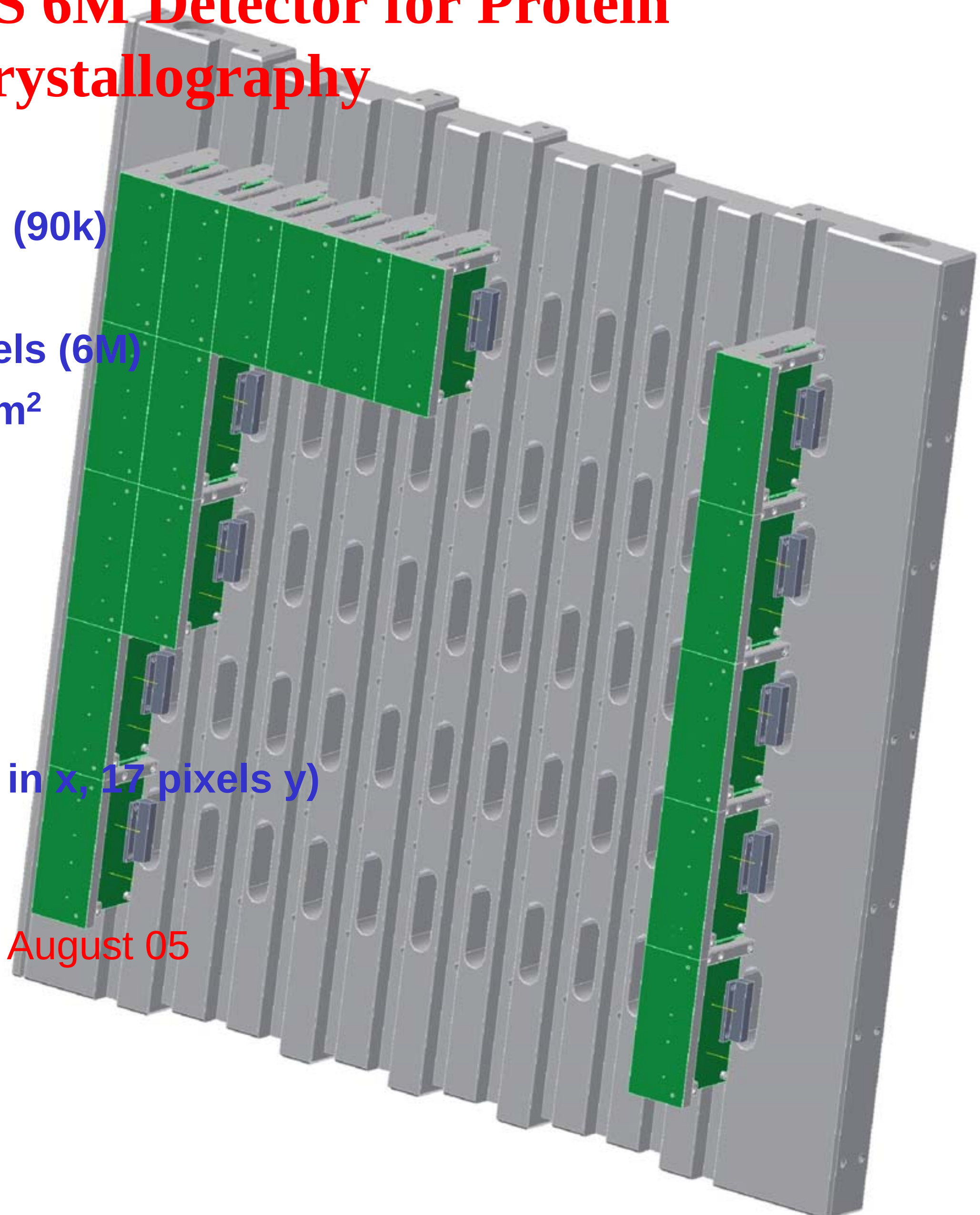


PILATUS II:
93120 pixels
0.27% overall defects
(mainly sensor defects)



# The PILATUS 6M Detector for Protein Crystallography

| | |
|---|---|
| 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 (6M) |
| 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) |



Status: Module fabrication starts in August 05

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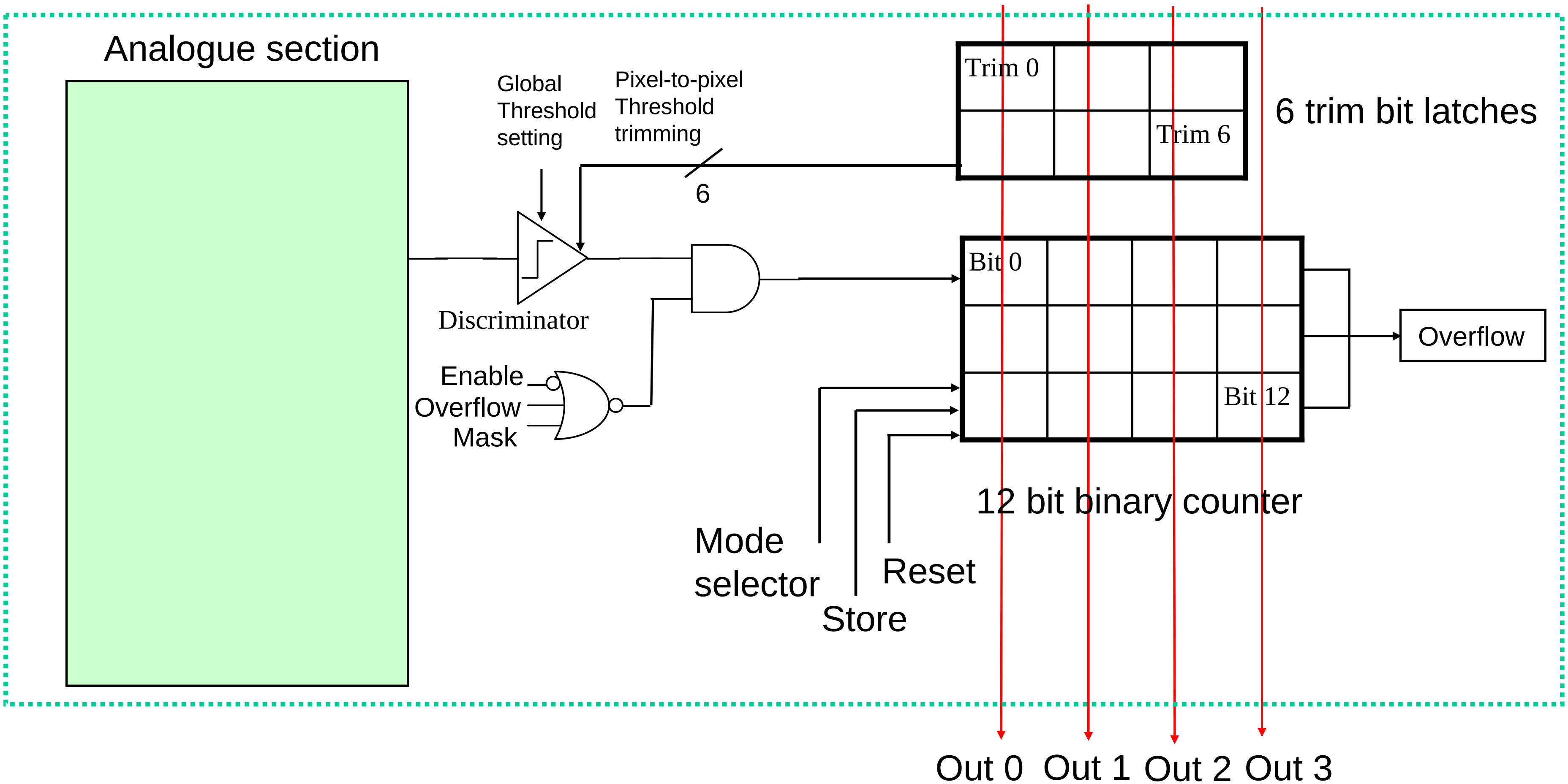
# PILATUS XFS: (eXtrem Framing System)

(R. Horisberger, R. Dinapoli and Ch. Broennimann)

| | Pilatus XFS | Pilatus II |
|---|---|---|
| Technological process | UMC 0.25 µm process | The same |
| Radiation tolerance | Radiation hard design (>4Mrad) | The same |
| Pixel array | 256 x 256 = 65536 | 60 x 97 = 5820 |
| Pixel size | 75 x 75 $\mu m^2$ | 172 x 172 $\mu m^2$ |
| Chip size | 19.2 x 19.2 $mm^2$ | 17.54 x 10.45 $mm^2$ |
| Counter | 12 bits, binary, configurable (4,8,12 bit mode) | 20 bits, pseudo-random, not configurable |
| Readout | Continuous | Separated from exposure |
| Local count rate | > $10^6$ /pixel/s | > $10^6$ /pixel/s |
| Overal count rate | > 3 x $10^8$/$mm^2$/s | > 5 x $10^7$ /mm2/s |
| Power consumption | < 5 uW/pixel | 10 uW/pixel |
| Frame rate full RO | > 10 KHz | < 300 Hz |

# Pilatus XFS, the pixel architecture

- **The chip is a matrix of 256 x 256 pixels of 75 x 75 $\mu m^2$ each.**
- **It has a configurable count mode, 4, 8 and 12 bits. Moreover, it can be used in simultaneous read-write mode.**
- **This results in 12.5 KHz framing rate @ 8 bit, continuous readout mode.**



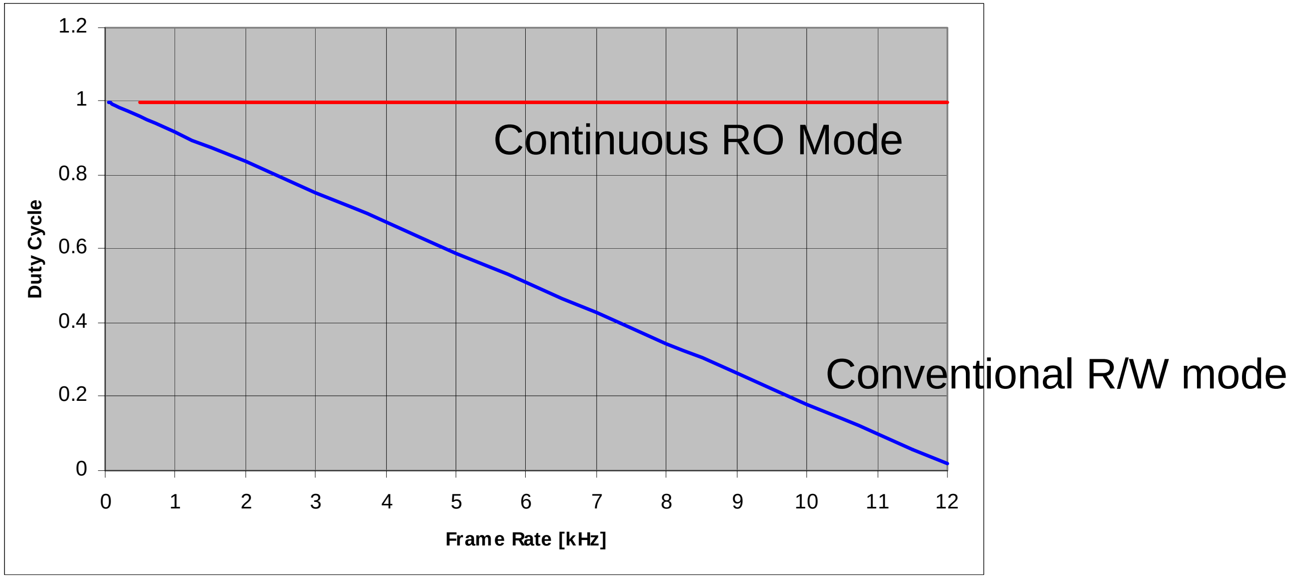
# Pilatus XFS main features

- **Count rate: 1MHz/pixel (3 x $10^8$ x-rays/mm$^2$/s)**

  **Max. frame exposure time before overflow:**

  - **$T_{max}$ @ 4 bit mode = 16 µs**
  - **$T_{max}$ @ 8 bit mode = 256 µs**
  - **$T_{max}$ @ 12 bit mode = 4 ms**

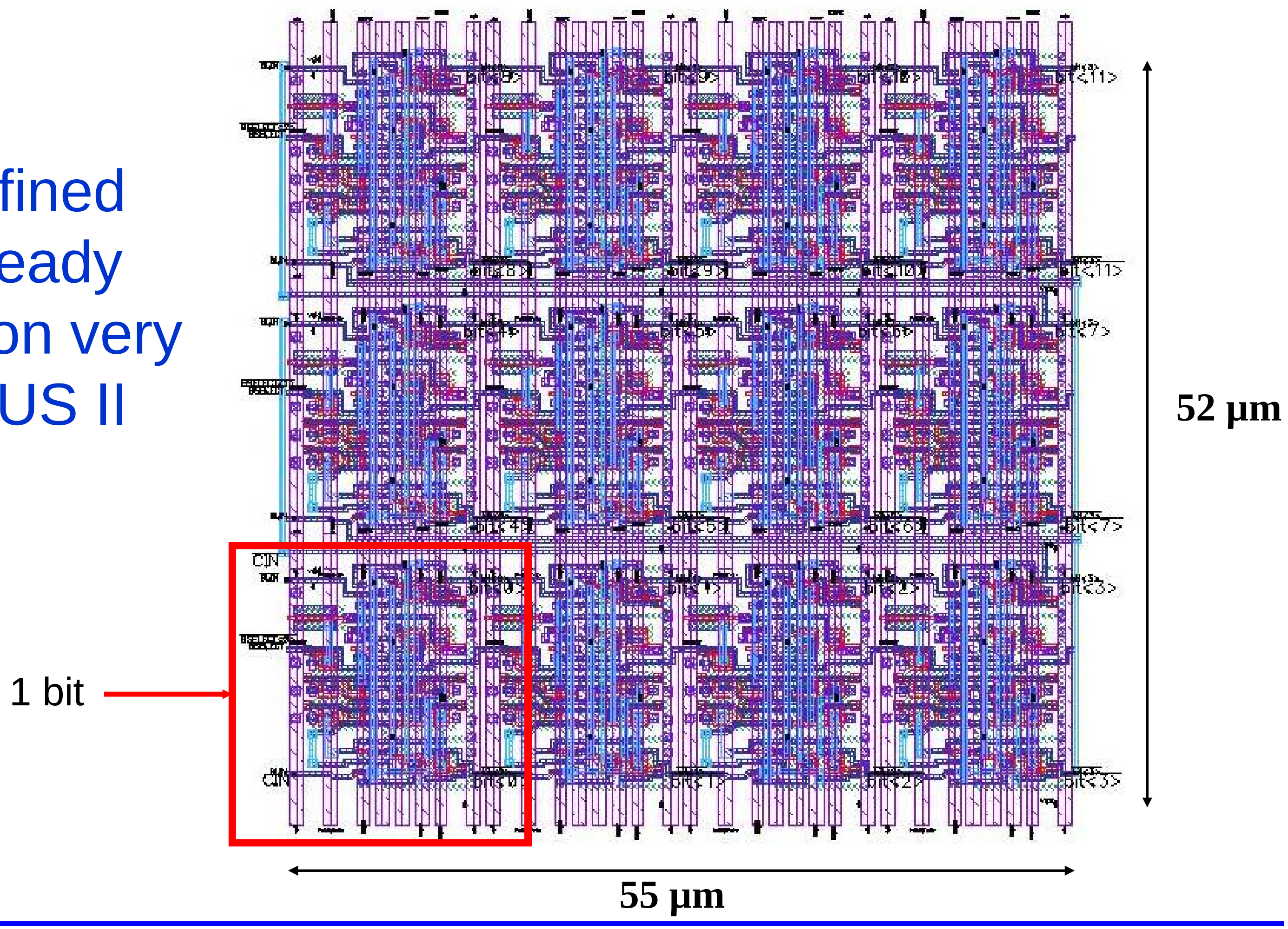
- **200 MHz LVDS readout (PII:75 MHz)**
  - **$T_{ro}$ @ 4 bit mode = 40.96 µs**
  - **$T_{ro}$ @ 8 bit mode = 81.92 µs**
  - **$T_{ro}$ @ 12 bit mode = 122.9 µs**
  - **In continuous readout mode, frame rate=1/readout time; 12.5 KHz @ 8 bit mode**



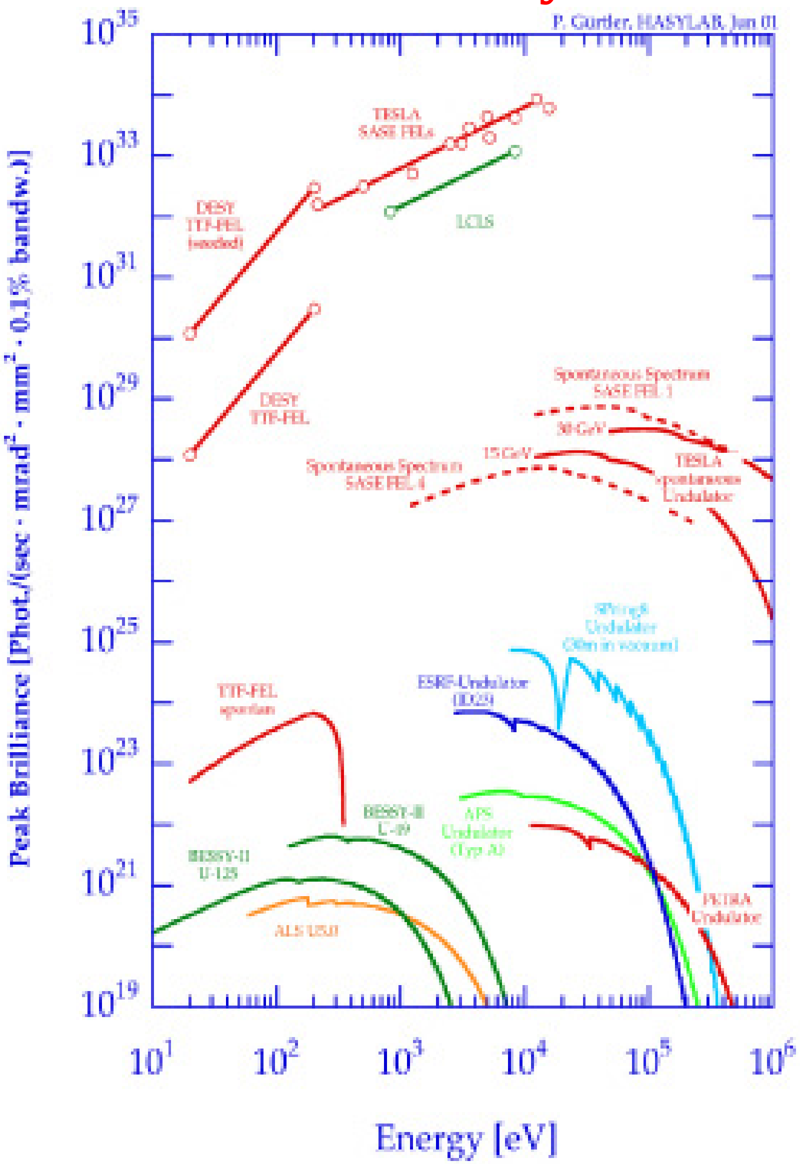
# Pilatus XFS, status

- Architecture defined
- 12 bit counter ready
- Analogue section very similar to PILATUS II

Configurable 12 bit counter with latch



# Future synchrotron sources




Peak intensities several order of magnitudes higher-> counting impossible

-> Integrating detectors

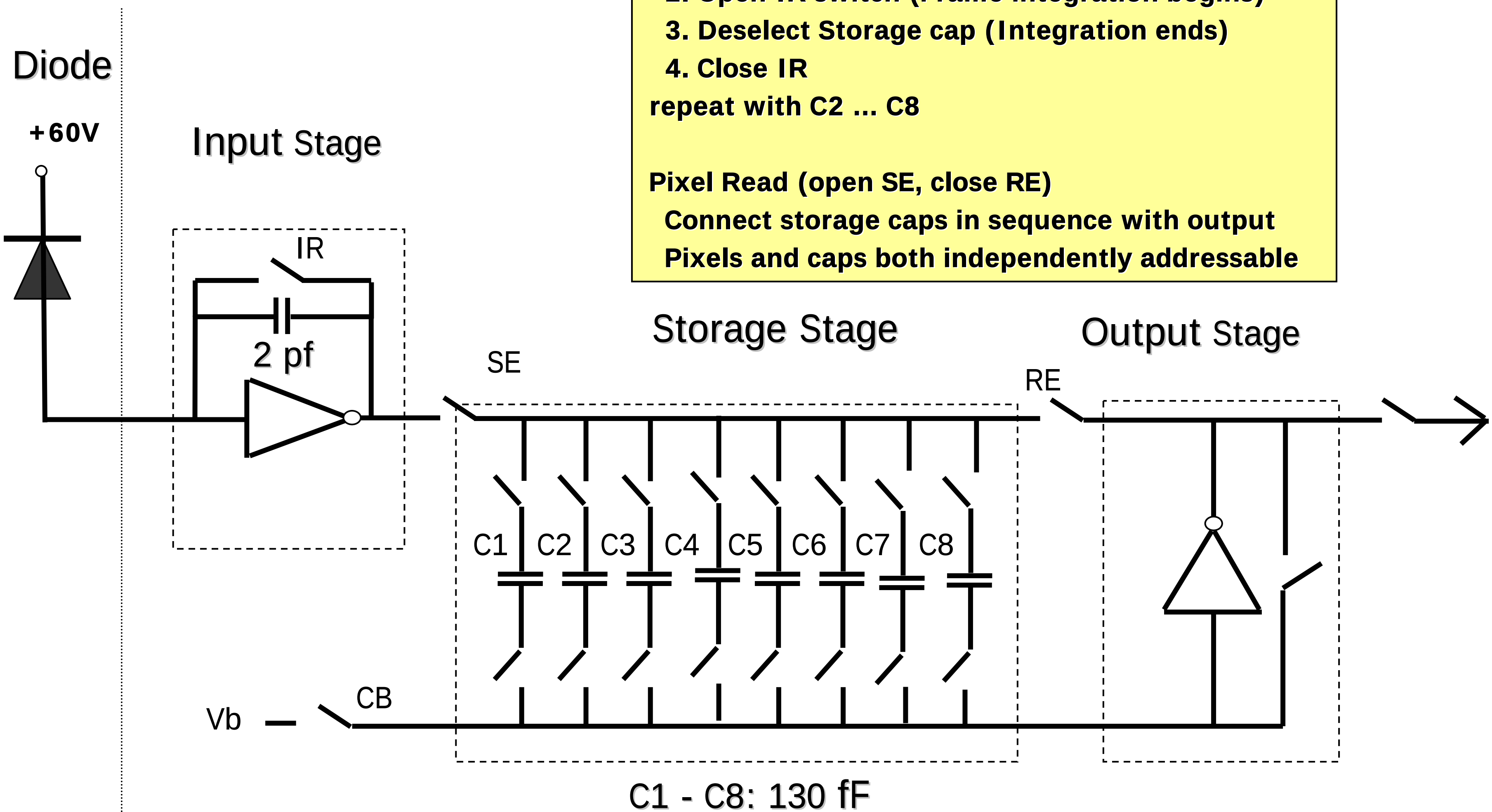
# Cornell Analog PAD

CHESS & LASSP

**Rapid framing (SE, IR closed)**
1. **select storage cap C1**
2. **Open IR switch (Frame integration begins)**
3. **Deselect Storage cap (Integration ends)**
4. **Close IR**

**repeat with C2 ... C8**

**Pixel Read (open SE, close RE)**
**Connect storage caps in sequence with output**
**Pixels and caps both independently addressable**



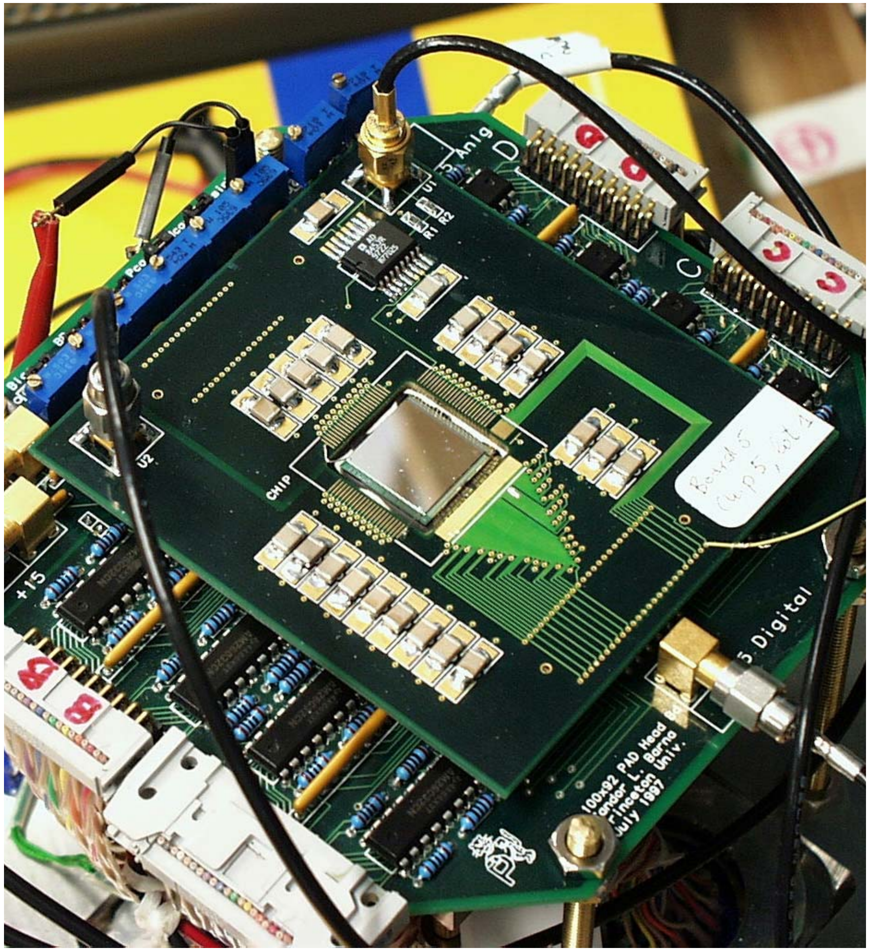

C1 - C8: 130 fF

CORNELL

# Cornell 100x92 Analog PAD

CHESS & LASSP

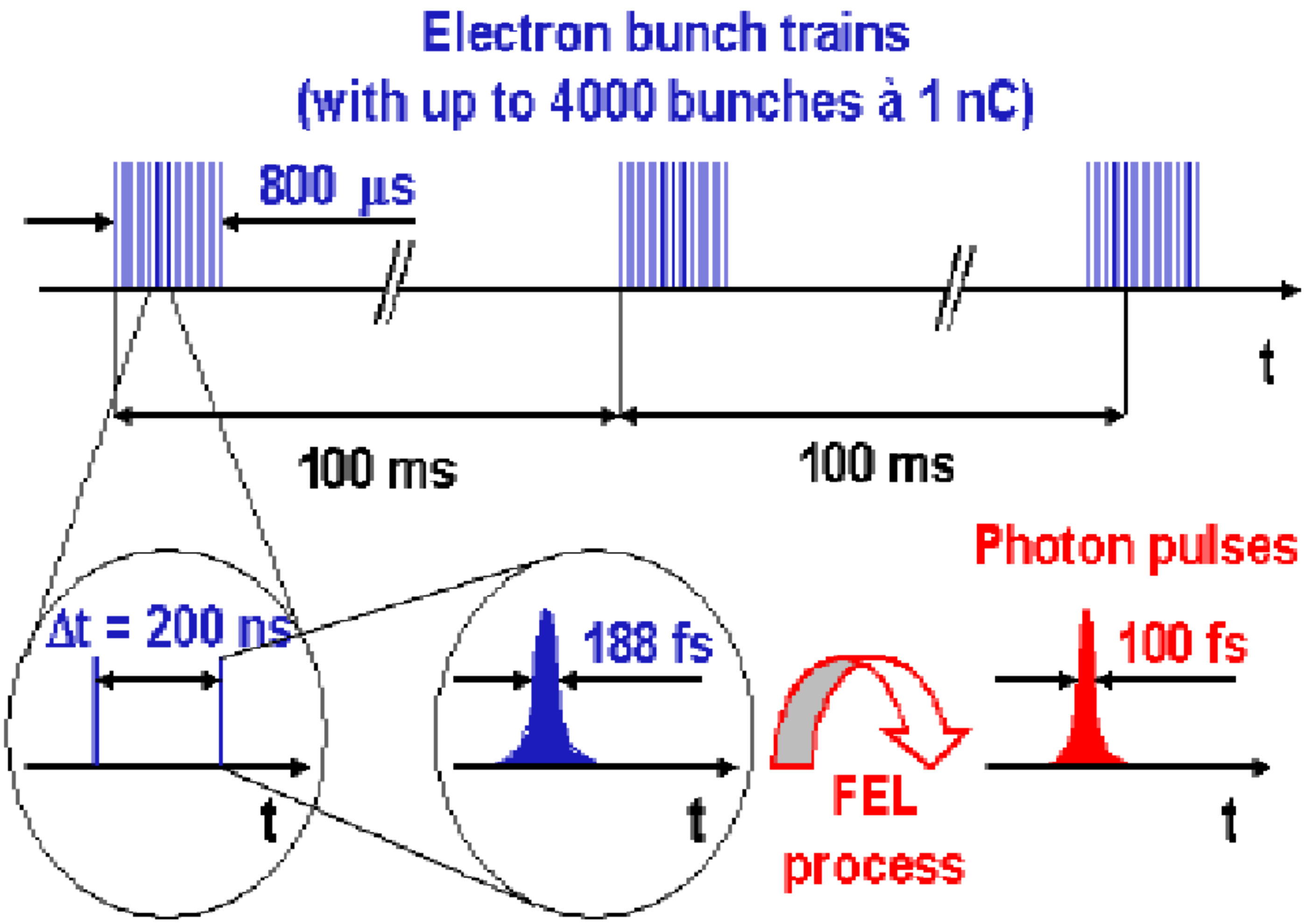
**1.2 μm HP CMOS process (MOSIS)**
**(Linearized Capacitors)**
**15 x 13.8 mm$^2$ active area; 100x92 pixels**
**150 μm square pixel**
**300 μm thick, high resistivity Si diode wafer (SINTEF)**
**120 μm solder bump bond (GEC-Marconi)**



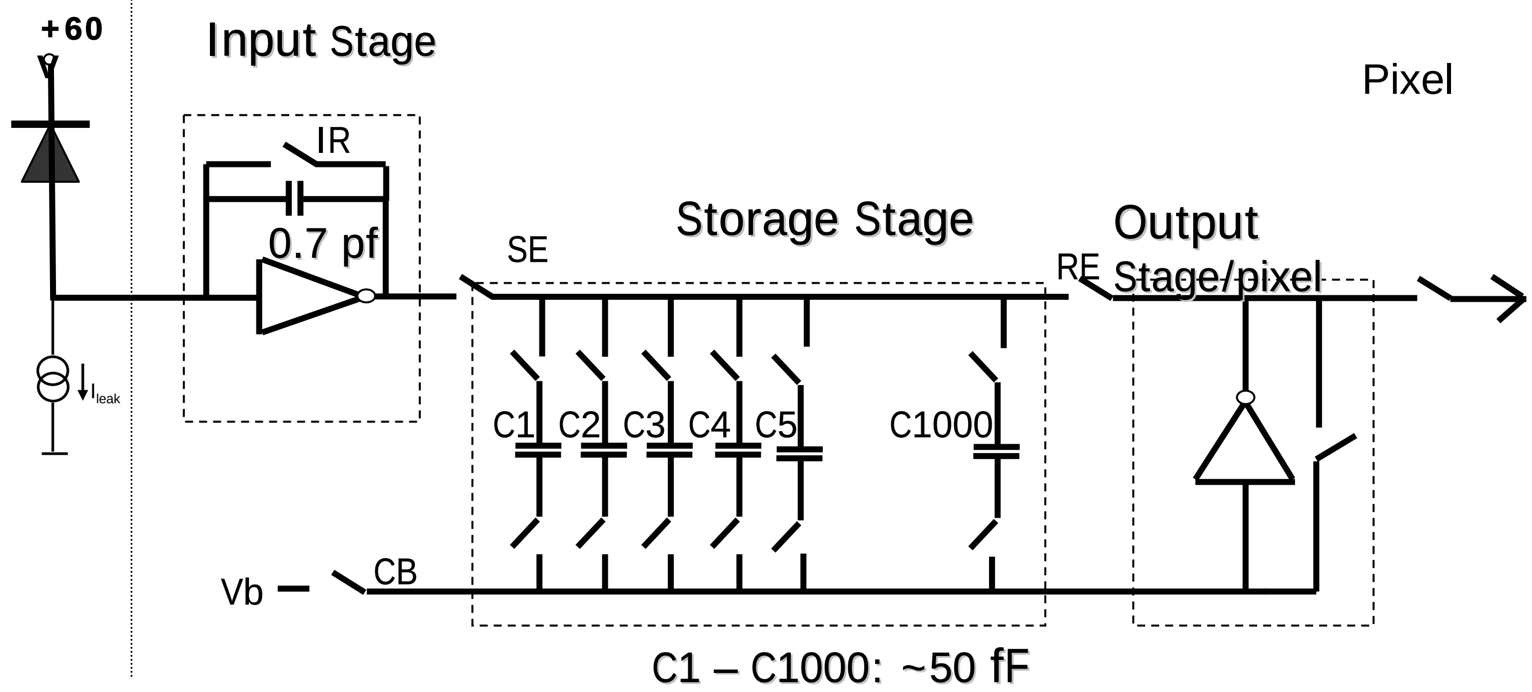

**100x92 PAD developers include:**
- **Sandor Barna**
- **Eric Eikenberry**
- **Alper Ercan**
- **Sol Gruner**
- **Matt Renzi**
- **Giuseppe Rossi**
- **Mark Tate**
- **Bob Wixted**

G. Rossi, *et al,* J Synchrotron Rad. (1999). **6**, 1095-1105.

# Tesla FEL


Electron bunch trains
(with up to 4000 bunches à 1 nC)
800 µs
t
100 ms
100 ms
Photon pulses
Δt = 200 ns
t
188 fs
t
FEL
process
100 fs
t

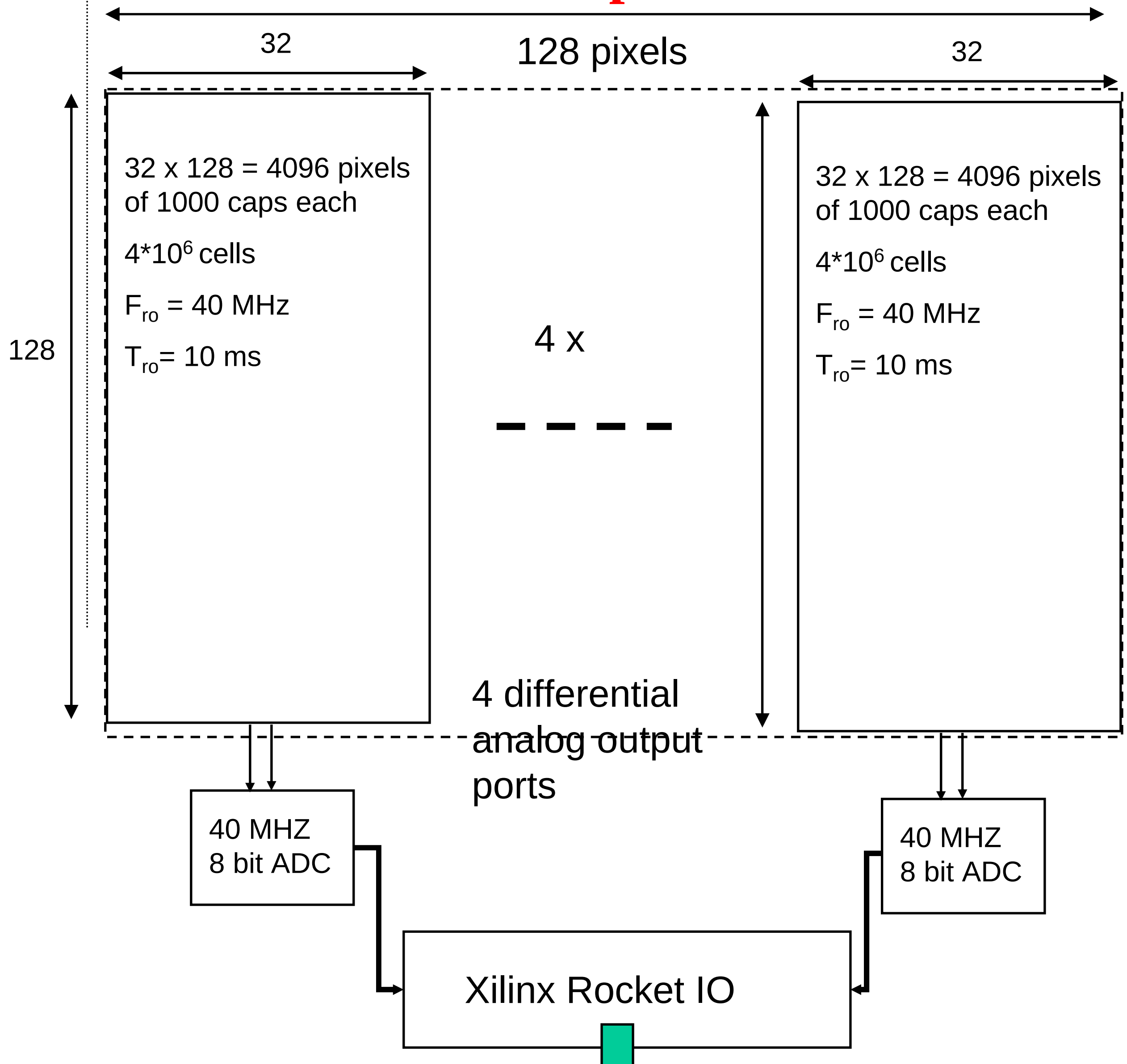
# Pixel Chip for Tesla FEL




Rough dimensions:

~ 20 um$^2$ / cap cell -> 1000 caps (frames) ~ 140 x 140 um$^2$
-> Pixel size ~ 160 x 160 um2

# Pixel Chip for Tesla FEL



# Detectors for Current and Future Synchrotron Light Sources

1. Introduction

2. Existing Detector Systems
   Rapid
   Mythen
   Pilatus

3. Future Detector Systems
   Pilatus XFS
   APAD
   Analog Hybrid Pixels for FEL Apps

4. Summary and Conclusions

# Time scales for detector developments

| | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rapid | MWPC Developements | | | | | First Beam Tests | | | Rapid 1 | | | | | Rapid 2 @SPring 8 | | | | | |
| Frelon | CCDs Since 1980 | | | | | | | | | | | | Commercially available | | | | | | |
| Pixels @CERN | | Omega 3 Chip WA97, 300kPix | | | Delphi Vertex 613 kPix | | | | | | | Alice Chip | | | | | | | |
| Medipix | | | | | | Medipix 1 64 x 64, $.17^2$ | | | | Medipix 2 (IBM) 256 x 256, $.05^2$ | | | | Medipix 2 Rad Hard | | | | | |
| CMS Pixel @PSI | | | | | PSI 30 22 x 30 | | | | | | PSI 46 (DM) 54 x 53 | | PSI 49 (IBM) 54 x 53 | | | | | | |
| Pilatus | | | | | | | | | | P I (DM) 44 x 78, $0.21^2$ | | P 1M $10^6$ Pix | | P II Chip PSI50 60 x 97, $0.17^2$ | | | | | |
| Mythen | | | | | | | | | M I (DM) 128, 0.05 | | M I 12 Mod 16 k Strips | | | M V2 (IBM) | | | | | |
| APAD | | | | | | | APAD 100 x 92 | | | | | | APAD Push Pull | | | | | | |
| Detectors for FEL | | | | | | | | | | | | | | | | | | | |

# Summary

Single photon counting pixel detectors are becoming more and more mature
-> much higher local and global count rates.

Next generation of single photon counting detectors are currently in the design phase ( Medipix 3? and Pilatus XFS)
Higher frame rates resp. higher spatial resolution

Next generation of SR sources will require analog integrating pixel detectors

Developments take roughly 7 years

If we want to be ready, we have to start now

PAUL SCHERRER INSTITUT

PMD05 Workshop

Paul Scherrer Institut | CH-5232 Villigen PSI | Phone +41 56 310 21 11 | Fax +41 56 310 21 99

- Home
- Scope
- Programme
- Invited Speakers
- Registration
- Accommodation
- How to get to PSI
- SLS Home
- SLS Beamlines
- SLS Users Meeting 2005

Updated:
23.06.2005


## PMD05:

## Workshop on Pixel- and Microstrip-Detectors for Synchrotron Radiation

Paul Scherrer Institute
October 18-19, 2005

**Contacts:**

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detws.web.psi.ch

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