Imaging of Particles in the Pico-second Range

Delayline detectors are true counting, imaging particle detectors with time resolution:

- time slice images can be taken with time windowing down to below 100 ps
- true single counting system, thus high linearity in hit rate response
- brilliant signal / background ratio and very high sensitivity

Applications:

- time of flight analysis for electrons and ions
- time correlated or coincidence photon and particle imaging
- gated imaging and spectroscopy tasks for X-ray spectroscopy, electron spectroscopy
- true counting imaging tasks with large areas up to 120 mm detection size

Methods and instruments equipped with delay line detectors:

- in electron energy analyzers and time of flight analyzers (XPS, UPS, EELS)
- in photoemission electron microscopy (time-of-flight PEEM)
- in medium energy ion scattering (MEIS with time of flight analysis)
- in atom probe tomography/microscopy (APT, 3D-AP)
- in X-ray absorption-emission spectroscopy (XAS, XES)
- in X-ray pico-second imaging by means of time gating for contrast enhancement
- in fluorescence lifetime imaging (FLIM, FLIM-FRET)
- in ion mass spectroscopy methods (MALDI-TOF, TOF-SIMS, FRES, COLTRIMS)
- in low energy electron diffraction (LEED, femto-Ampere-LEED)
- in imaging of ultra-cold quantum gases in expansion, operates in intense burst mode

High speed camera systems:
(typ. 1/10000 sec., sequentially sampled frames)

Delayline detectors:
(typ. 1/10000000000 sec., but all single events of all relative times measured simultaneously sampled over many periods)

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Application examples for Surface Concept DLDs

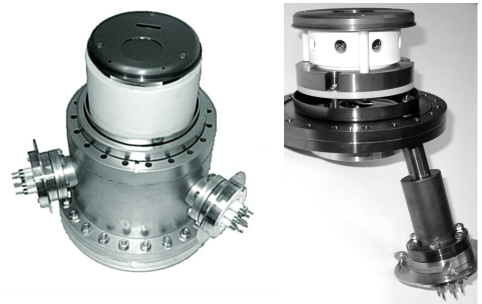
Time-of flight experiment for photo-cathode design and characterization for Free Electron Laser applicatons

120 mm DLD for MEIS with ToF-analysis

Electron image detector for time-correlated UPS in electron analyzer

Electron image detector with mini lens for parallel imaging UPS and spin detection behind the lens

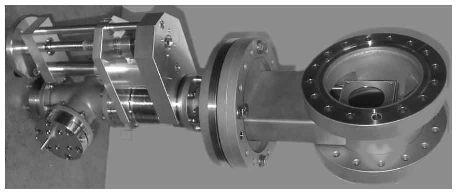
High energy XPS electron image detectors, the left layout includes a spin detector (MOTT)



4-fold DLD with 80 mm diameter and precise positioning stage x, y and rotation for time resolved imaging of intense neutral particle bursts out of ultra-cold quantum gases in expansion (1 million atom hits within 30 ms)

X-ray DLD encapsulated with polyimide window for contrast enhancement in imaging from a pico-second source by time gating on the peak

Interchangeable electron image detector for electron microscopy with a conventional imaging detector behind



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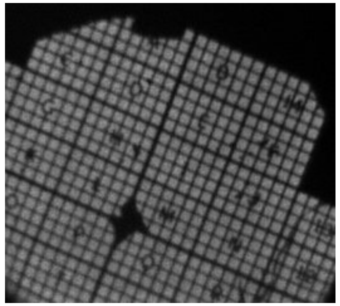
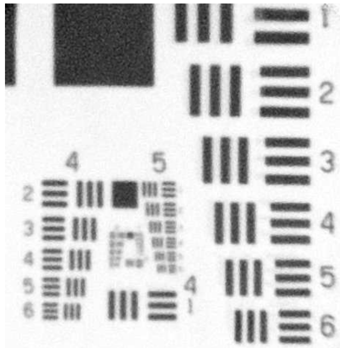
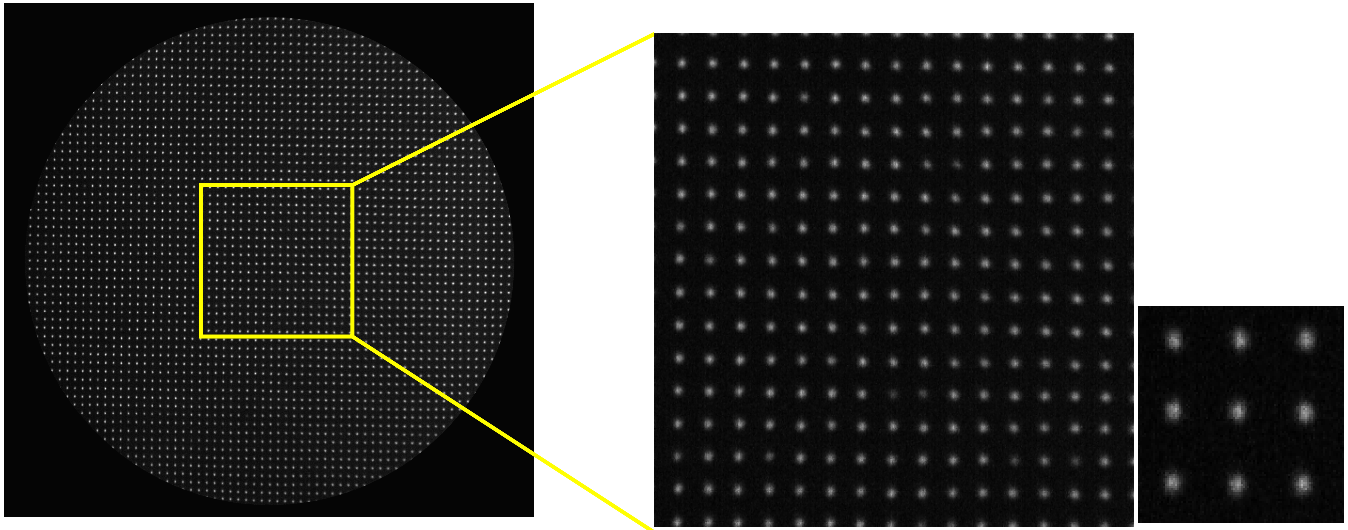
Achieved Performance with DLD Systems

- **Permanent random rates improved for DLDs from the 10^5 CPS range to above 5*10^6 CPS**
- **A lab test setup delivered already 10^7 CPS random**
- **Pixel resolution of below 10 µm reached for large DLDs**
- **Relative time resolution of 13.7 ps**





dot mask, 3 mm in front of the DLD,
pitch 700µm, 150µm holes



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Delay line detector purpose

A delay line detector (DLD) is a position (x, y) and time (t) sensitive microchannel plate area detector for imaging of single counted particles with or without temporal resolution in the pico-second range.

The (x, y, t) histograms are gathered over very many excitation cycles of the particle generating process as the system is a single counting device. Particle images can be collected from continuous running processes with randomly incoming particle sequences without time correlation as well.

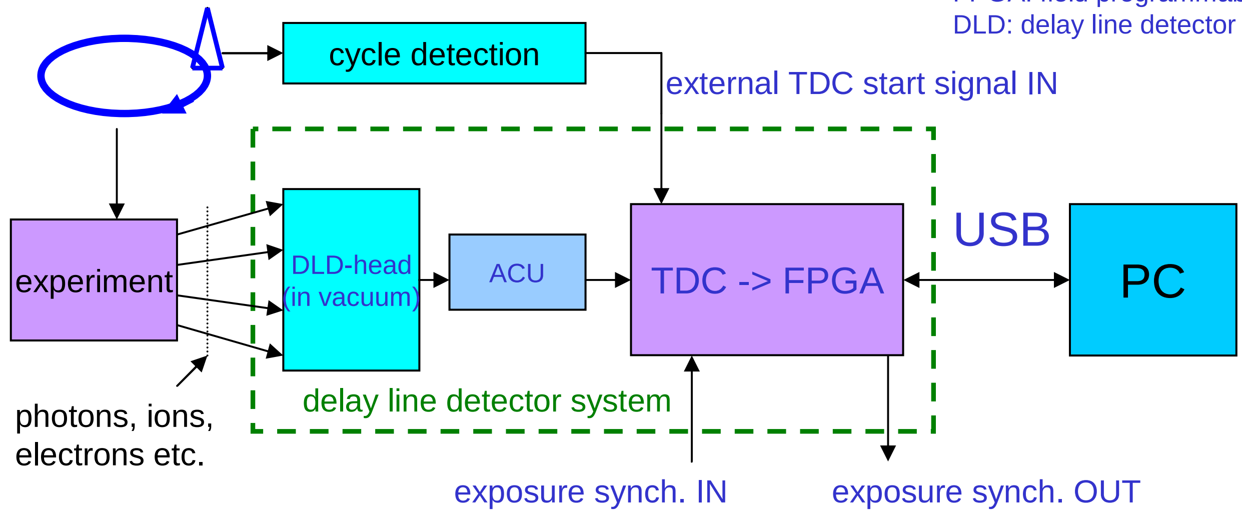
The dead time of these single counting devices are as small as 10 ns – 20 ns, which enables even live imaging with highest sensitivity, collecting high count rates of randomly incoming particles in the millions counts per second range, as well as imaging with a very high dynamic range of 10^6.

Unlike for other pico-second imagers, delay line detectors collect all incoming particle hits continuously without any gate window duty cycles, thus (besides the device dead time limits) all hits are collected even when they represent random time positions within the excitation cycle time period.

Delay line detector data acquisition functionality

ACU: fast pulse processing electronics
TDC: time-to-digital converter
FPGA: field programmable gate array
DLD: delay line detector for subsequent single particle detection (x,y,t)

Cyclic running excitation source



On the PC:

- event coordinates (x, y, t) are counted up into 2- or 3-dimensional histograms building an image or a stack of (x, y) images for different times t. For 3D, the time t should be measured with respect to the “external TDC start signal”.

- The time duration for event data collection is called an “exposure run” and spans usually over very many cycles of excitation.

- Exposure runs are in general not and do not need to be synchronized with the source cycles.

- 2D-histograming, i.e. (x, y) single imaging, is also possible, therefore the external start signal can stay unused and the excitation source may work in a cyclic or in a continuous mode.

Exposure functionality:

- Any measurement (or exposure run) starts when the FPGA is ordered from the PC application to measure and to send data for collecting a new image histogram or time resolved image stack within a well defined measurement dwell time. Live 3D image frame rates can reach 5 3D-frames per second.

- The exposure run start can be specified to wait for the next “exposure synch. IN” which is in general not required to be in phase with the excitation cycles. As well, the user can define a sequence of image stack exposures, synchronized to that signal without any USB down communication time delay overhead between exposures within a sequence.

- The exposure run lasts exactly the time in milliseconds that has been specified by the PC application before the exposure start order takes place. It ends when a quartz controlled counter reaches the end of the specified duration time window (exposure duration range: 1ms – 600h).

- Within the exposure run duration, the FPGA is pre-conditioning and sending event coordinate data (simultaneously to running measurements) via USB and signalizes the end of the exposure run via USB and additionally always in real time with a TTL output pulse at “exposure synch. OUT”

The user must*:

- provide particles to the DLD input at a rate within the specifications: multiple hits of single particles of at least 10 ns time distance, but in average only with a random rate of below 2-8 million hits per second (maximum depends on the individually used DLD type)

The user can, but do not need to*:

- provide an “external TDC start signal IN” for time histogram and/or time resolved image measurements in phase to the source cycle
- provide synchronization signals for exposure run controlling

**** The user must take care about the correct use of the appropriate initialization settings for the used operational mode, respectively.***

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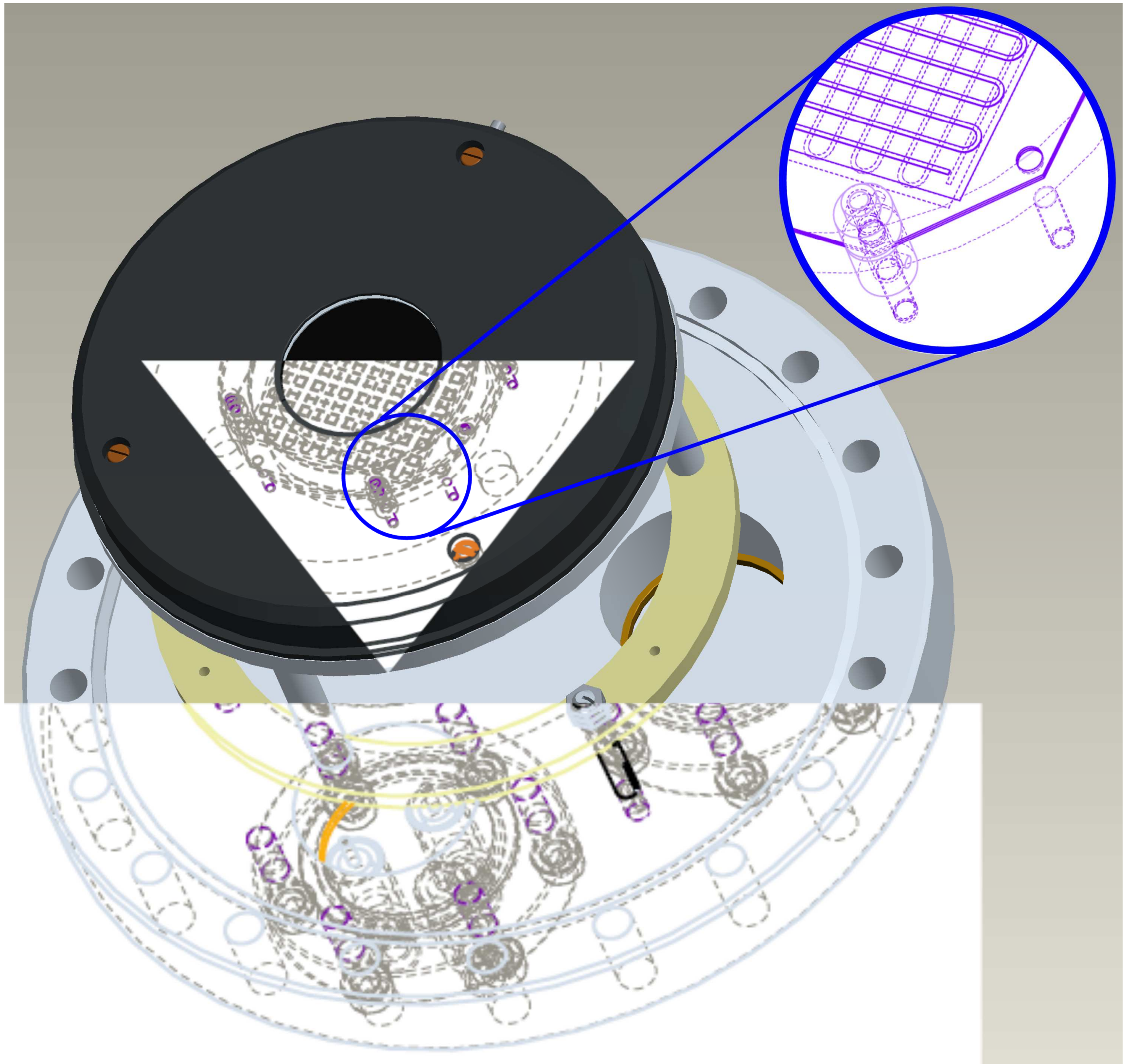
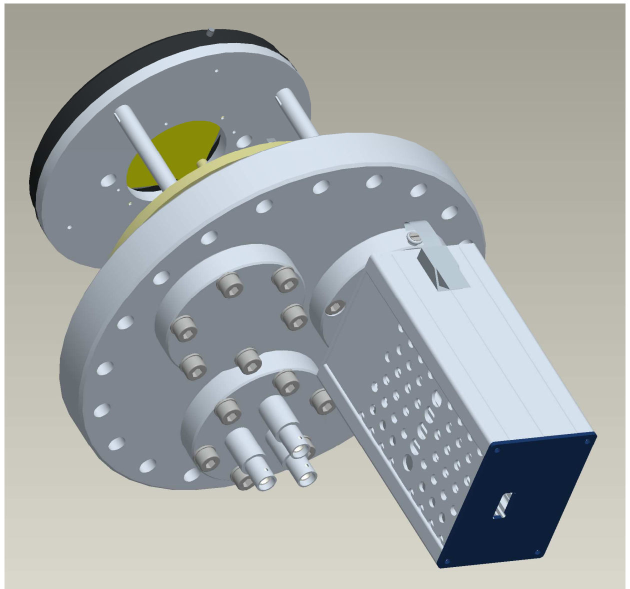
Delayline Detector Layout





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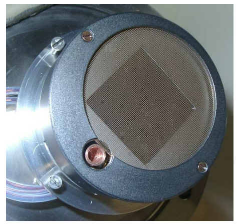
Custom Delayline Detectors

Surface Concept is an expert in custom designed delayline detectors. We build all parts of delayline detectors (active areas, housings, mounting flanges) adapted to the customer's application.

Some of our custom designed detectors out of the last few yea

- DLD 120120
  - active area: 120x120mm²
- special sized DLD 1818
  - active area: ∅18mm
  - CF40 mounting flange
  - also with interchangable system
- DLD4242H9
  - hybrid design of a DLD and a 9-segment-detector
  - active area: 42x42mm²
- High Voltage (HV)DLDs
  - base potential of up to -15kV
- HV DLD/ MircoMott Detector Combination
  - HV DLD combined with a micromott detector
  - base potential up to -15kV
- DLD3030-4quad
  - 4-Quadrant Delayline Detector for multiple hit detection
  - active area: 60mm x 60mm
- Encapsulated X-Ray DLDs and EUV DLDs



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The Origin of the Delayline Readout for MCPs

(Nuclear physics: Spark chambers and gas proprtional counters:
G. Charpak et al., Nucl. Instrum. Methods 65, 217 (1968))

Orange type beta spectrometer GSI Darmstadt
H. Keller, G. Klingelhöfer, and E. Kankeleit.
A position sensitive microchannelplate detector using a delay line readout anode.
Nucl. Instrum. Methods A, 258, 221-224 (1987).

X-ray/UV astronomy, Space Science Lab Berkeley, GALEX, COS, FUSE missions,
M. Lampton, O. Siegmund, and R. Raffanti.
Delay line anodes for microchannel-plate spectrometers.
Rev. Sci. Instrum., 12, 2298-2305 (1987).

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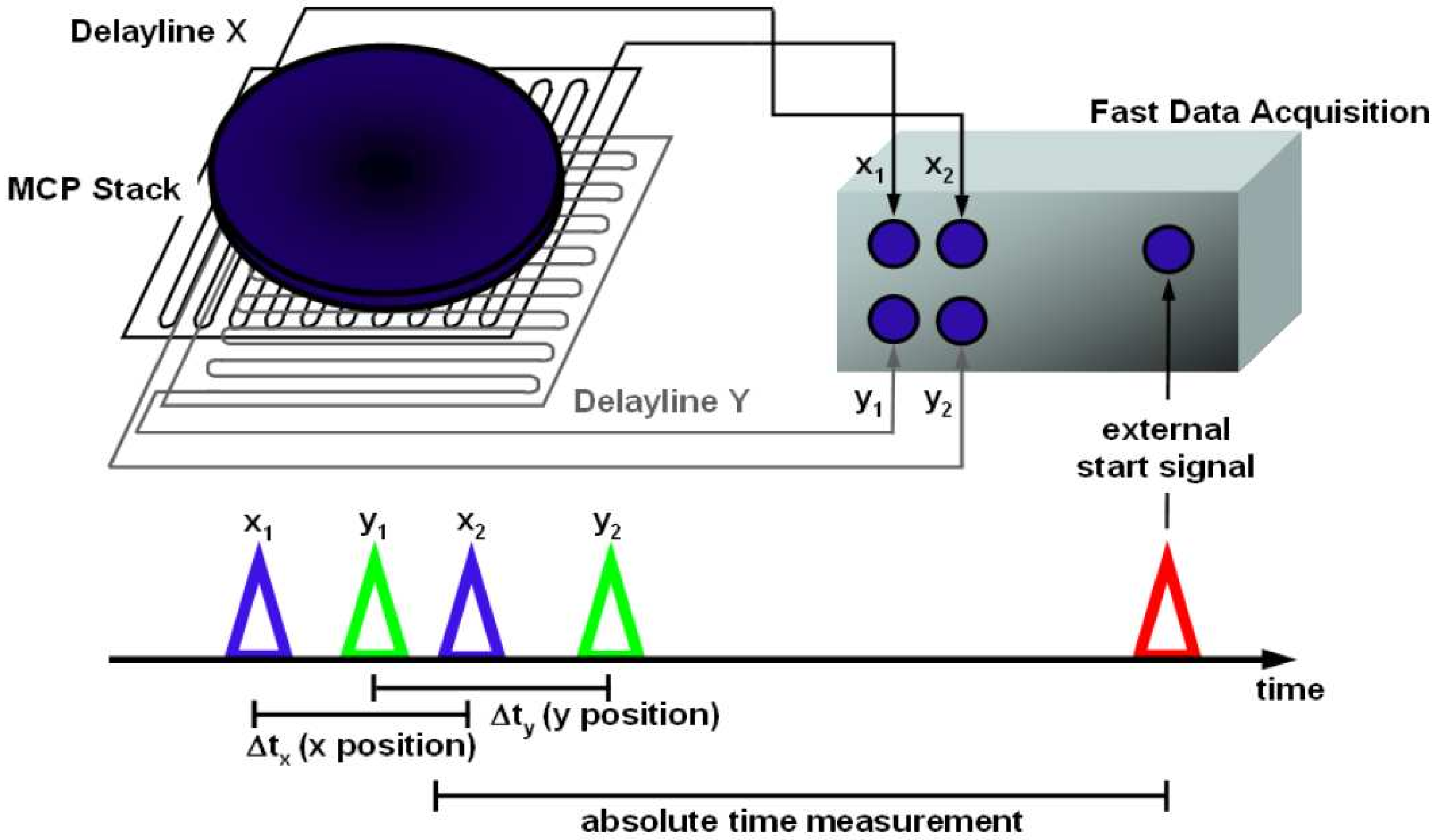
Delayline Readout of MCPs



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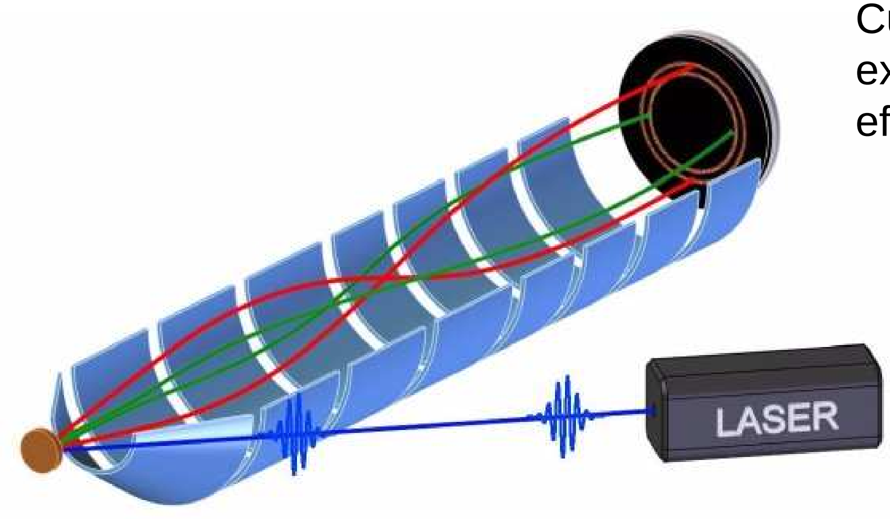
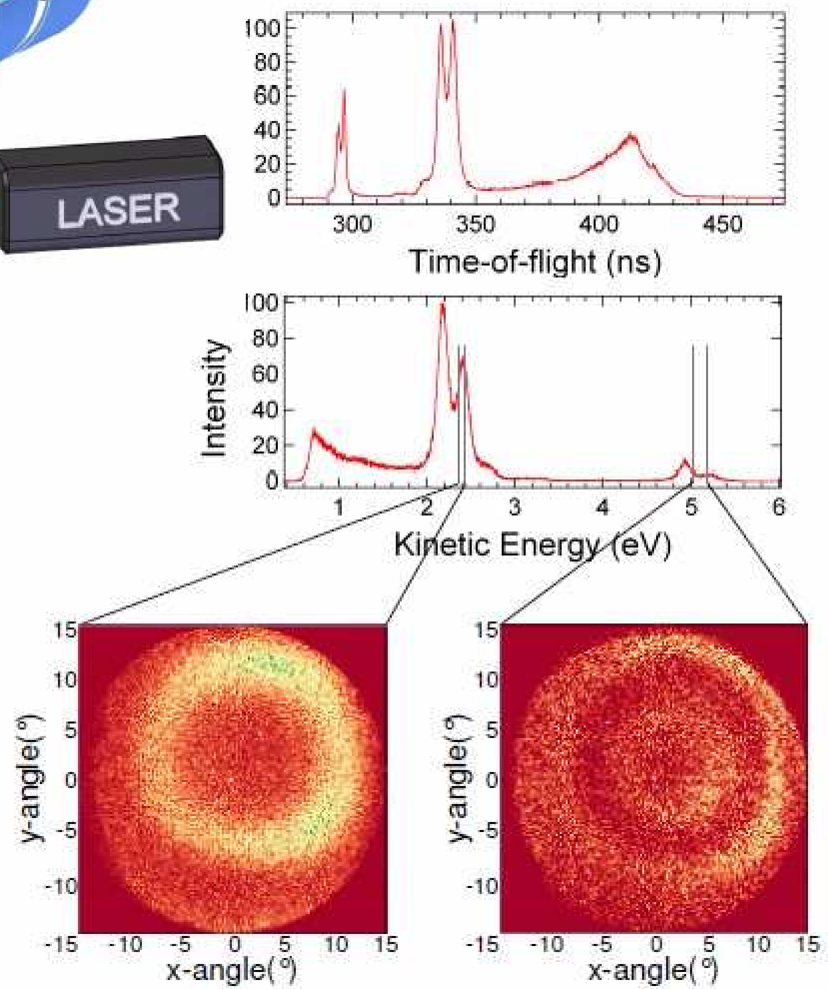
Time of Flight Spectrometers

Cu (111), electron emission and Shockley surf. states
excitation:UV: 4.68 eV (265 nm), IR: 2.10 eV (590 nm)
effective masses m*(n=1) ≈ 0.4 and m*(n=0) ≈ 1.1





upper panel: *Typical time-of-flight spectra recorded at normal emission ±1 ° and deduced energy spectra, measured in normal emission*
lower panel: E*lectron distribution on the detector for the marked energy range* (left picture) *Shockley surface state* (right picture*) inner circle : Shockley surface state (n=0); outer circle: n=1 image-potential state*

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Martin Teichmann,
Martin Weinelt,
Max Born Institute,
Berlin

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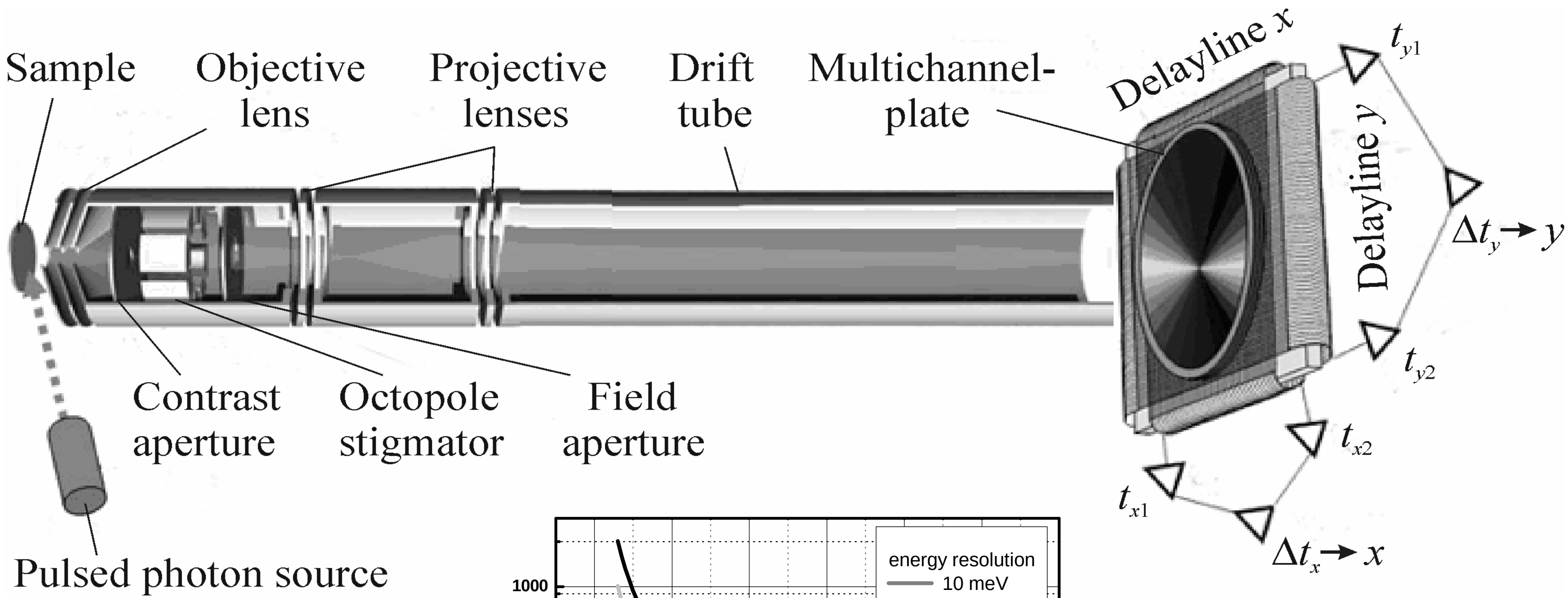
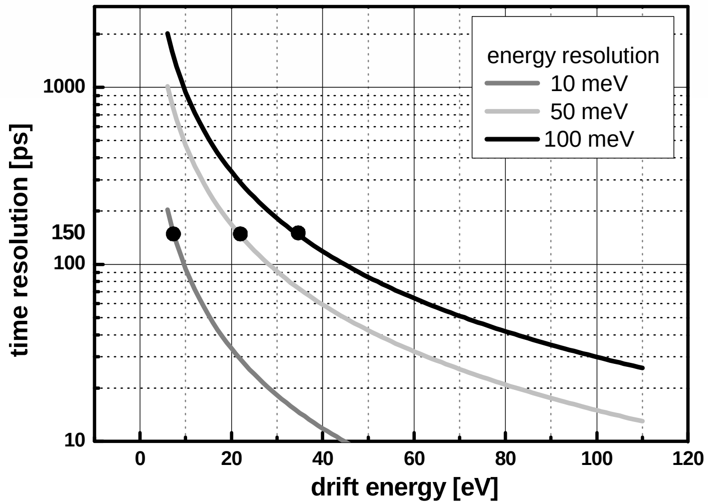
Time of Flight Photoemission Electron Microscopy





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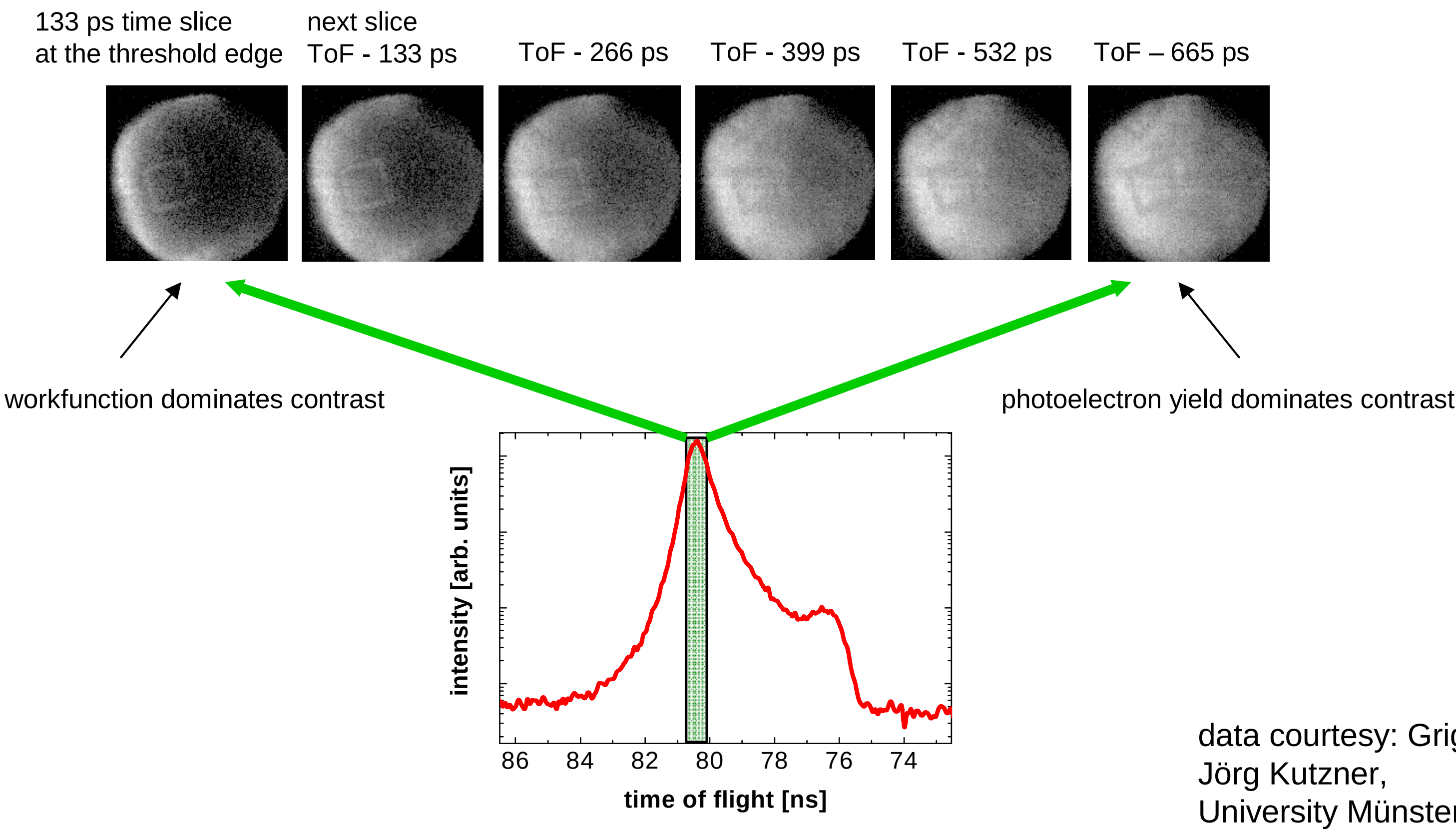
Temporal Resolved Imaging with Delay Line Detectors

Observation of a workfunction contrast change crossing the photoemission threshold edge from a Ni-Fe frame (25µm size) at a copper surface. It was measured using a 1kHz pulsed femtosecond VUV laser source (hν = 27eV) for excitation. Each time slice of 133 ps corresponds to a kinetic energy window of 0.15 eV given by the used settings of the ToF instrument (drift energy of 50 eV).

The same time resolution would enable an energy resolution of 0.014 eV @ 10 eV drift energy, that was already proven for high quality imaging with the same instrument.



data courtesy: Grigorios Tsilimis,
Jörg Kutzner,
University Münster, Germany

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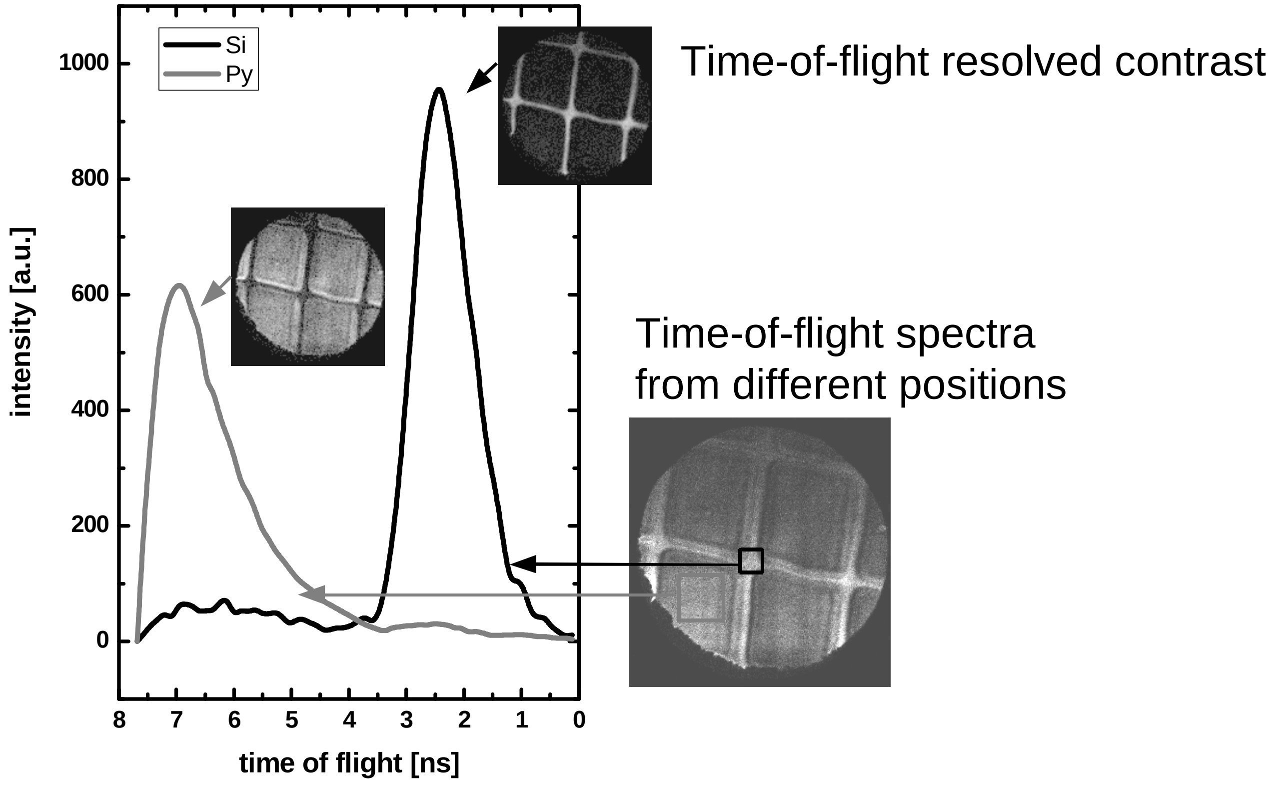
ToF Spectro-Microscopy / Micro-Spectroscopy



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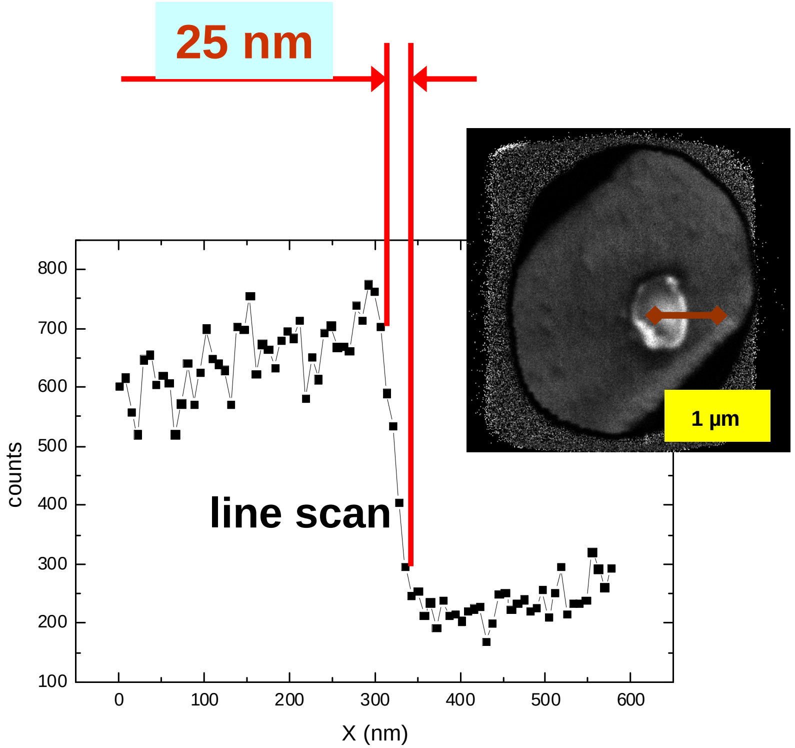
Time of Flight Photoemission Electron Microscopy

The use of dalayline detectors does not restrict the intrinsic spatial resolution of a state-of-the-art PEEM:

A superior spatial resolution could be achieved using a delayline detector as imaging unit at the FOCUS-IS-PEEM (HBO100 UV-excitation); Right: The line scan crossing the edge of a sub-micron size particle at a Pd strip demonstrates at least 25 nm in spatial resolution; due to the very low noise measurements using delayline detectors, even at weak contrasts one may measure reliable in the high resolution mode (see small structure elements at the Pd stripe).



data courtesy: Nils Weber, Focus GmbH, Hünstetten, Germany

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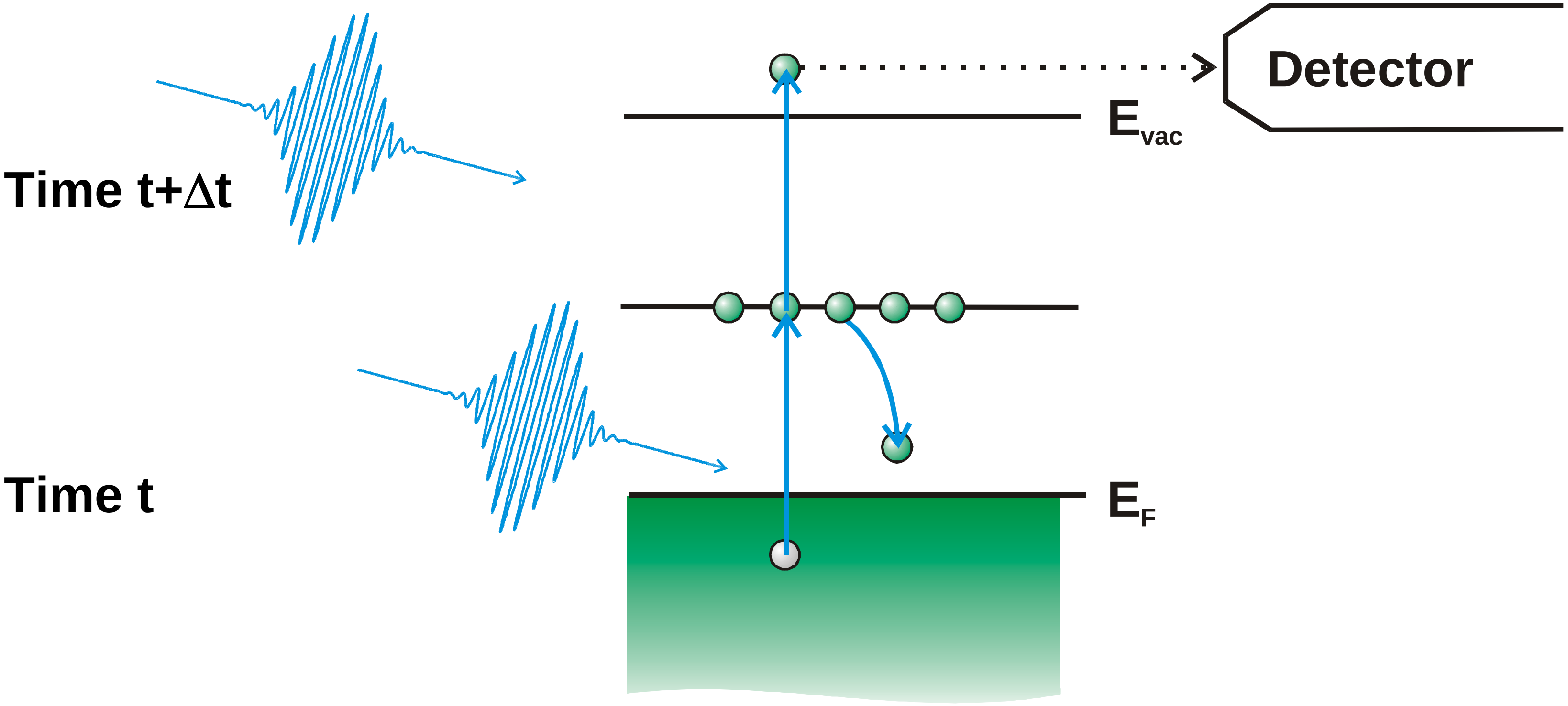
Imaging in Pump-Probe Experiments

Time-resolved two-photon-photoemission



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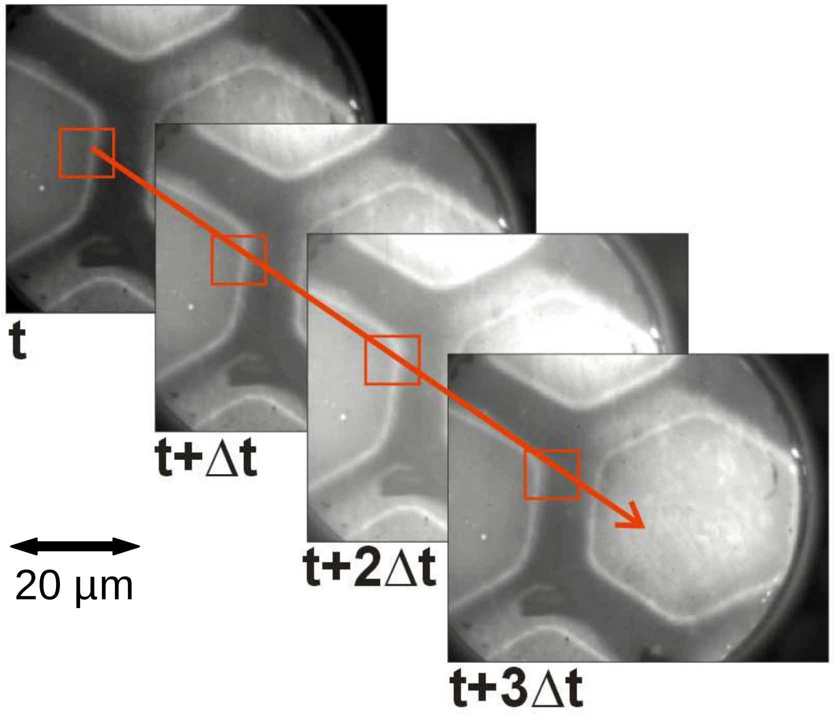
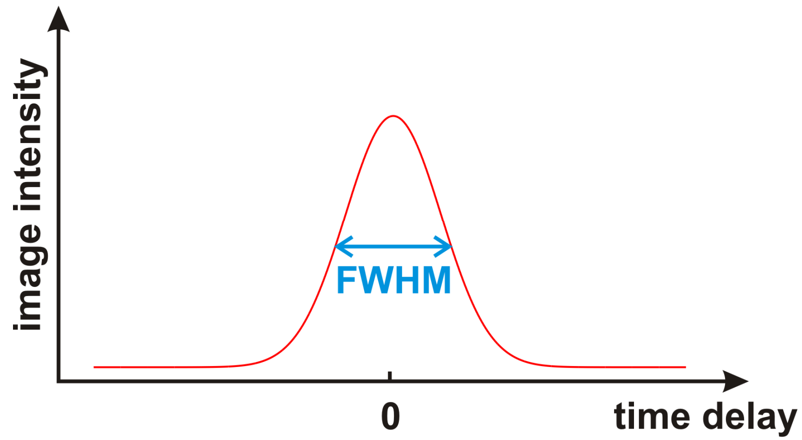
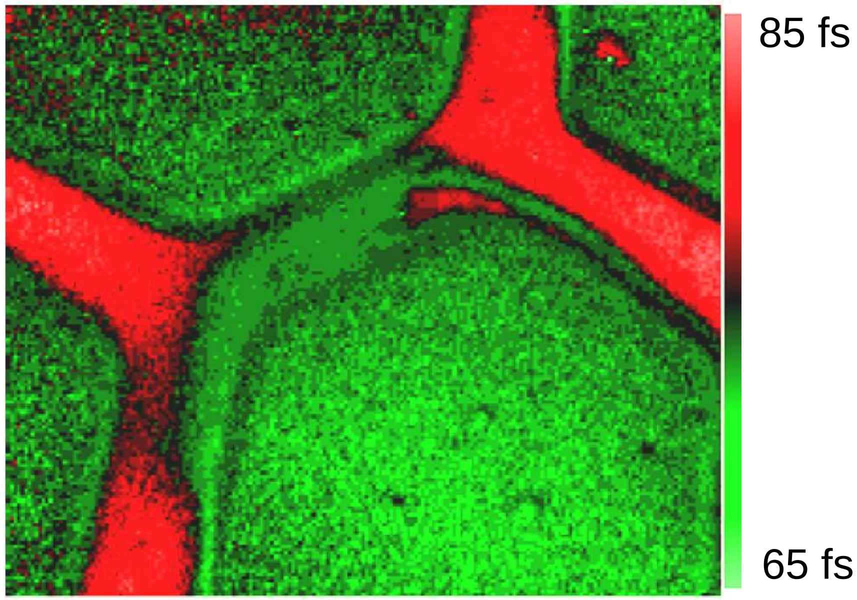
Lifetime Mapping with fs-Laser Pump Probe





Lifetimemap



[M. Bauer, Appl. Phys. B 74, 223–227 (2002)]

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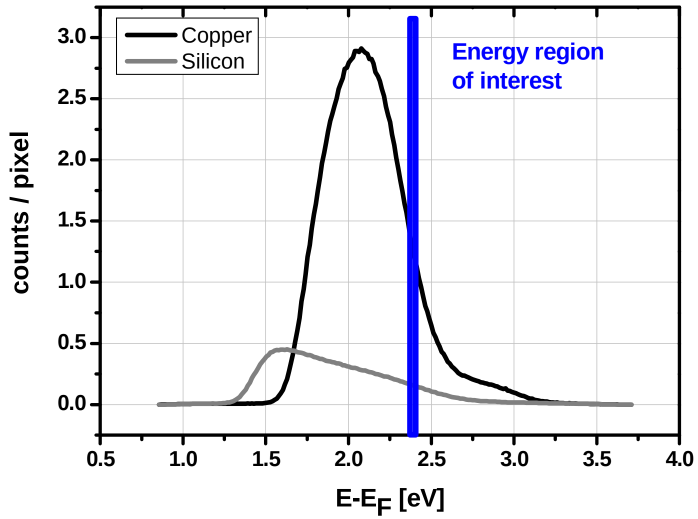
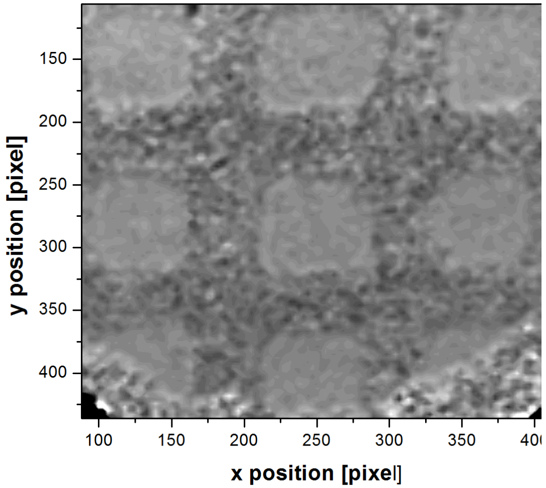
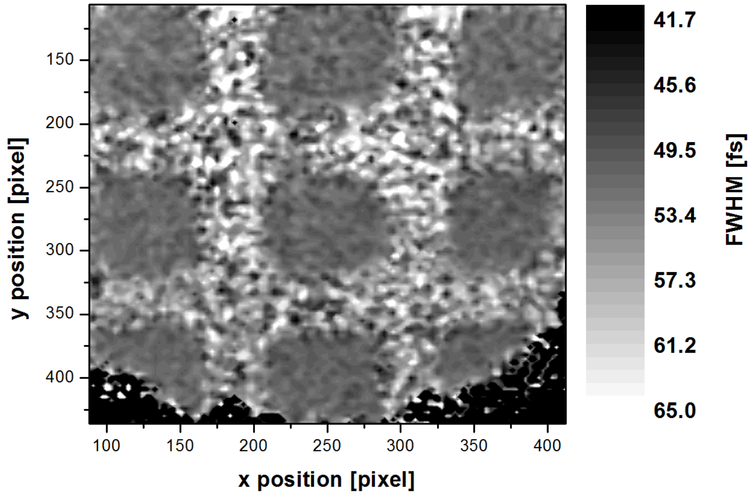
Improvement of Lifetime Mapping by ToF Imaging







Christian Schneider, Martin Rohmer, Martin Aeschlimann, University Kaiserlautern

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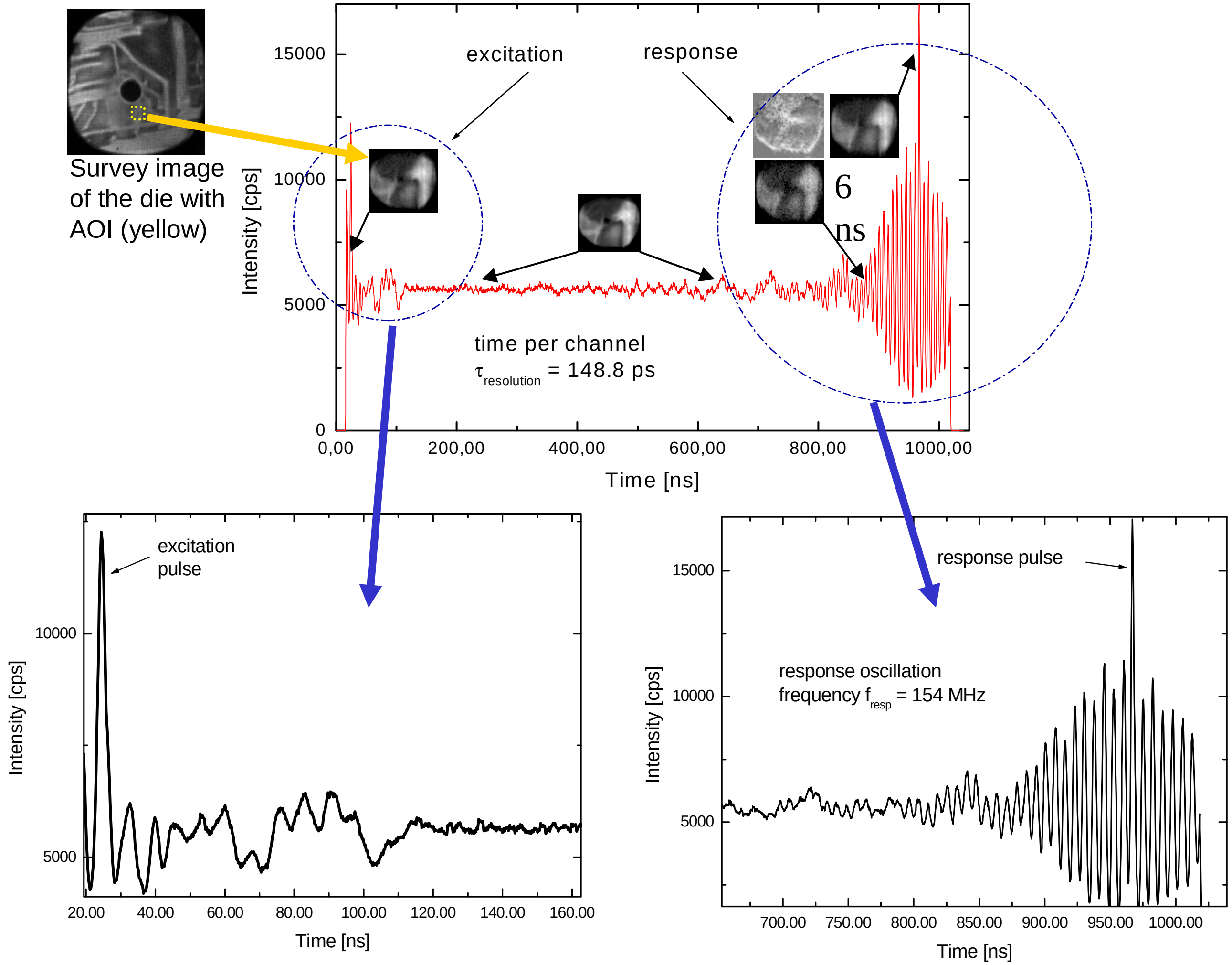
Chip Time Response Test by Electron Microscopy

Testing the pulse response of a wire junction at a micro-chip surface:



The principle of the detector data acquisition reveals a unique ability to group the x,y,t data triples in every possible combination. While a measurement is running or after a complete acquisition was taken; every valid subsequence order can be used to observe the signal evolution in a free accessible area of interest (AOI).

A die test with PEEM demonstrates the power of this method:
While a small voltage pulse is electrically coupled into the die, the Mini-PEEM observes a certain area of interest at its surface. The photo-electron excitation has been chosen continuous using a Hg-lamp. All measurements at the delayline detector are referenced with respect to the initial pulses and spatial resolved the 3D-detector signal responds with small changes in the 3D histogram of data.
The time variation of a small 2D-cut in space is shown directly at an electrical junction within the circuit. The initial pulse as well as the circuit response at this position are clearly seen in the data set. The complete acquisition time here was about 15 min.

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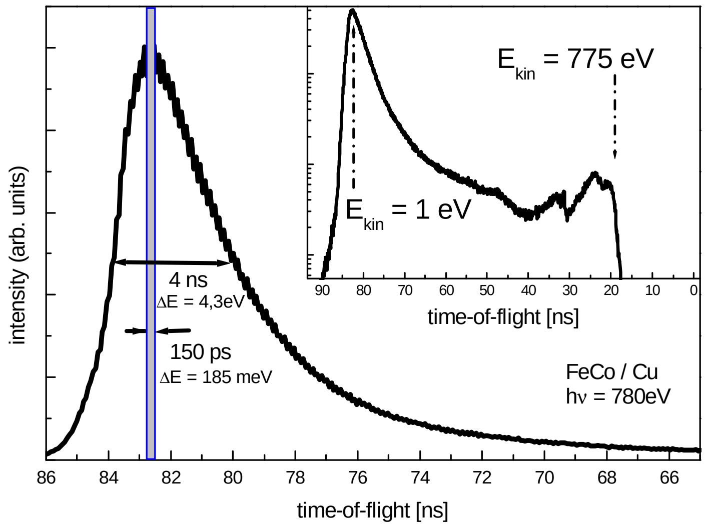
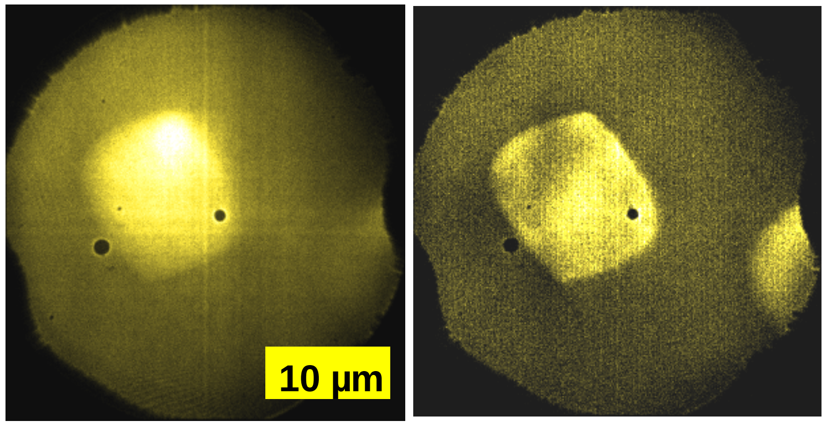
„Crono“ Correction in ToF-PEEM

Time-of-flight spectromicroscopy

chromatic selector



TOF –filtered image



no Δt selection **Δt = 150 psec**

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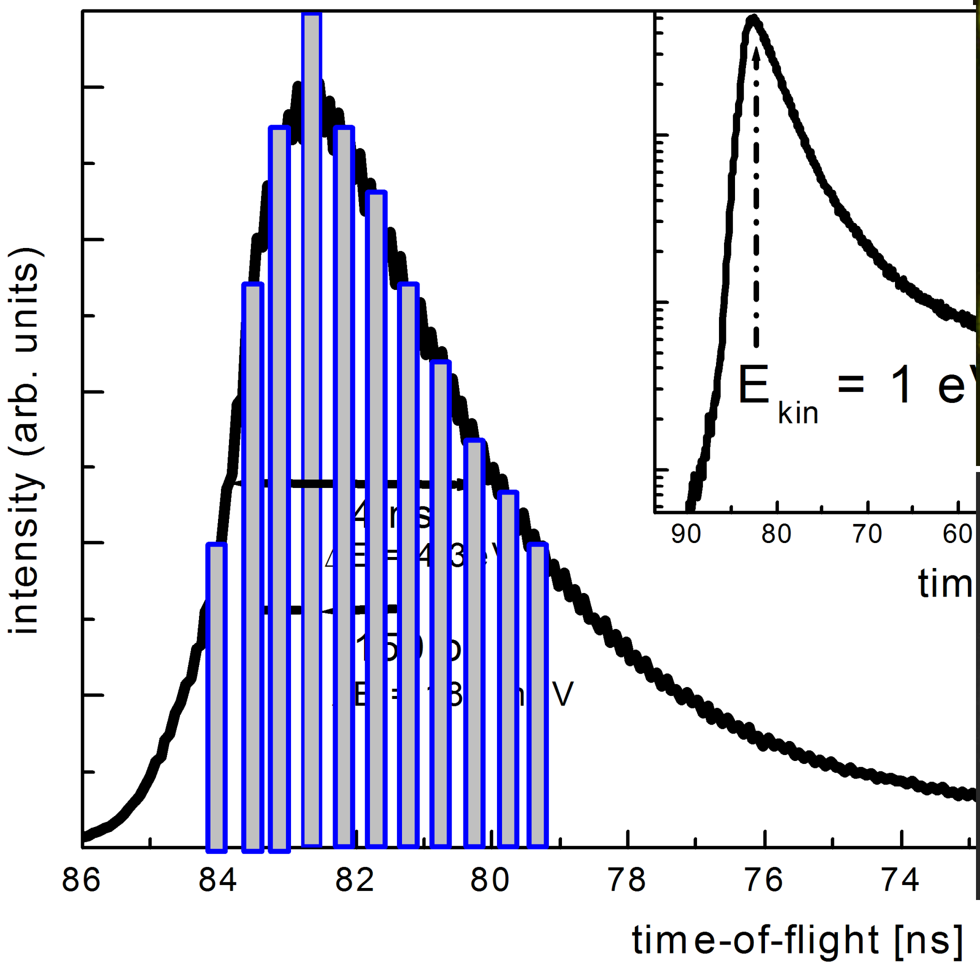
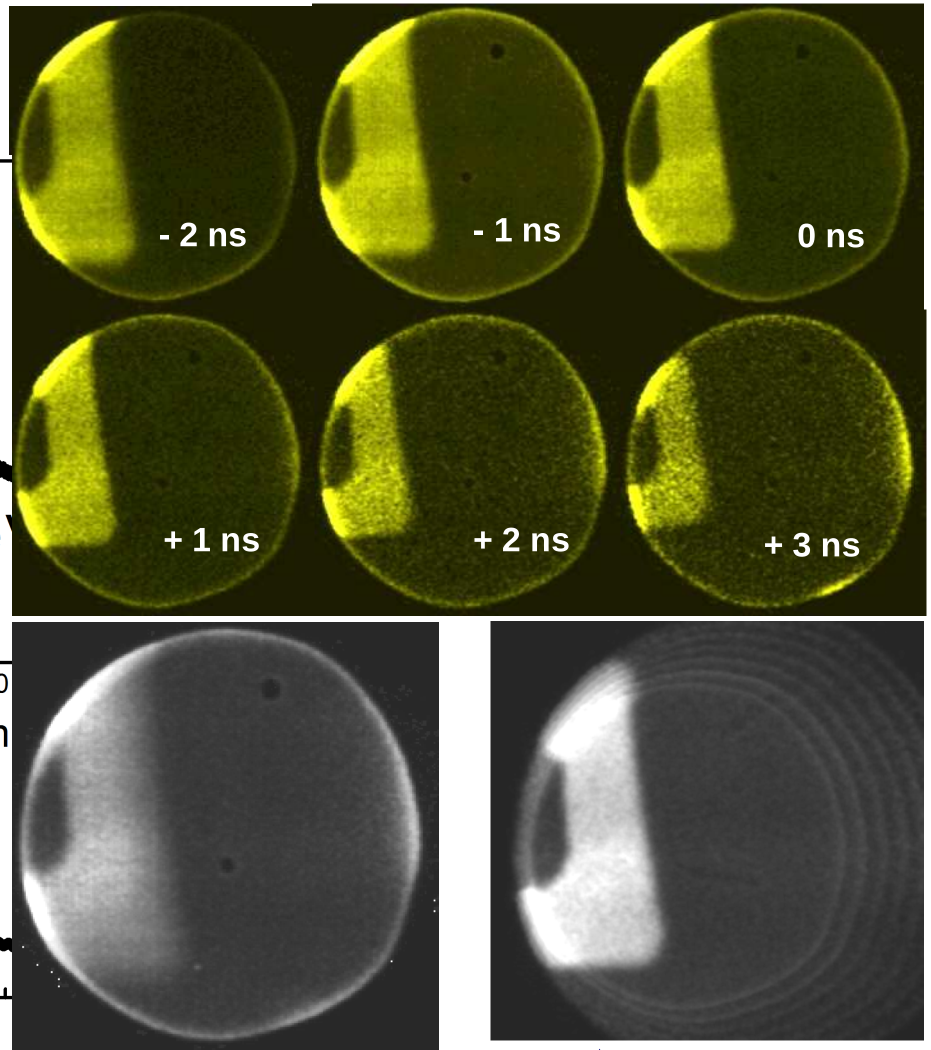
„Crono“ Correction in ToF-PEEM

Generation of many partial images ⇨ „*time - slices*“ ⇨





without correction

with correction
i.e. lateral rescaling

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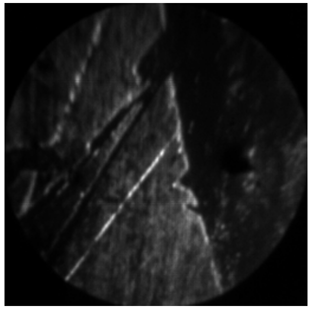
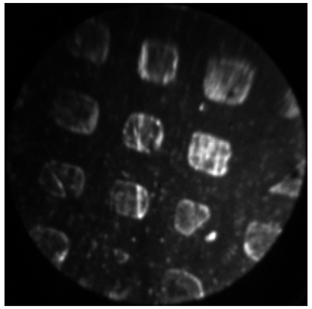
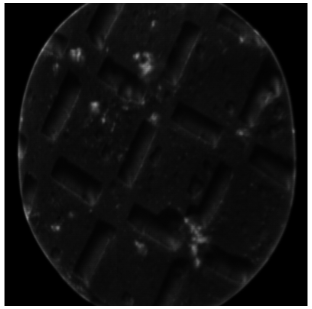
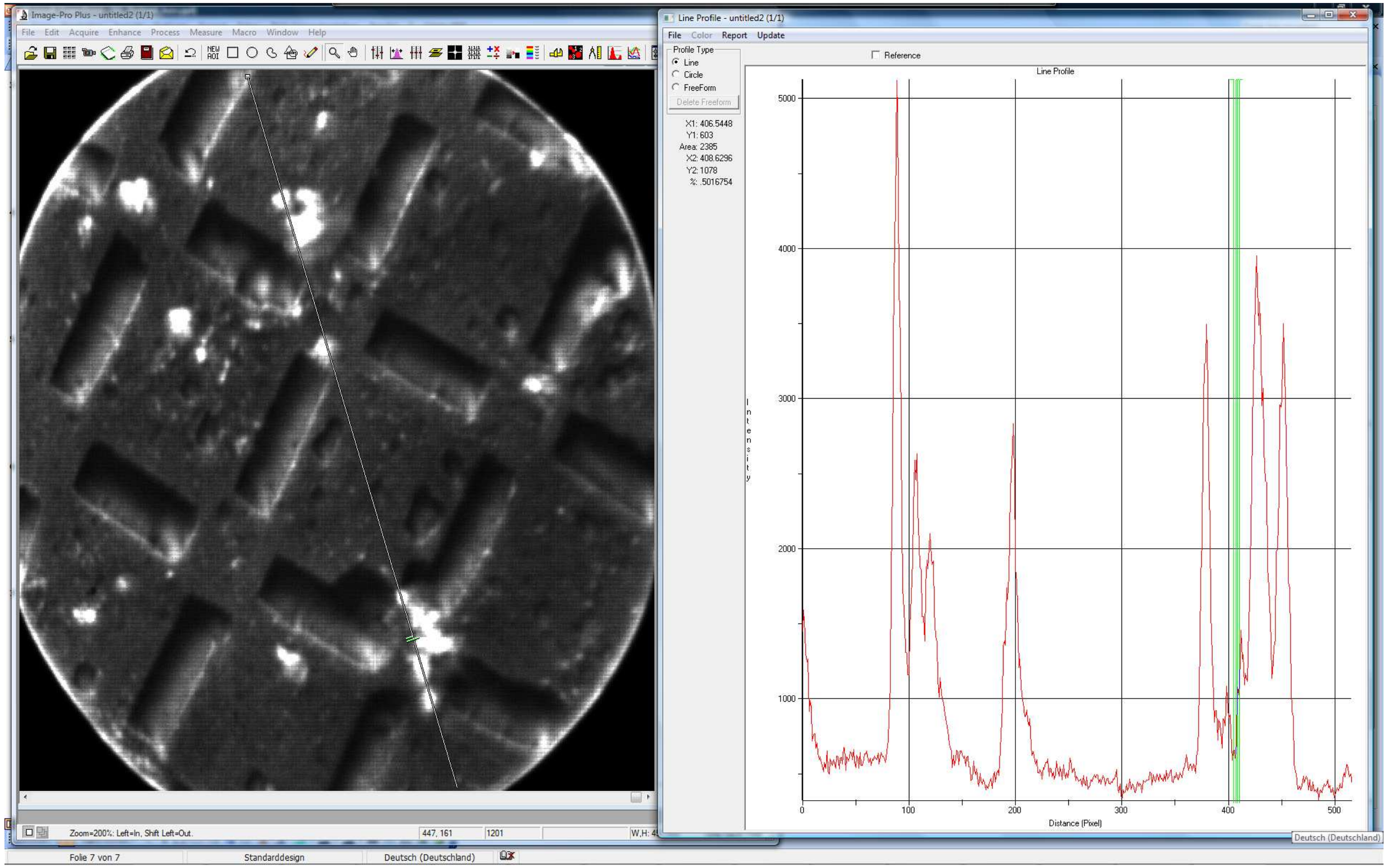
Today's delayline detectors can permanently operate above 3 MCPS.
Most of our 2D/3D devices show limits even between 5-7 MCPS.
The record in our lab tests could be seen at about 10.5 MCPS.









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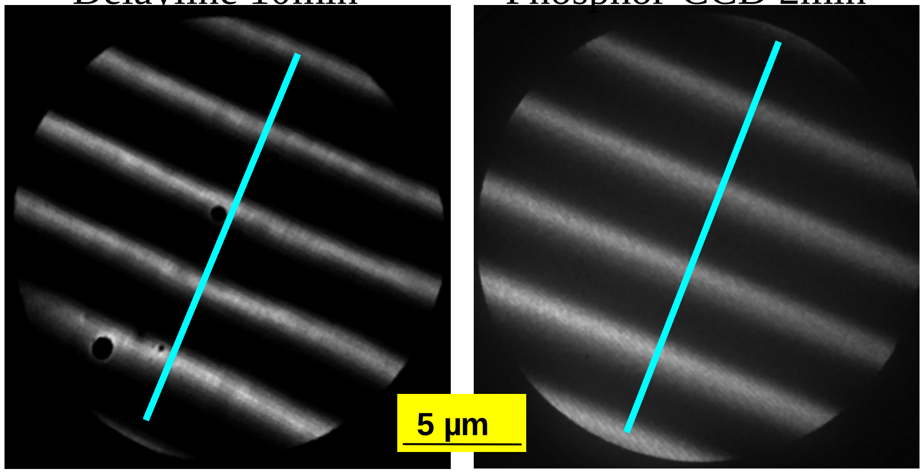
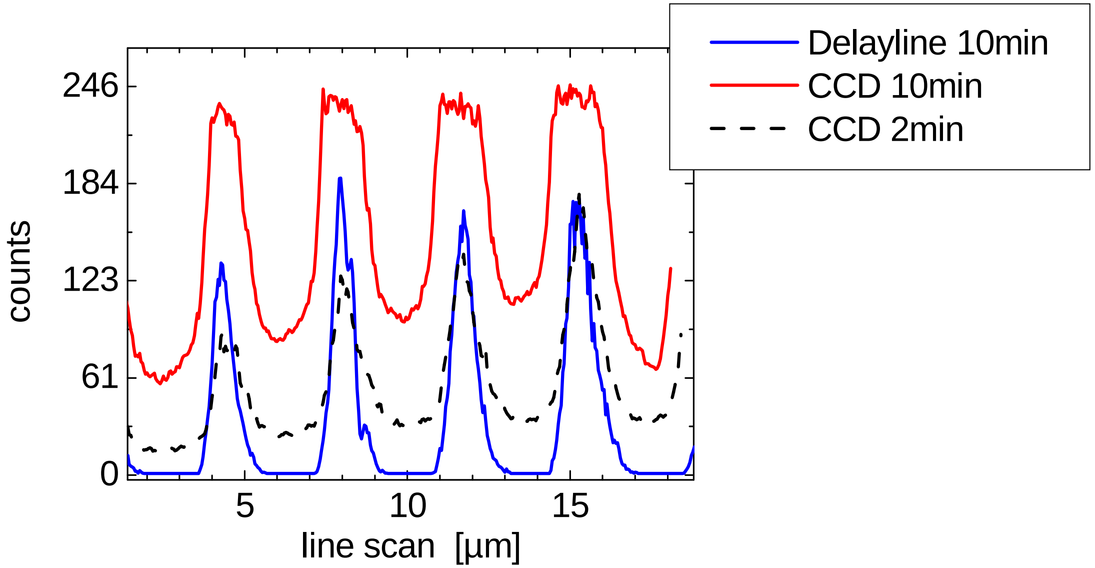
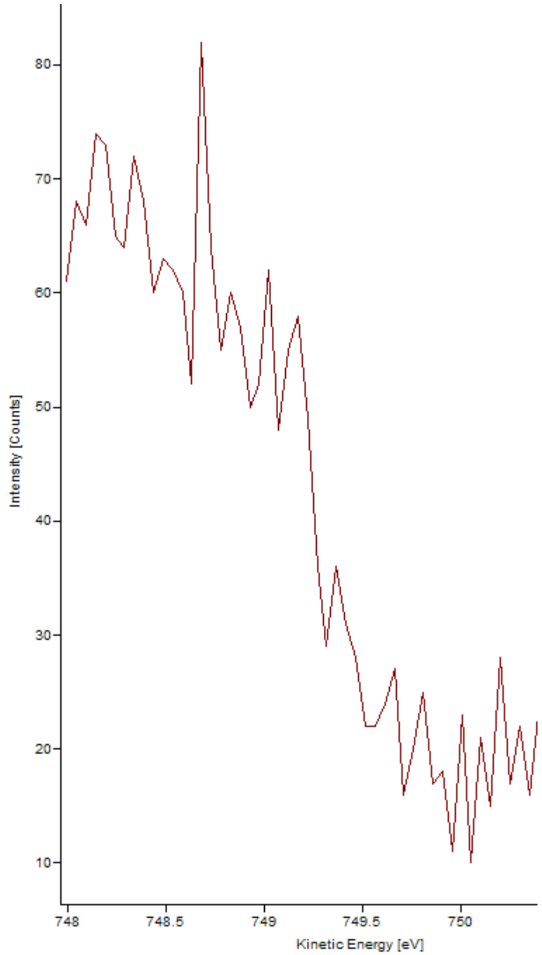
Delayline vs. Phosphor-CCD

Delayline 10min Phosphor-CCD 2min





low signal XPS: resolving the fermi edge at 3 CPS with the delay line detector:



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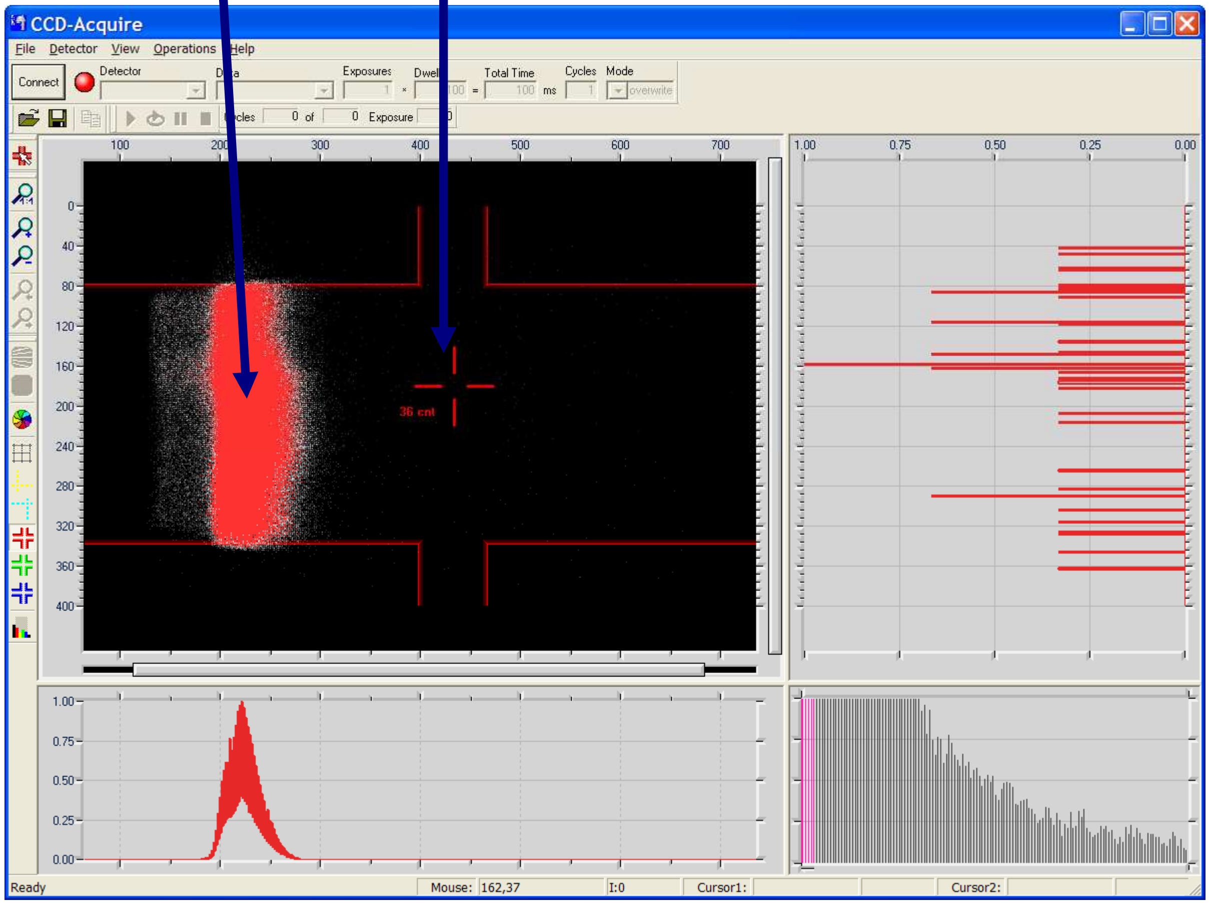
Challenge of 10^6 Signal-Background Ratio

>10^7 counts

36 counts;
(only MCP dark counts)



Elastic peak in EELS, left are lower, right are higher energies

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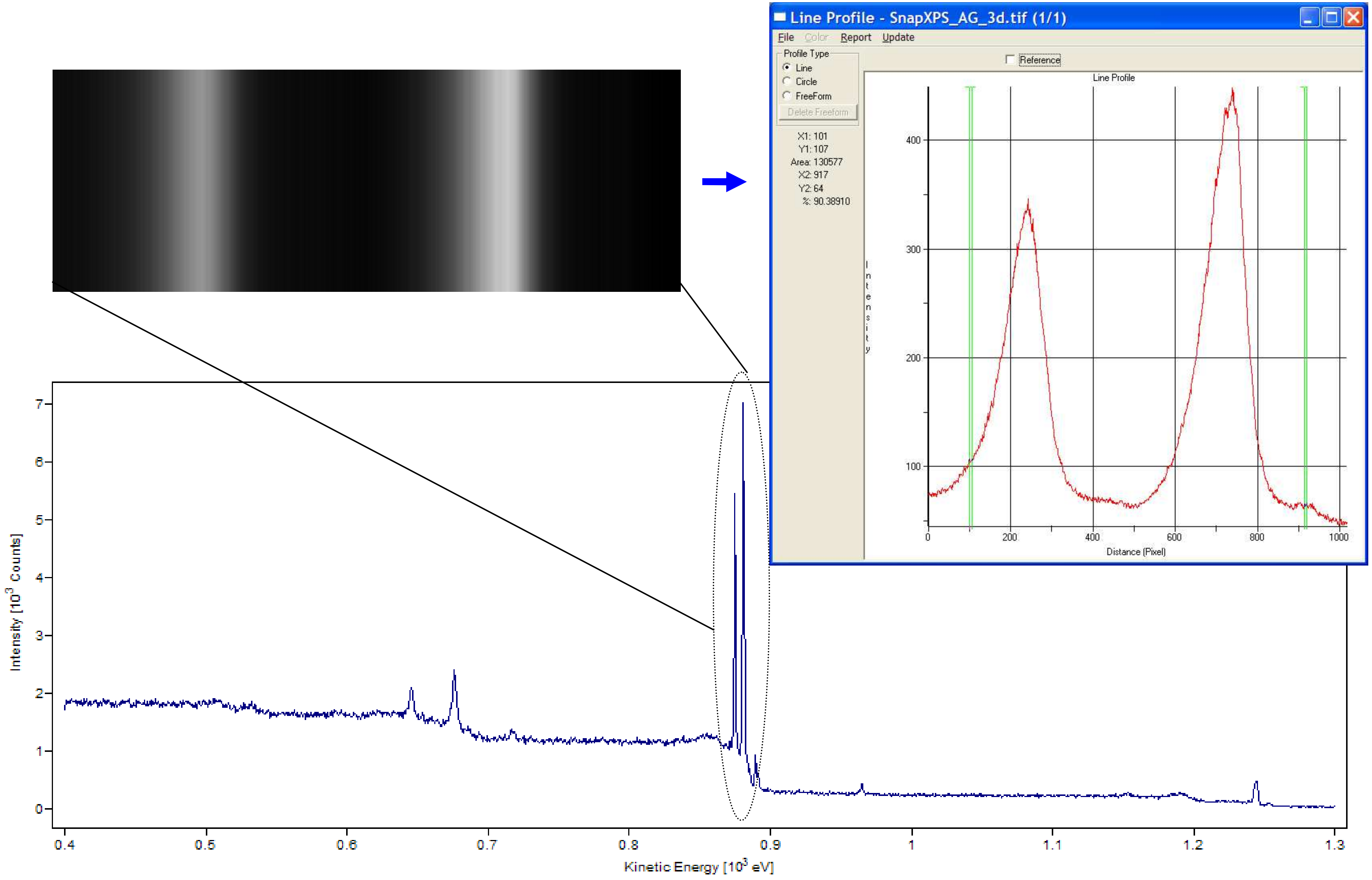
Spectroscopy Snapshot Mode with Multichannel DLD



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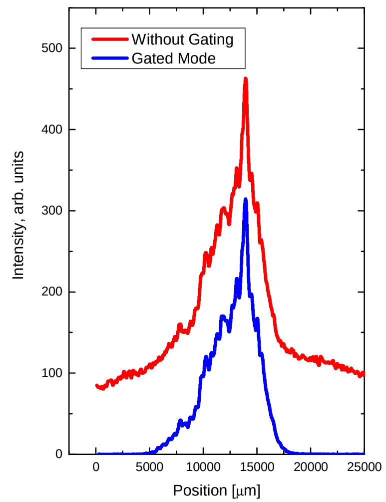
Background Suppression by means of Time Gating

Exposure time: 40 min

Counts outside gate window: 8558 (time period duration 12500 ps)
Counts inside gate window: 1789 (time gate window: 492 ps on peak)

Line scans



Time distribution of events

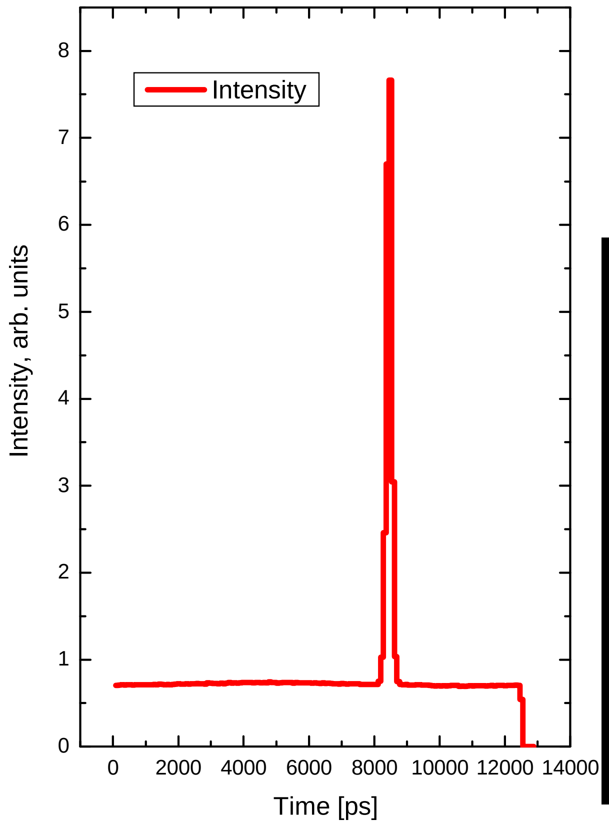


Image taken without time gating

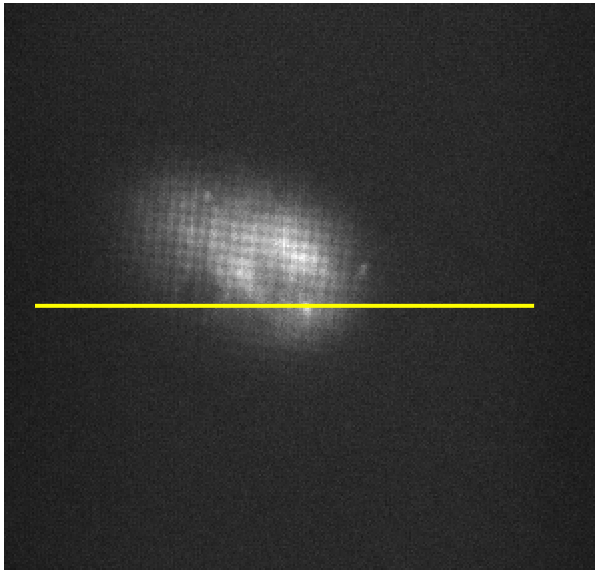
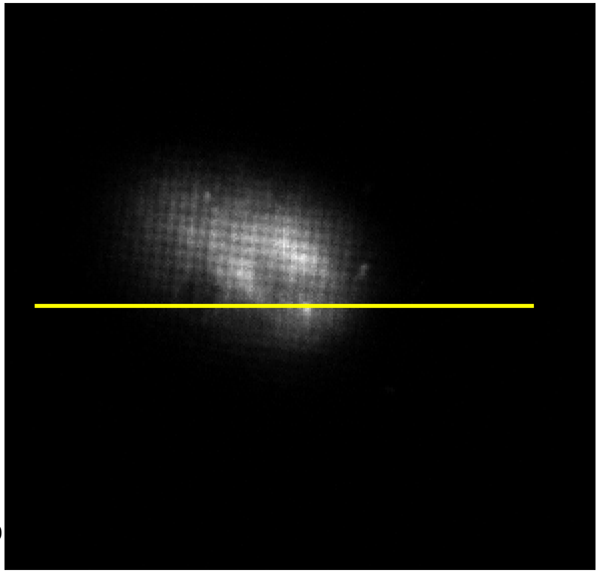


Image taken with time gating



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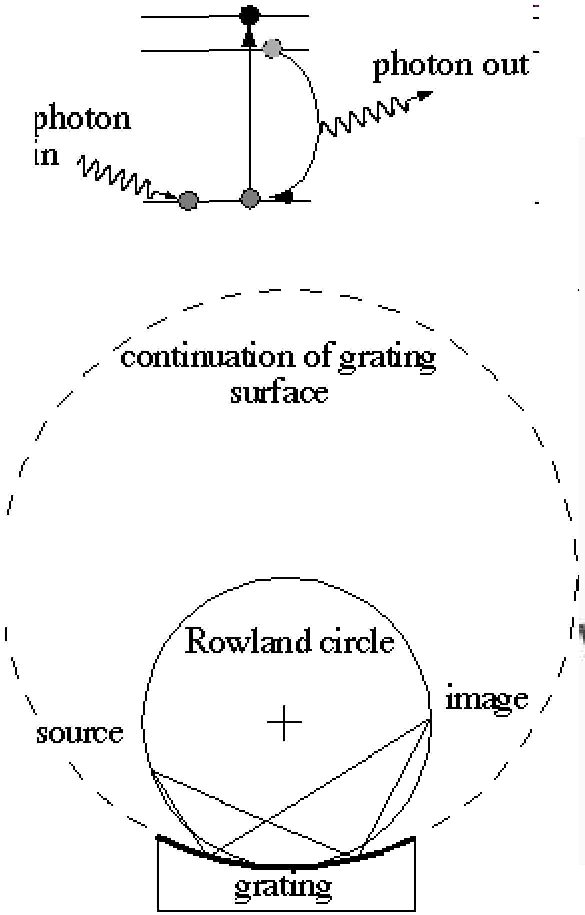
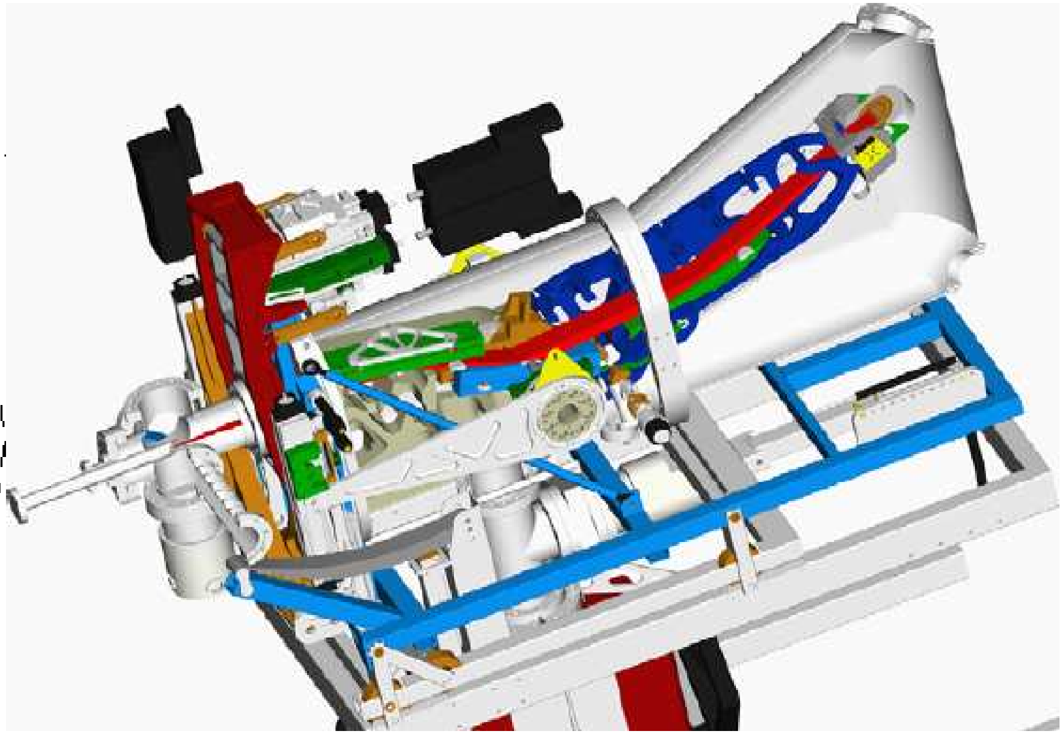
X-ray Emission Spectroscopy





M. Agaker et al., Nucl. Instr. and Meth. in Physics Research A 601 (2009) 213–219

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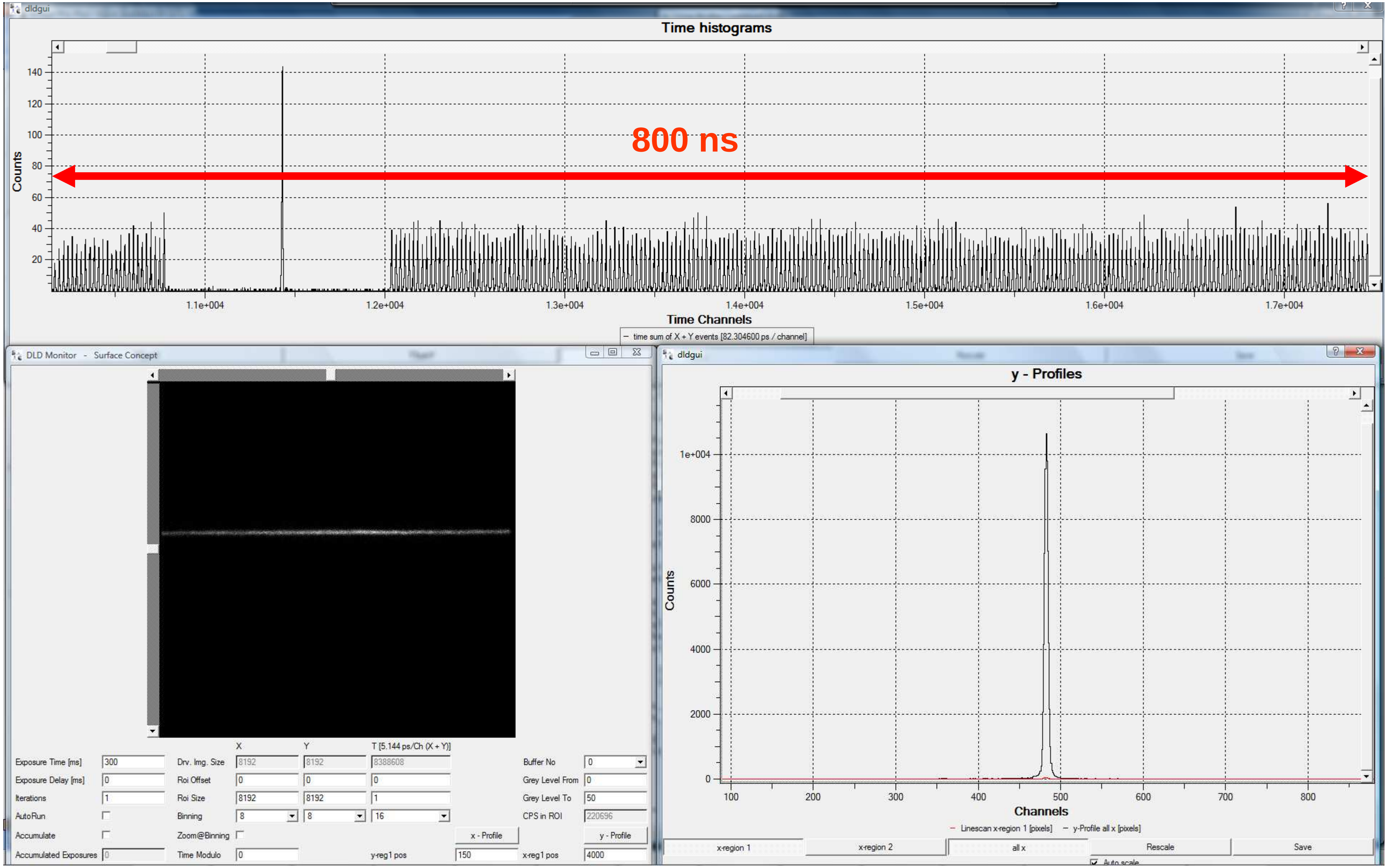
Gated Application in X-ray Spectroscopy



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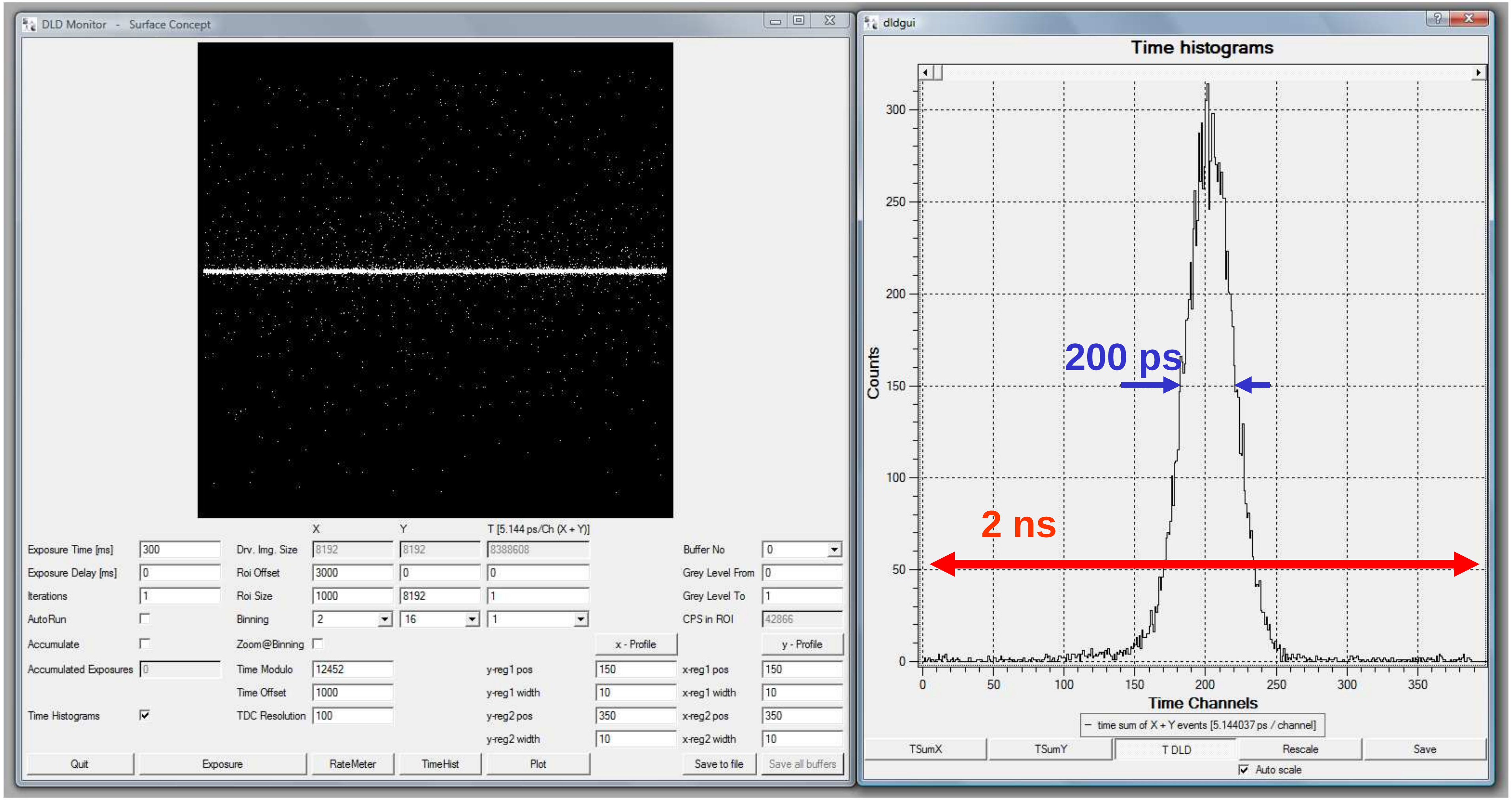
Gated Application in X-ray Spectroscopy

Much of the noise outside of the X-ray line without gating is not in the peak!



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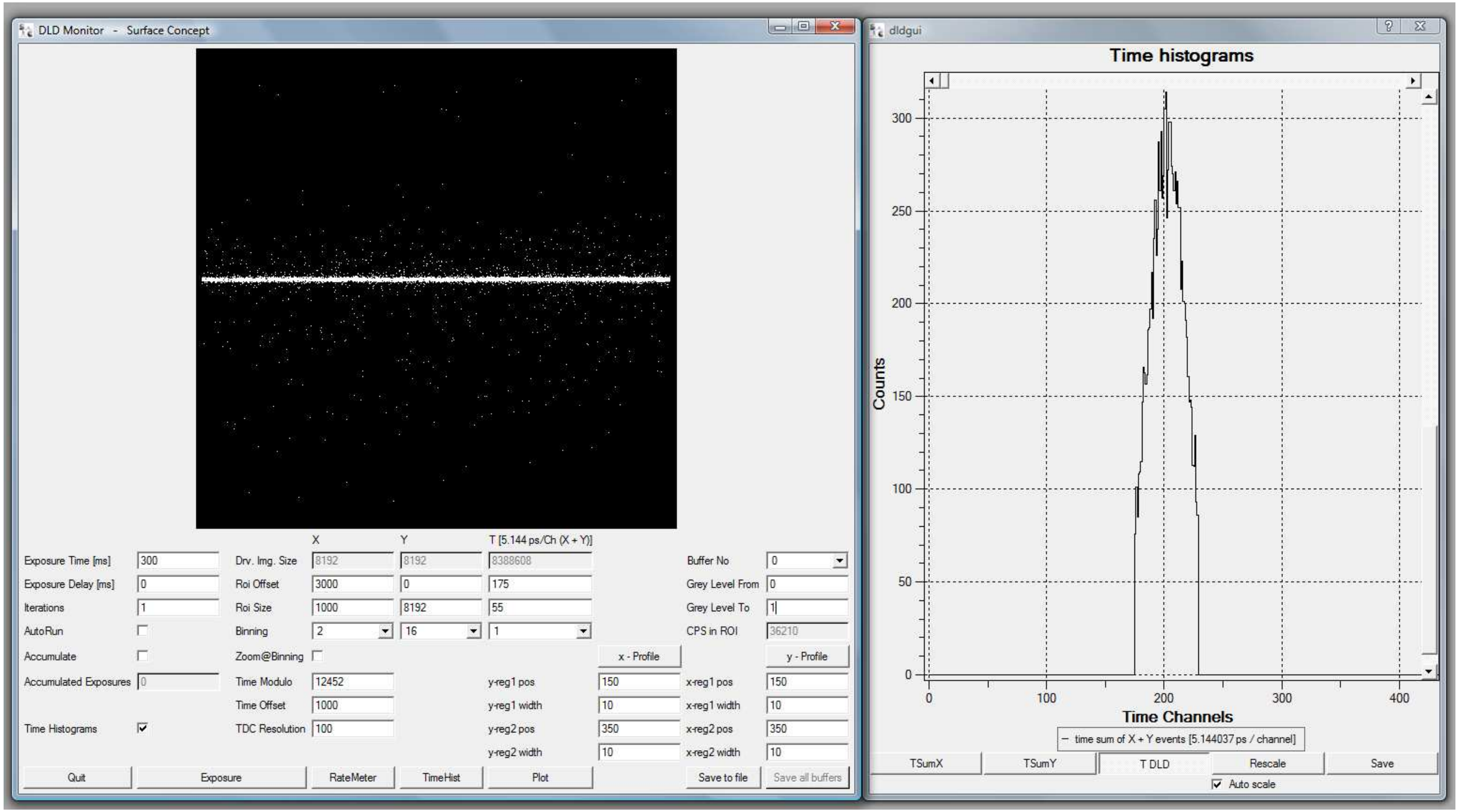
Gated Application in X-ray Spectroscopy

Significant noise reduction due to software gating at the peak:



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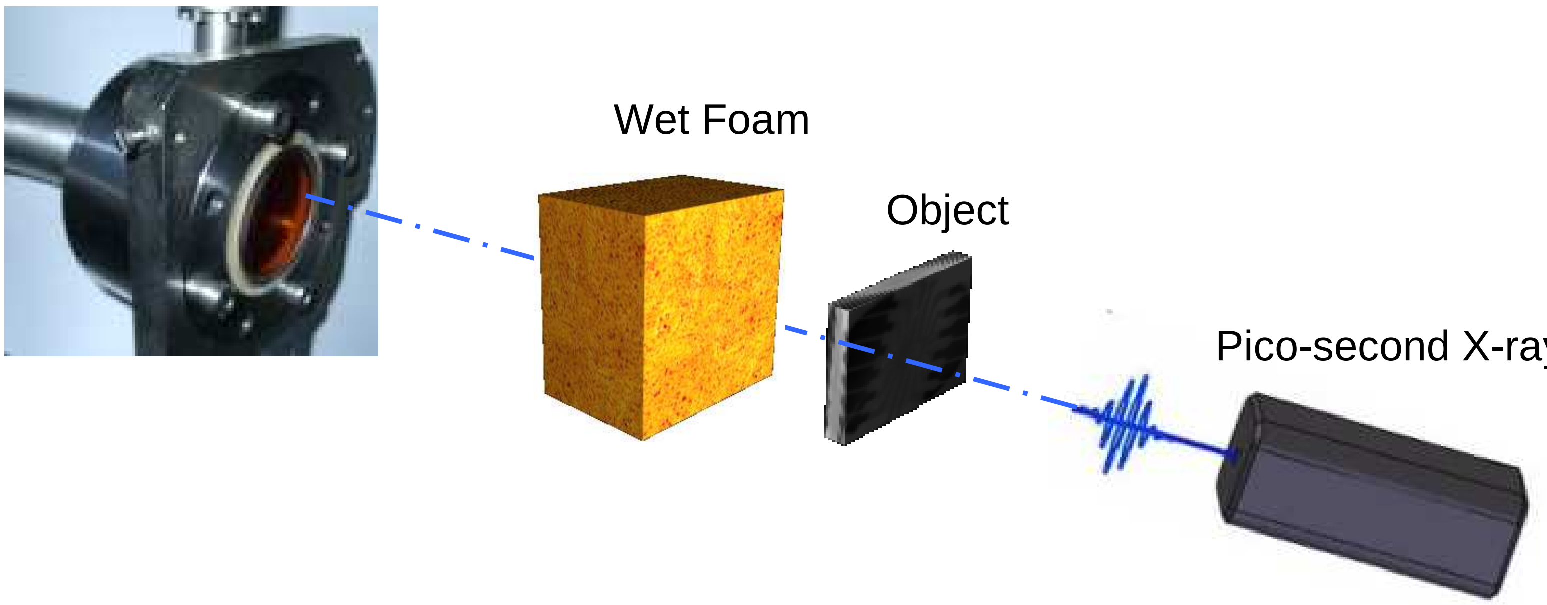
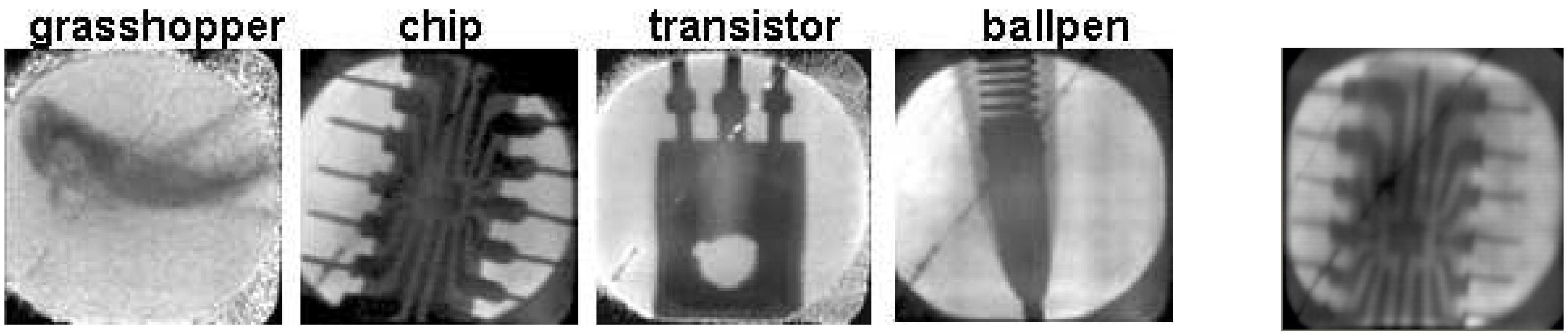
X-ray Imaging with Delayline detectors

X-ray Delayline Detector





Ulf Hinze, Boris Chichkov, Laserzentrum Hannover, Andreas Oelsner, Surface Concept

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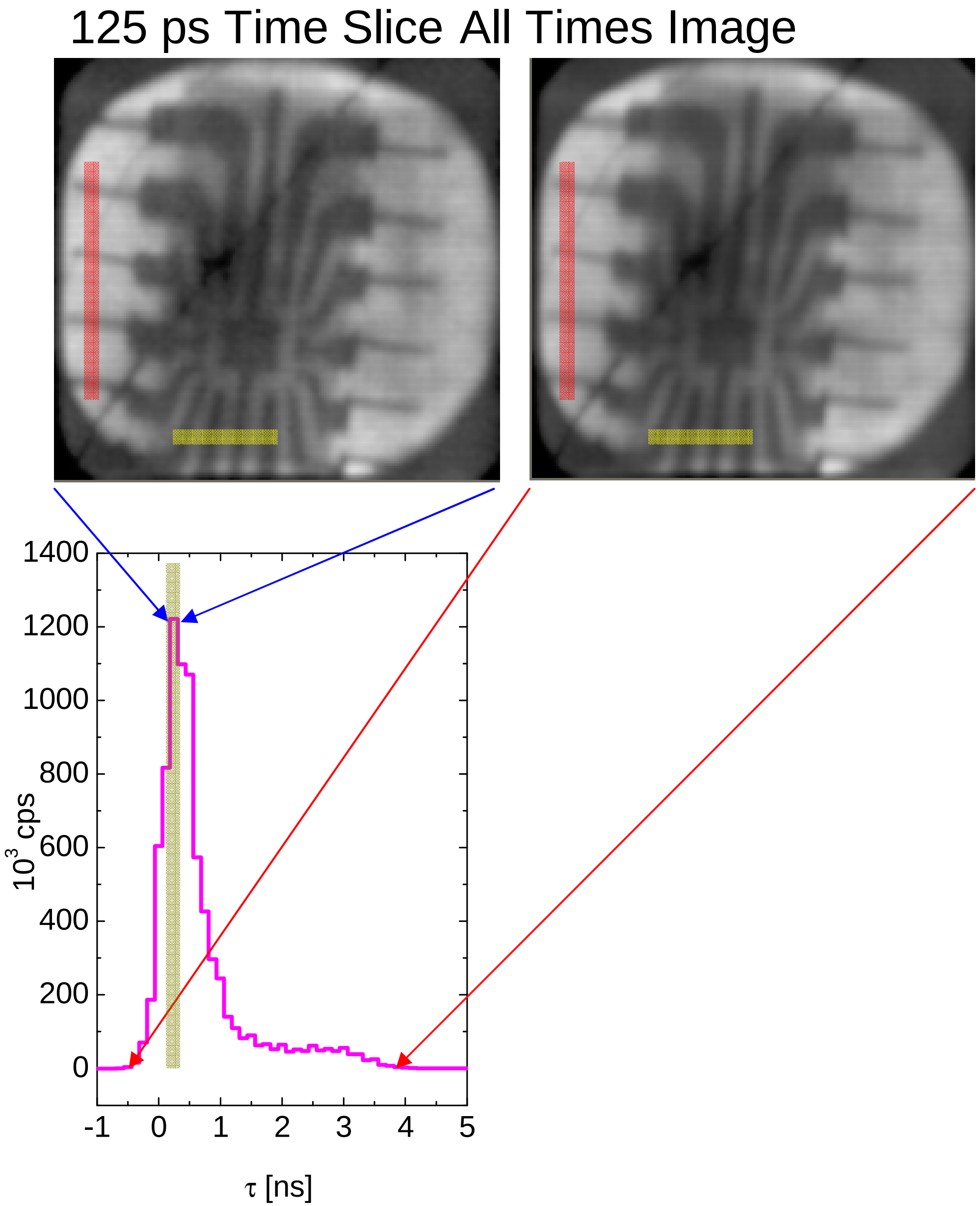
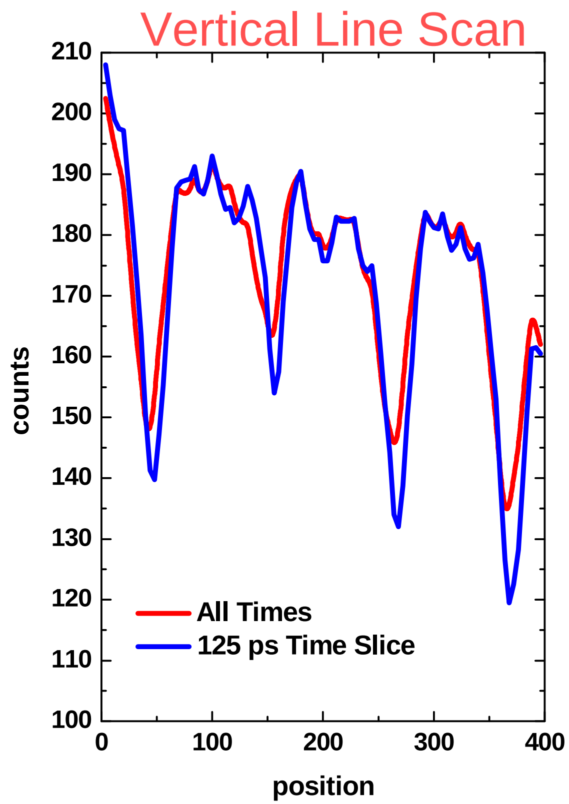
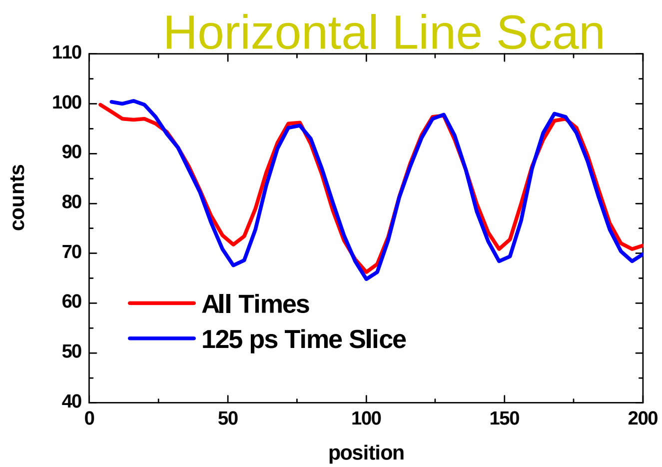
Contrast Enhancement by Time Sliced X-ray Imaging







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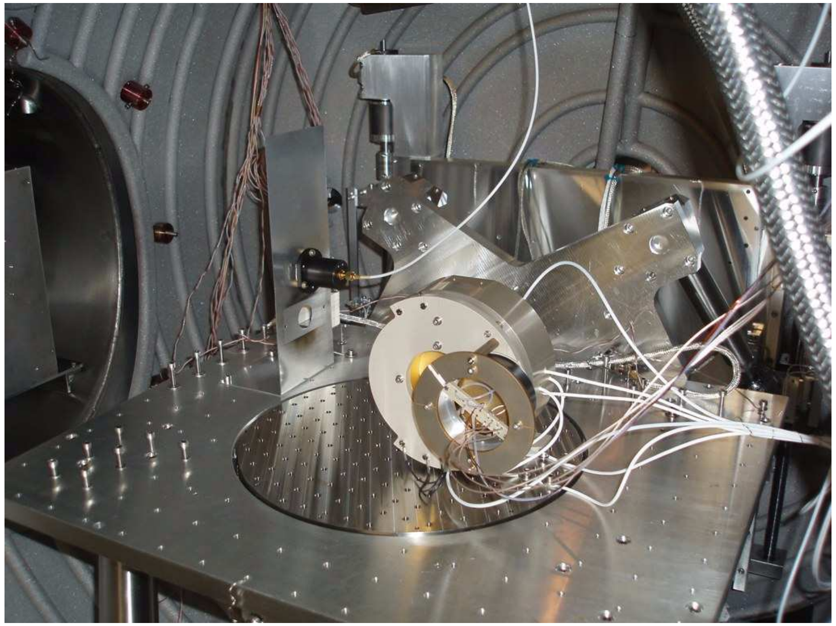
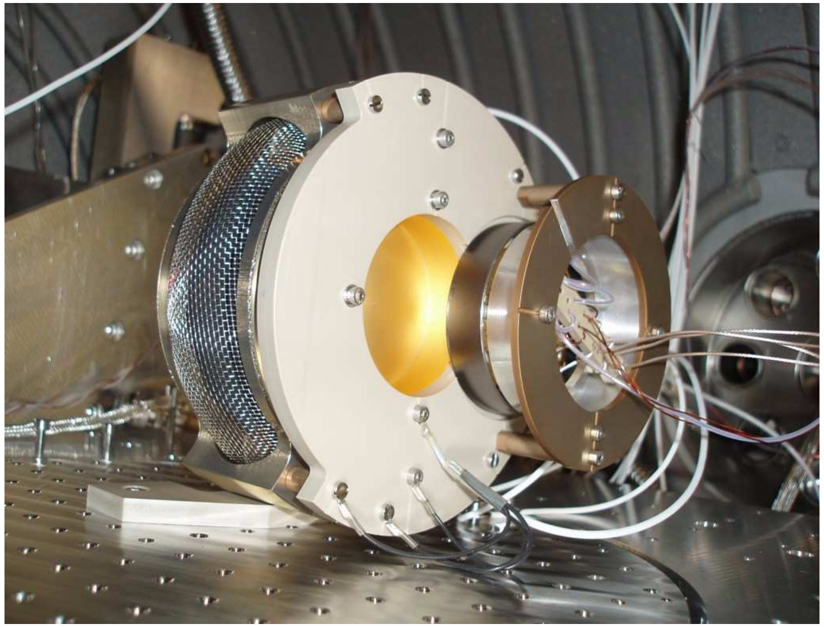
Imaging of Ions using Delayline Detectors

MEFISTO Calibration Facility
MEsskammer für **F**lugzeit**I**n**S**trumente und **T**ime-**O**f-Flight
Calibration Facility for Solar Wind Instrumentation





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University Bern, Switzerland

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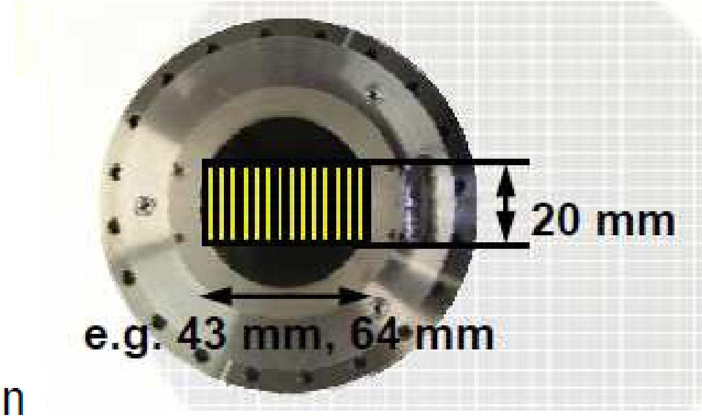
One Dimensional DLDs for Spectroscopy

Max. count rates of today's 1D systems goes above 14 MCPS!



- Increases in analyzer performance
- Enables higher resolving power
- Facilitates time resolved experiments
- Snapshot capability for fast spectrum acquisition
- Lower costs for multiplier replacements

Detector comparison of peak rates in high resolution XPS (Ag 3d5/2):

Resolution	MCD-9	1D Delayline
0.85 eV	1,200,000	1,600,000
0.60 eV	600,000	1000,000
0.50 eV	150,000	250,000

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Temporal Control comes with DLDs to Spectroscopy

There are different reference period time ranges T_r available which operate with different time resolutions and digital dynamics:

Range	Specification
High precision range	T_r = 1 ns - 40 µs 2 - 16 time intervals freely definable Resolution 27 ps Using 21 bits dynamics in time measurement results
Extended high precision range	T_r = 1 ns - 950 s 2 - 16 time intervals freely definable Resolution: 27 ps – 232 ms Time results will be binned together in multiples of two by a user parameter in order to reach longer ranges of T_r using 12 bits dynamics in the time measurement results
Low precision range	T_r = 1 µs - 100 s 2 - 16 intervals freely definable Resolution: 25 ns Using 32 bits dynamics in time measurement results

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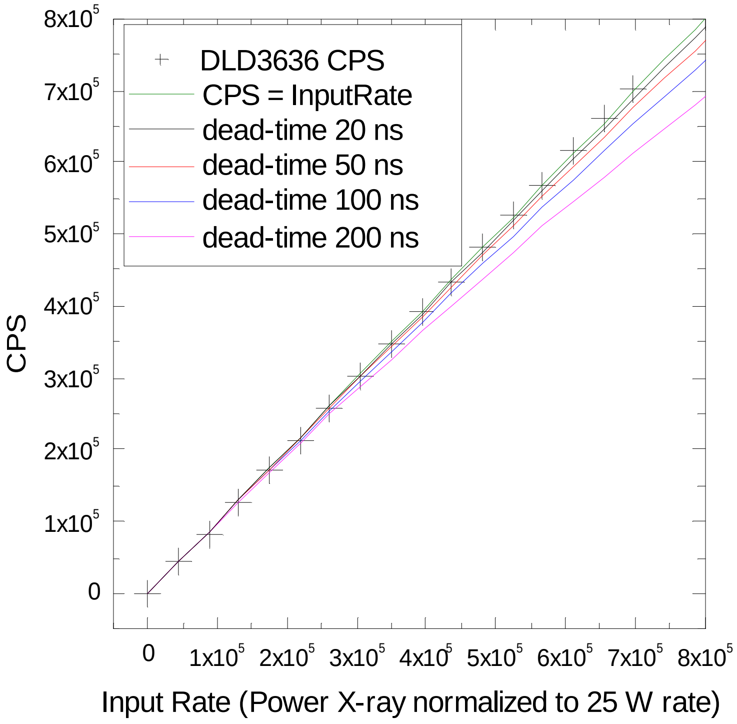
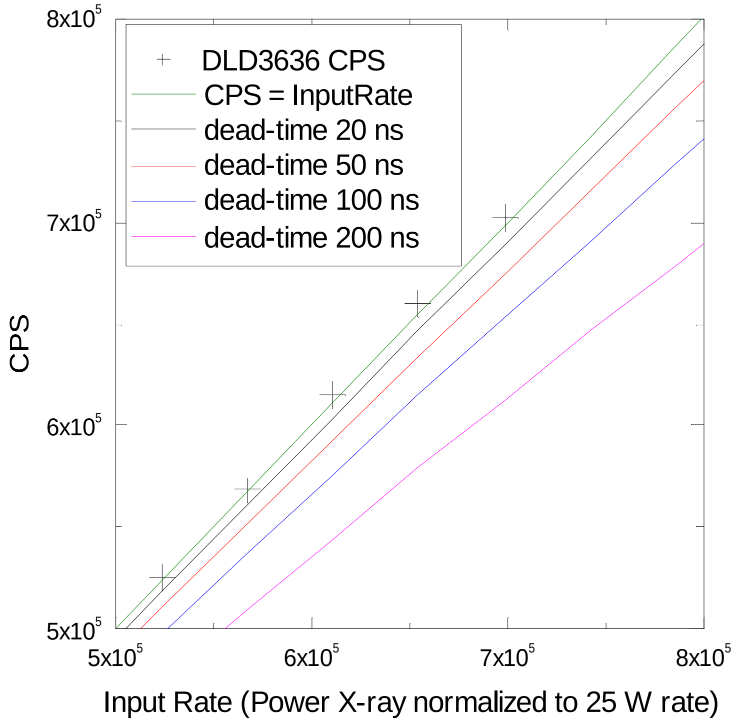
Dead Time in Counting Applications

Dead-time of DLD system determined to be below 20 ns

The dead time fits follow the relationship of count rate N1 to be observed and
The true count rate N for an ideal counter with a non-extended dead time τ:

$$N1 = N / (1 + N \tau)$$





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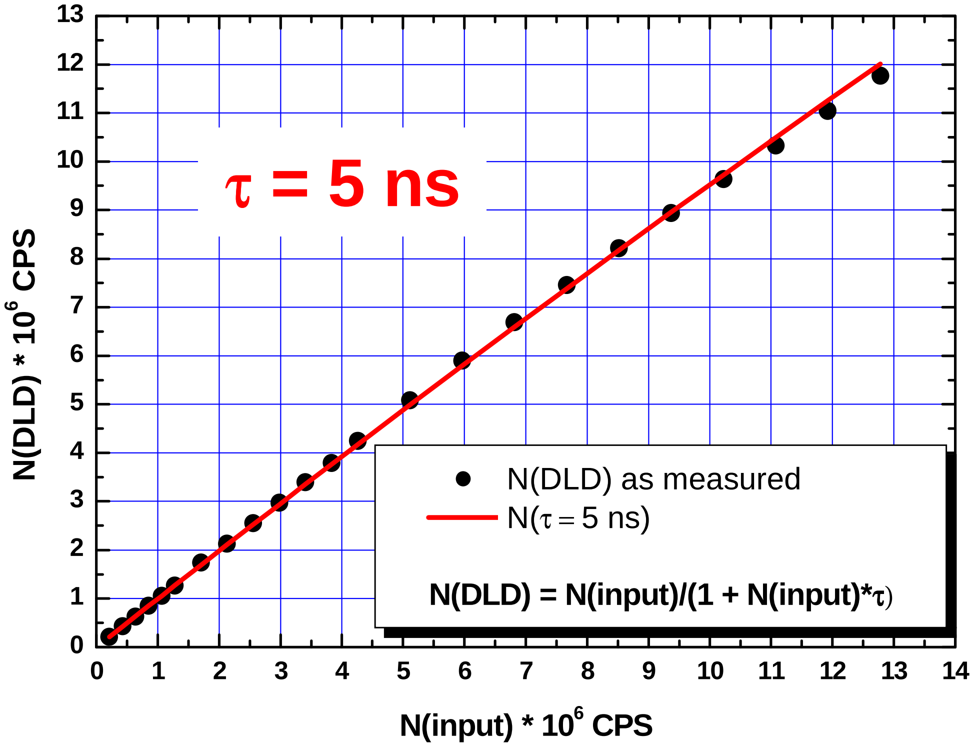
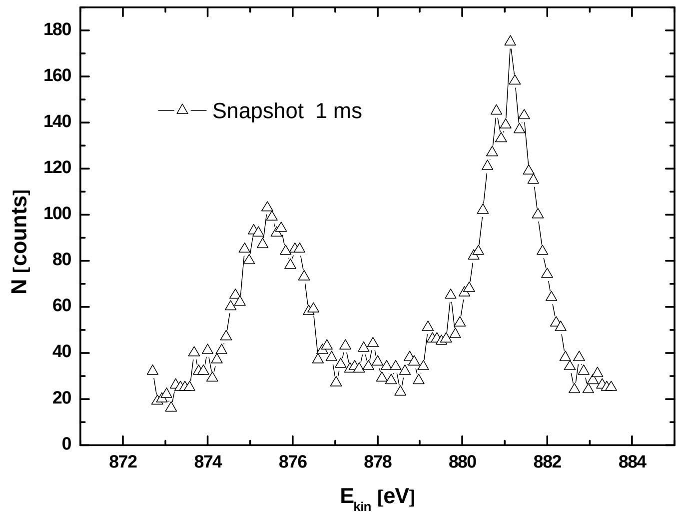
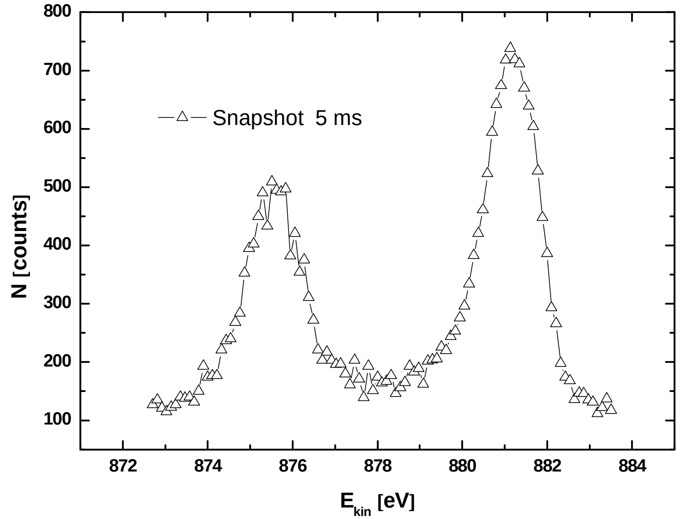
High Countrate Performance of 1D DLDs

Dead-time of 1D DLD system



Short snap-shot performance





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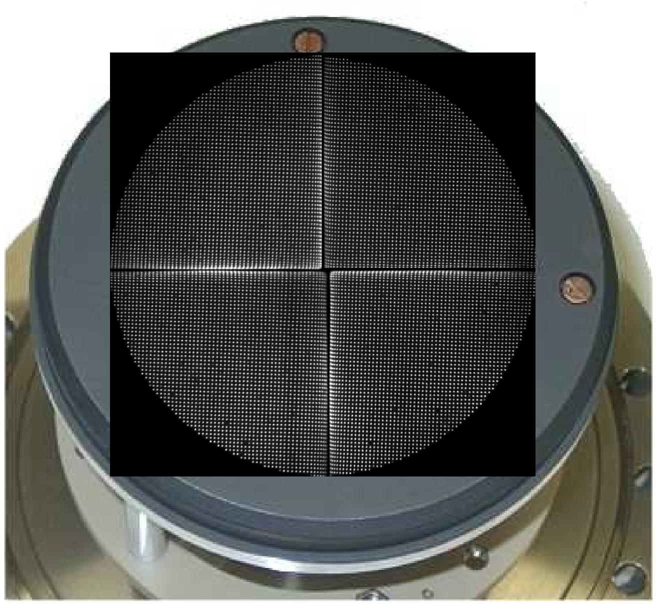
4 fold 3D Multihit DLD 3030 4Q

4 Quadrant multi-hit delayline detector for fast burst imaging

- *Multi-hit 4 fold detector optimized for fast burst recognition above 100 MCPS equiv.*
- *Large detection area 60 mm x 60 mm (larger areas possible as well)*
- *Real parallel detection of 4 hits without any dead time due to the fourfold design*
- *Multi hits on single quadrants (all 10 ns possible) are always unambiguous, no data redundancy problems due to the short single delays of about 9 ns.*



Features

- Multi-hit 2D/3D 4-fold delayline detector
- Up to 4 multi hits with zero dead time
- Up to 400 multi hits per 1 µs
- Burst rates above 100 MCPS equivalent
- 60 x 60 mm² active area of DLD body and ∅ 82 mm active MCP area
- Down to 50 µm of pixel size
- < 250 ps over all time resolution
- Linear response due to single event counting
- Extremely low dark count rate: ≤ 10 cps
- Up to 10.5 MCPS cont. count rate in 2D/3D mode

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Outlook

What may <u>single</u> delayline detectors deliver today and were does the journey go to within the near future?

<u>Today:</u>

Time resolution: 140 ps – 240 ps (peak reproducibility 13.7 ps)

Spatial resolution: 20 µm – 100 µm (depending on anode layout)

Maximum random count-rates: 5 MCPS – 9 MCPS

<u>Within the next few years:</u>

Time resolution: 50 ps (peak reproducibility 5 ps)

Maximum random count-rates: 20 MCPS – 80 MCPS

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