



Recent progress in high resolution photon counting detectors with Microchannel Plates

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MCP detector configuration

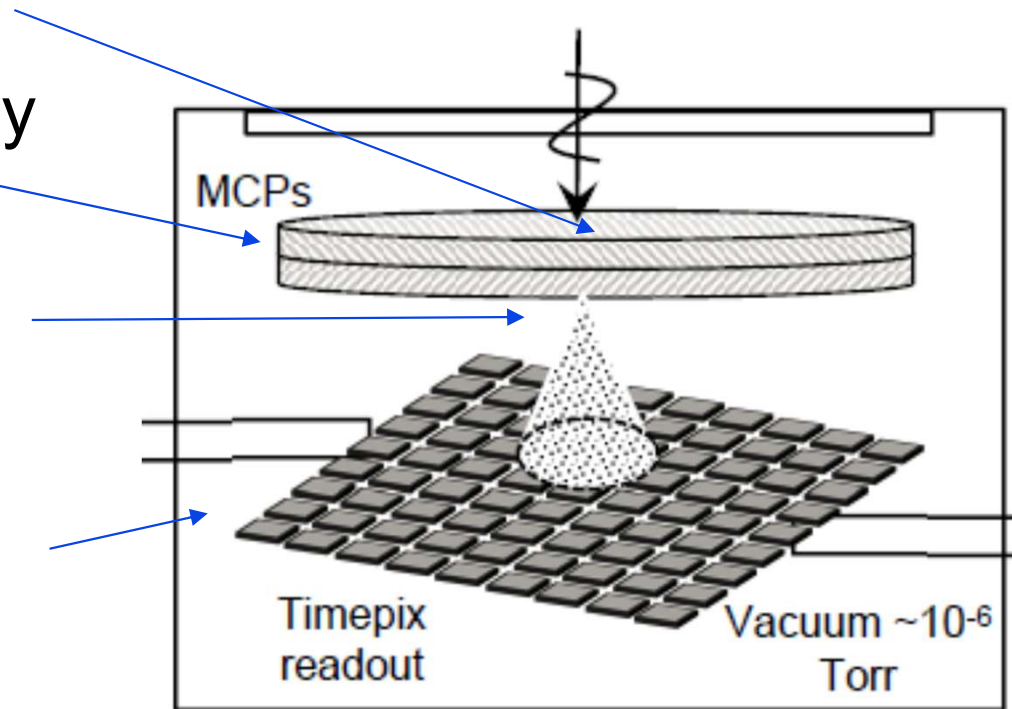
Primary particle is converted into electron

MCP(s) amplify electron by 10^3 to 10^7

Rear field accelerates electrons to readout

Different readouts can be used, optimized for a particular application

Photocathode can be used for photon detection



Selective detection of photons, ions, electrons, neutrons, alpha particles



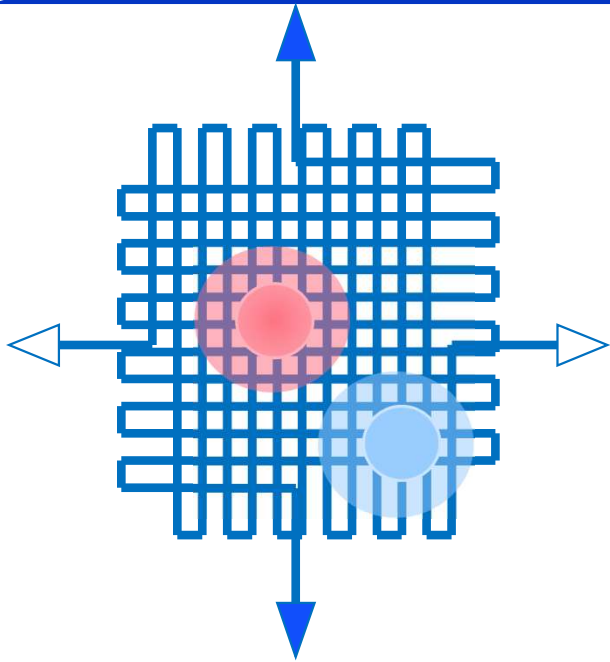
Advantages/disadvantages of MCP detectors in particle counting applications

- **No readout noise**
- **Time and position for every detected particle** ($\sim 6 \mu\text{m}$ with event centroiding, $\sim 10 \text{ ps}$ event spread time in MCP)
- **Event counting**
- **TOF applications**
- **High counting rates** possible with latest readouts ($> 100 \text{ MHz}$)
- **High detection efficiency** (UV, soft X-rays, neutrons, electrons, ions, alphas)
- **No afterpulsing**
- **No intrinsic energy resolution**
- **Small area** (up to 10 cm)
- **Require vacuum**
- **Require high voltage**
- **Image distortions**

Highly generalized!



Readout types



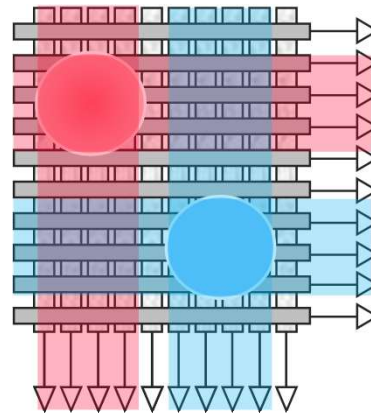
**Cross Delayline
(XDL)**

4 amps

Gain $\sim 10^7$

Rate $< 1\text{MHz}$

$\Delta t \sim 50\text{ ps rms}$



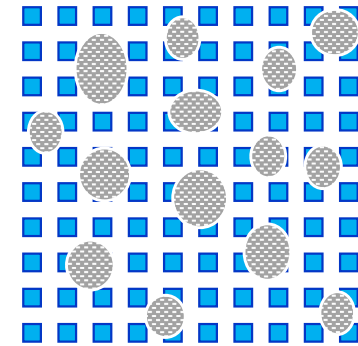
**Cross Strip
(XS)**

2 x N amps

Gain $\sim 10^6$

Rate $\sim 10\text{ MHz}$

$\Delta t \sim 100\text{ ps rms}$



**Medipix/Timepix
ASIC**

N x N amps

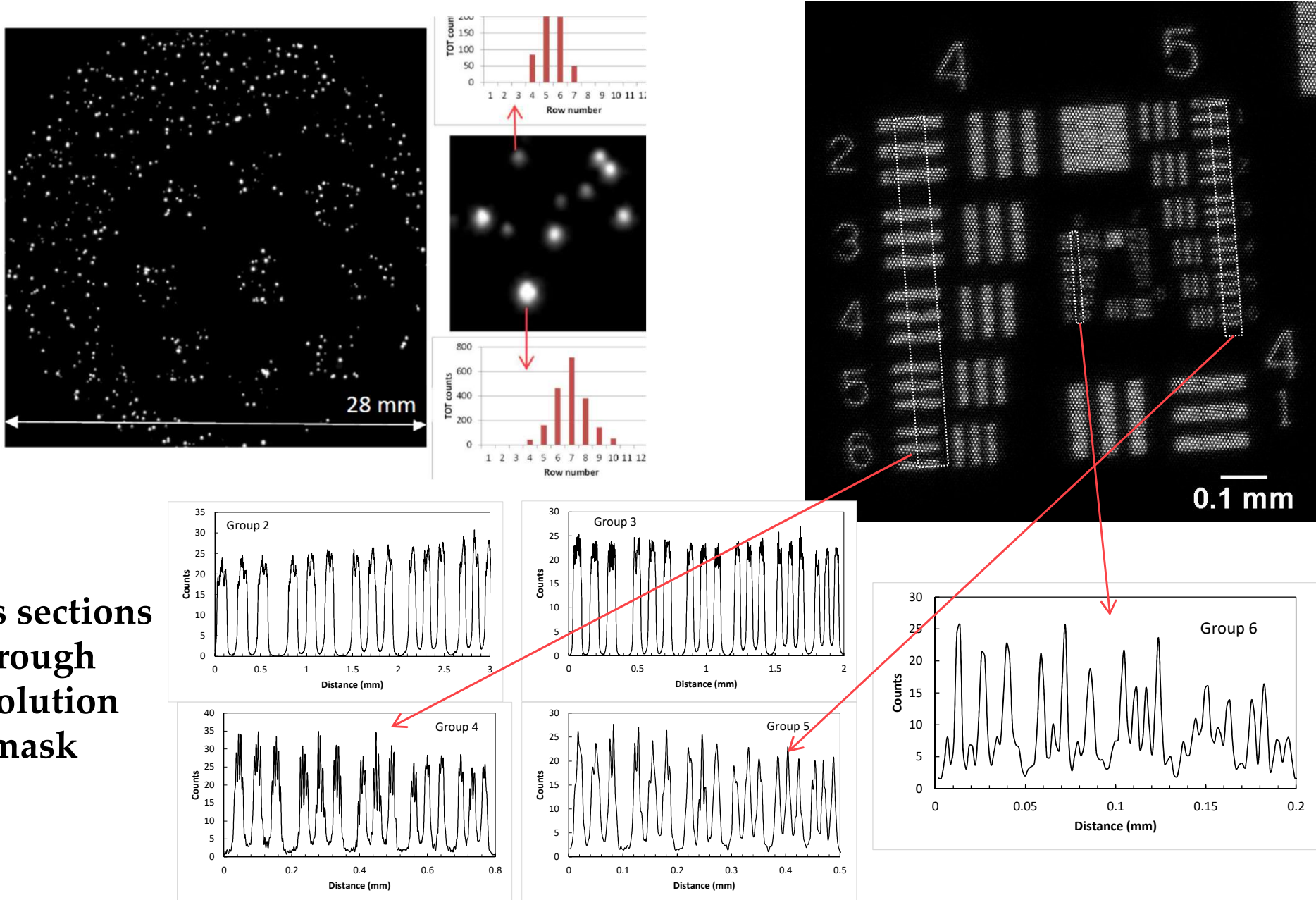
Gain $\sim 10^4\text{-}10^5$

Rate $> 500\text{MHz}$

$\Delta t \sim 1.6\text{ ns (}200\text{ ps?)}$



High spatial resolution of $\sim 6 \mu\text{m}$

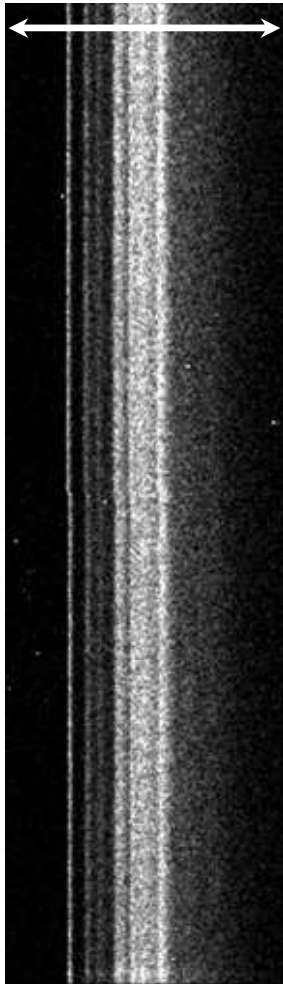




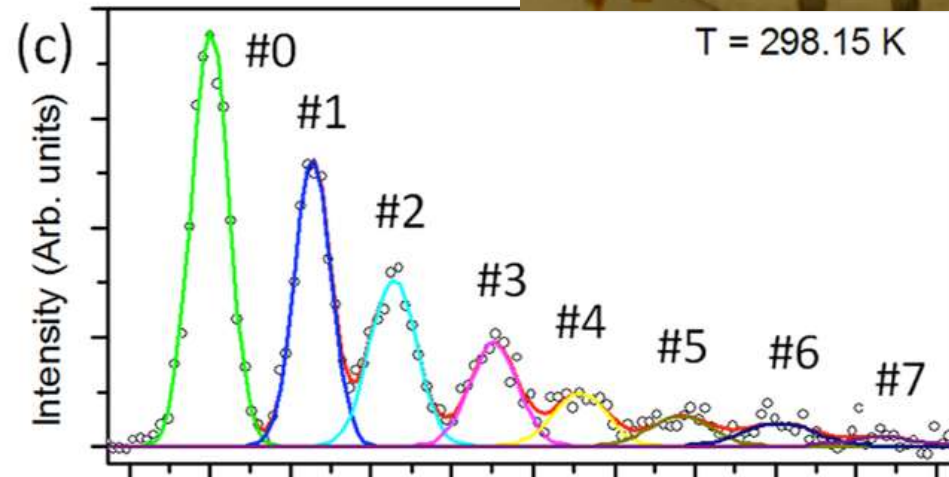
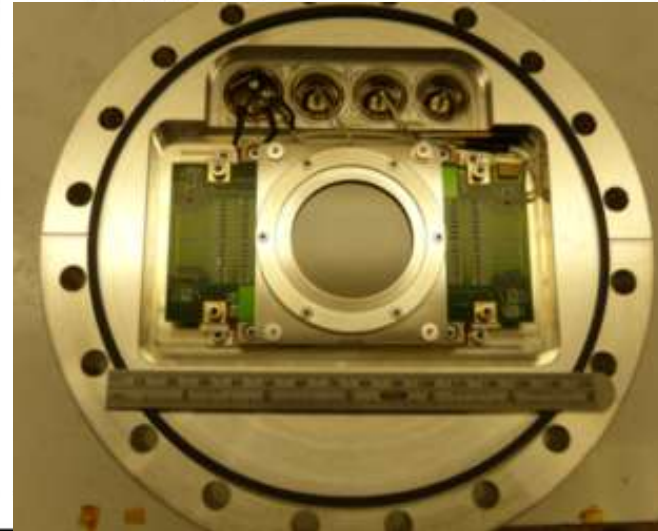
RIXS: initial tests of MCP/TPX systems at ALS and LCLS



~8.5 mm

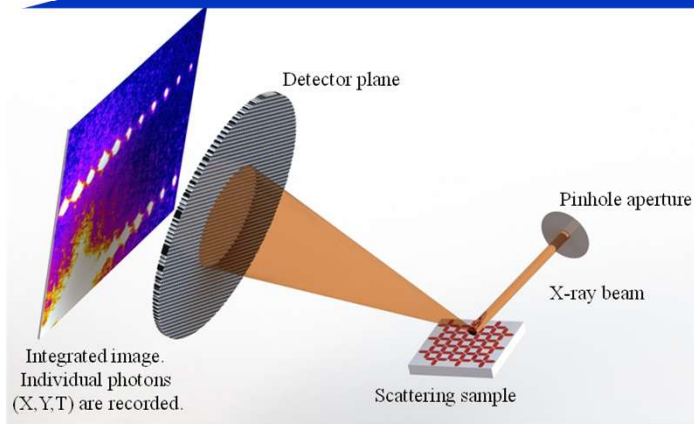


Raw image



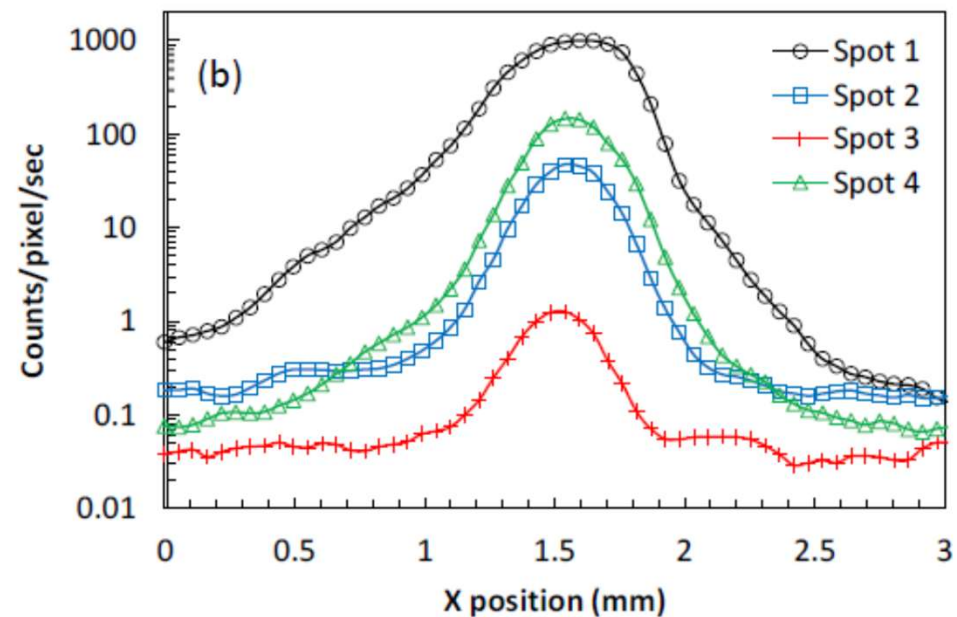
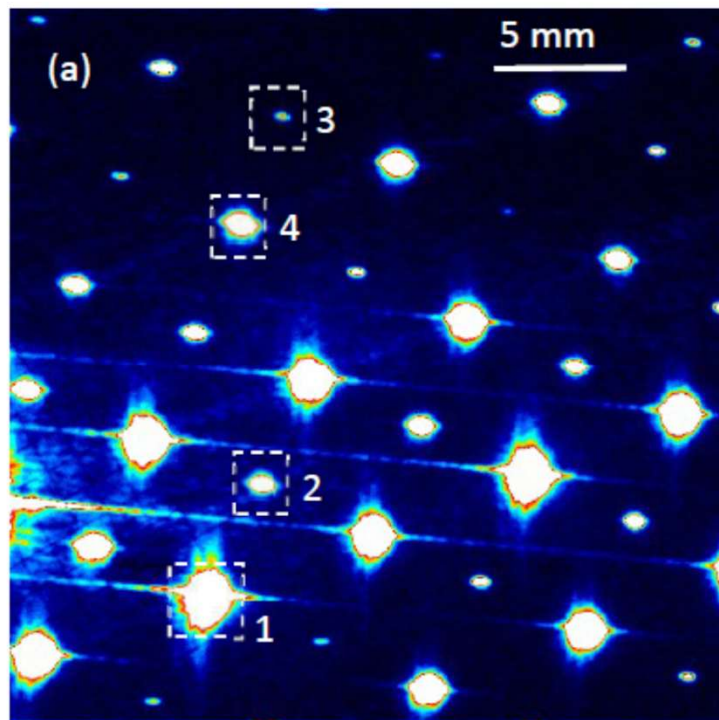
HOPG elastic
peak vibronic
coupling

X. Feng et al., Phys. Rev. Let 125, 116401 (2020)



Beamline experiments on the MCP optimization

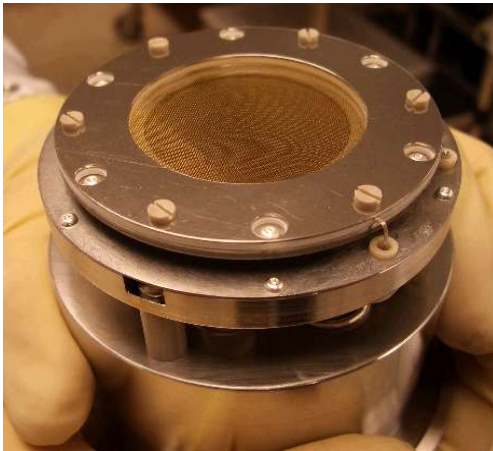
- MCP/Timepix detectors enable operation at a very large dynamic range (photon counting within very bright and very dim spots at the same time).
- The count rate within different spots in that image





Detector hardware implementations

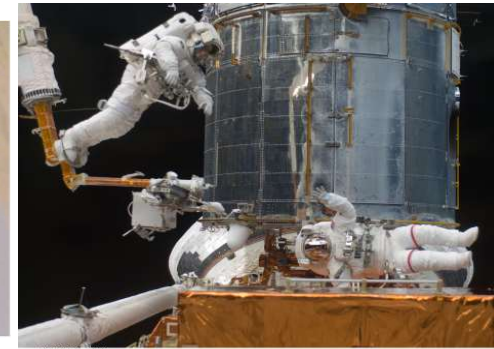
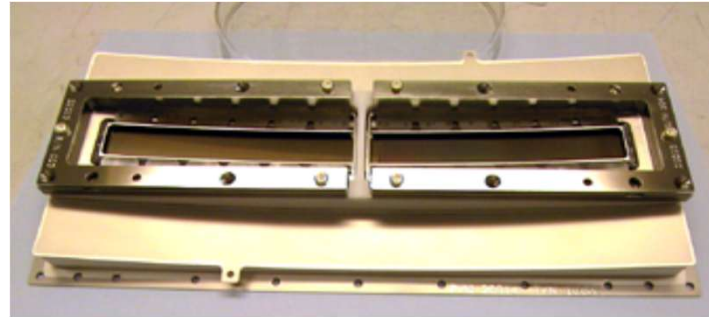
Synchrotron beamline detectors:
ARPES – angular resolved
photoelectron emission spectroscopy



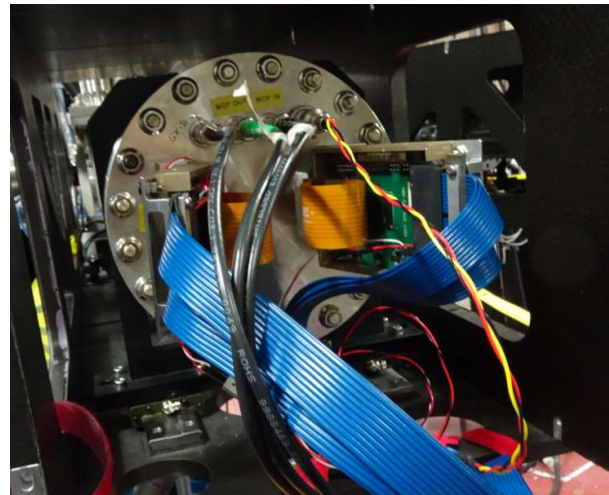
RIXS and XPCS @ ALS



**COS detector
Installed on Hubble Space Telescope**

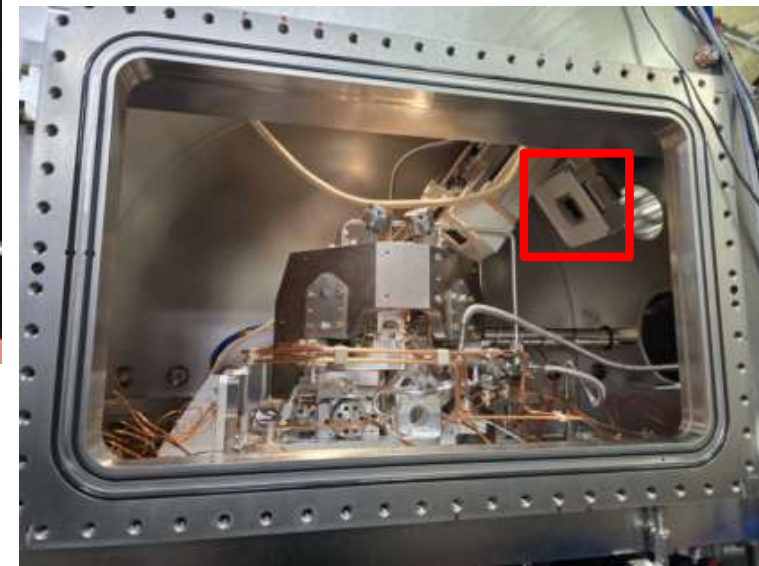


NASA Shuttle STS-125 Mission



Scientific Reports (2020) 10:22226
Phys. Rev. Lett 125, 116401 (2020)
Phys. Rev. Lett 126, 117201 (2021)
Rad. Meas. 130 (2020) 106228

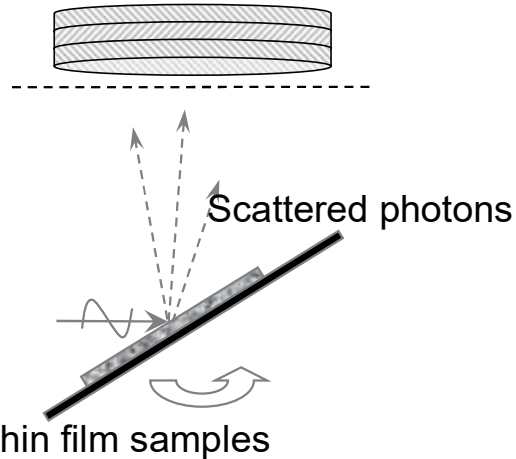
**In-vacuum TPX3 system
installed on a rotating arm**



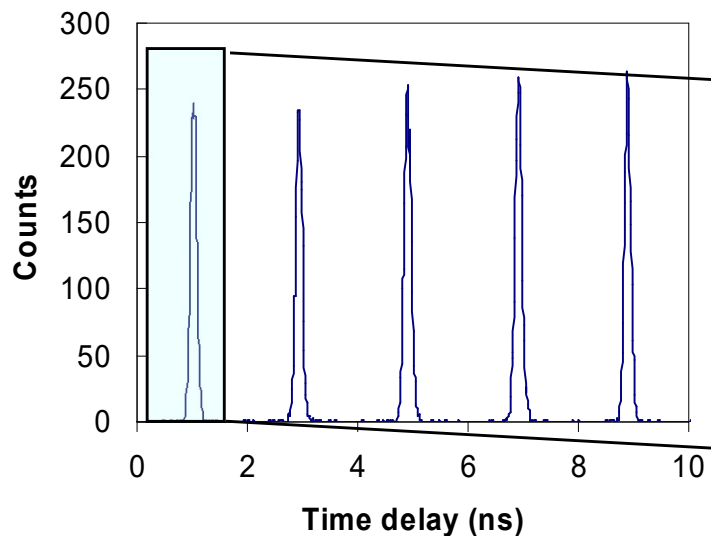


Intrinsic MCP timing resolution

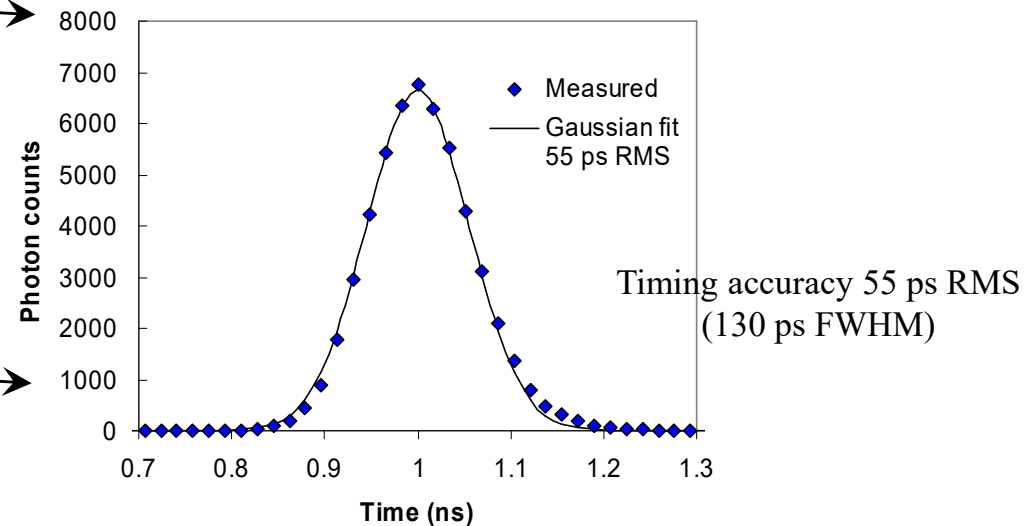
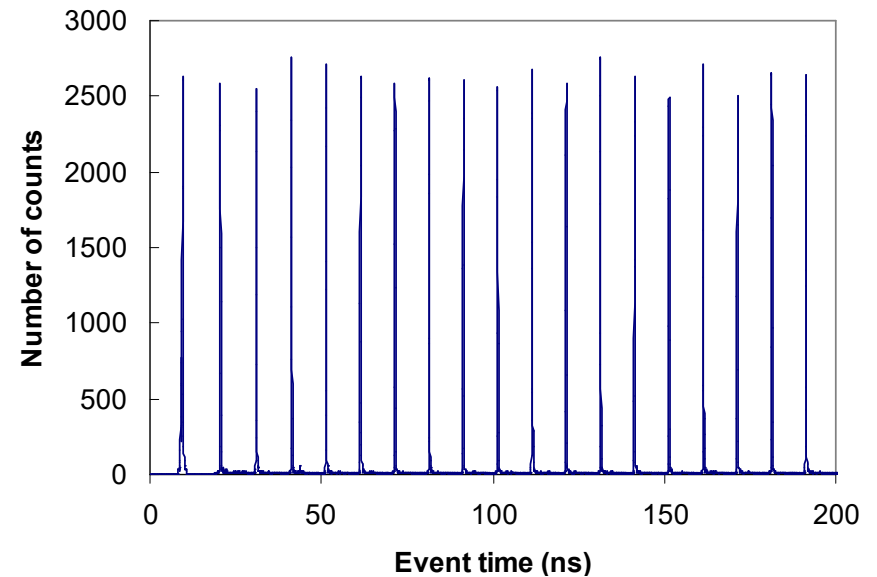
2D Imaging +
time for each
detected photon



Synchrotron generated
photon pulses
~ 70 ps wide, 2 ns
apart



Linearity of measured timing



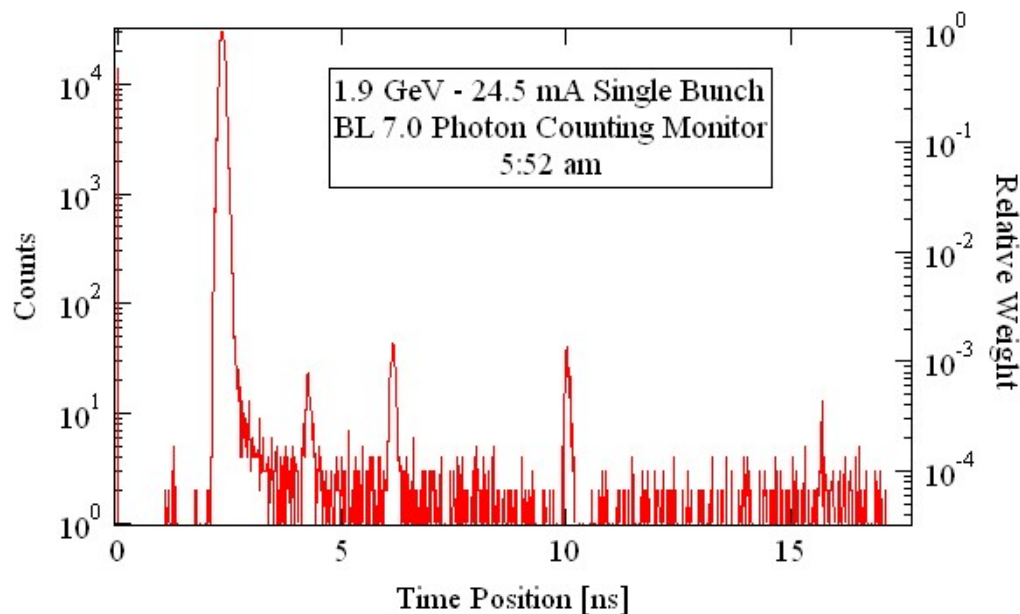
A.S. Tremsin, et al., Nucl. Instr. Meth. A 580 (2007) 853.
A.S. Tremsin, et al., IEEE Trans. Nucl. Sci. 54 (2007) 706.



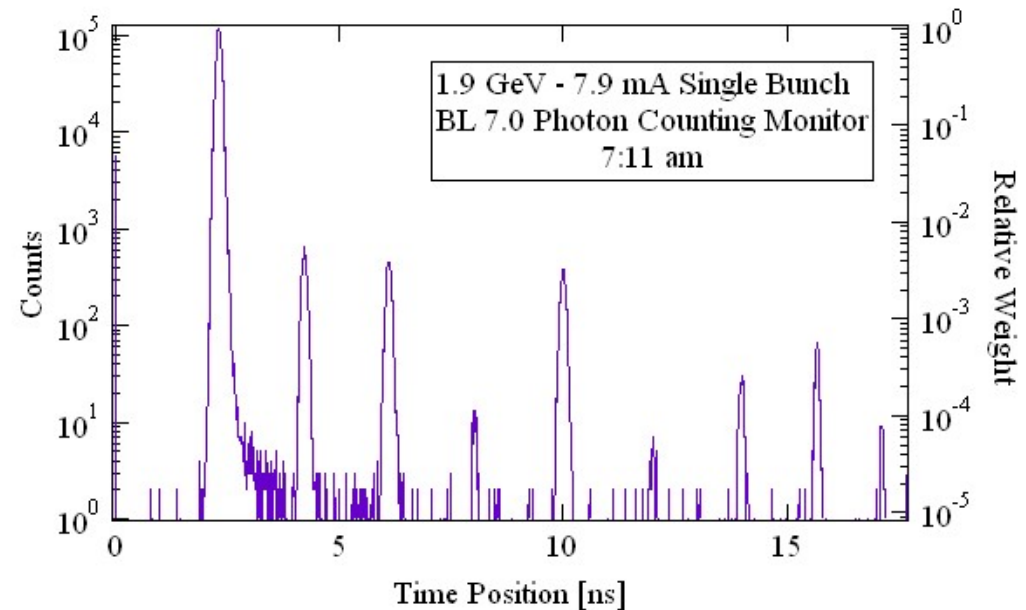
MCP detectors dynamic range

Advanced Light Source at Berkeley: two bunch mode

Bunch population after injection



Bunch population ~76 min later



Diffusion of electrons between the adjacent bunches can be studied with the detection system

W. E. Byrne, et al., Proceedings EPAC'06, June 2006

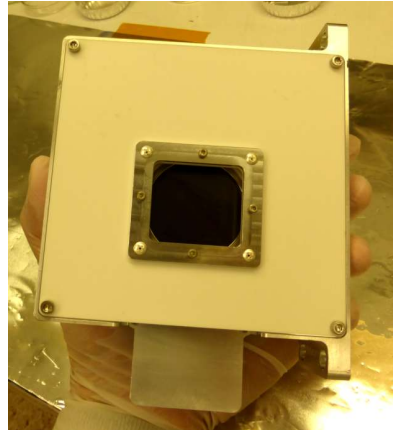
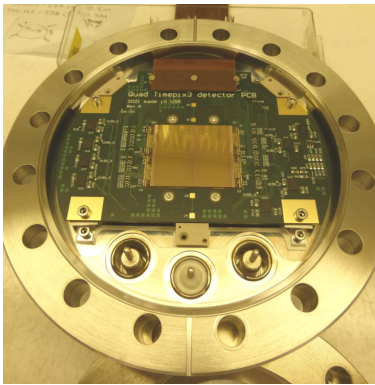


Can this timing resolution of MCP detectors be sustained for:

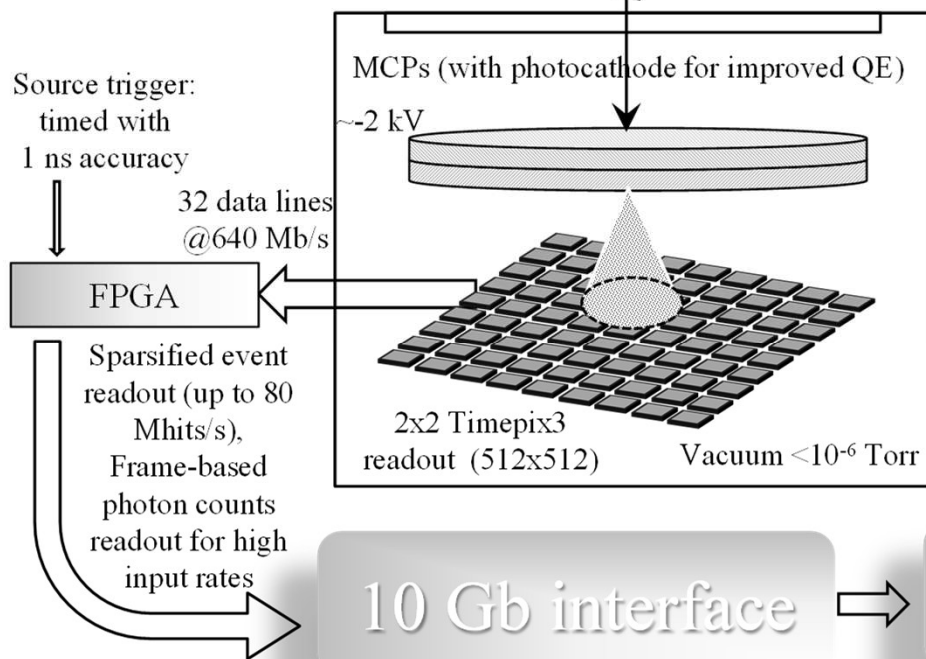
- **High spatial resolution (~6 μm)**
- **High counting rates (>100 MHz)**
- **High dynamic range**
- **Large format detectors (5-10 cm)**
- **Many simultaneous particles (thousands)**



MCP/Timepix3 detector (28x28 mm²)

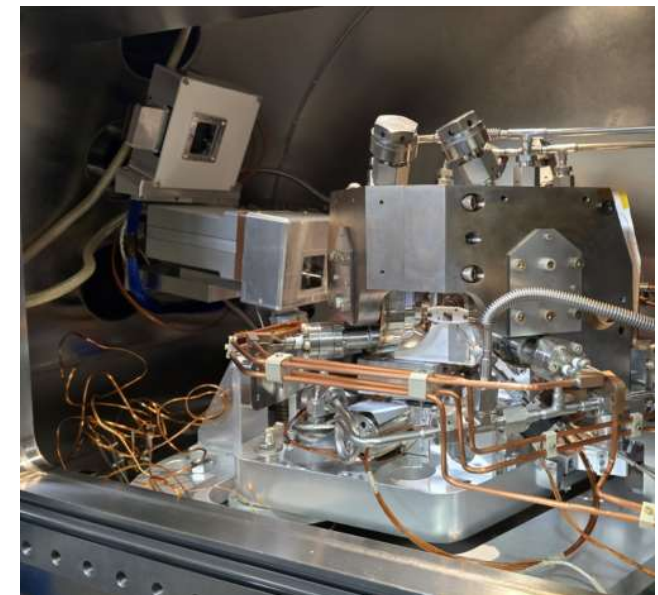


6 inch ConFlat flange Fully in-vacuum system



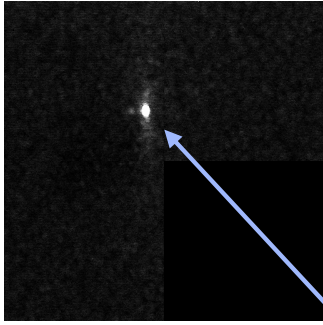
- **Data-driven readout**
- **No dead time**
- **Both high spatial and high timing resolution possible** (two counters in each pixel)
- **Maximum event rate ~100 Mhits/s** (~ 10^7 photons/s)

512x512 matrix of 55 μm pixels with <math><70</math> e rms noise. Event driven mode enables high timing resolution (~1.6 ns) with time walk correction.

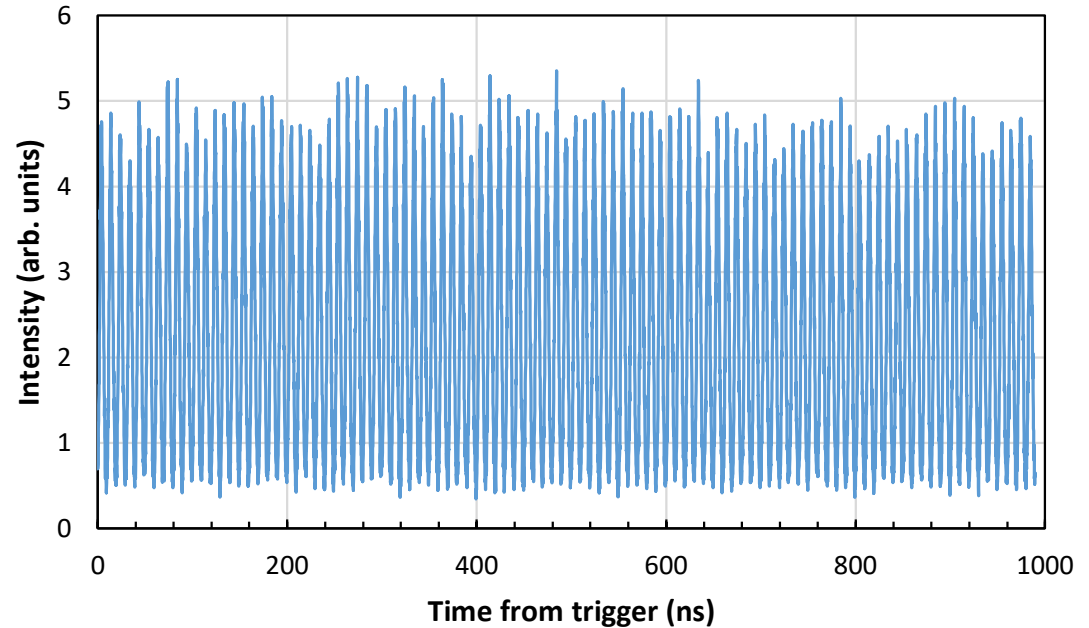




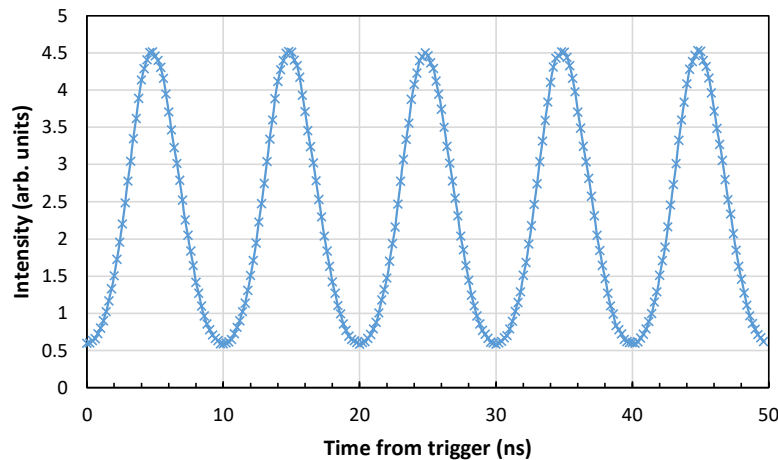
Timing resolution: MAX-IV synchrotron bunches



Data integrated over a small spot on the detector. Synchrotron trigger is used to synchronize the detector with the ring at 100 kHz repetition rate.



Histogram of time differences between measured photons and the source trigger.



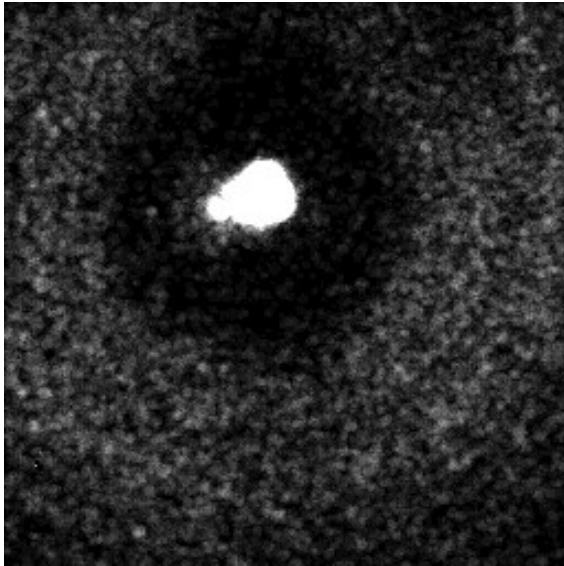
Individual synchrotron bunches (10 ns apart) are resolved.

Time resolution

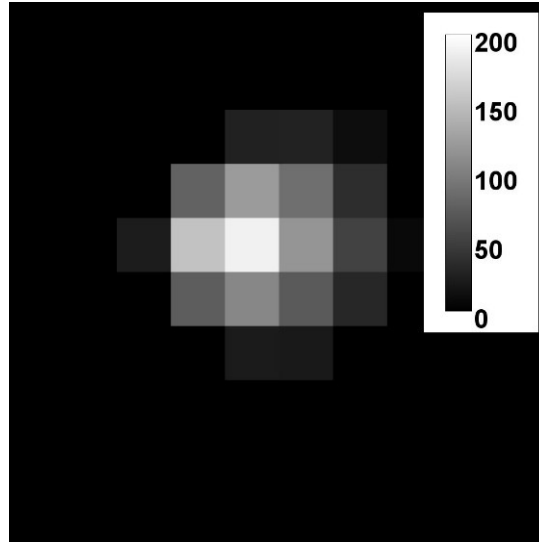
1.78 ns rms (4.2 ns FWHM)



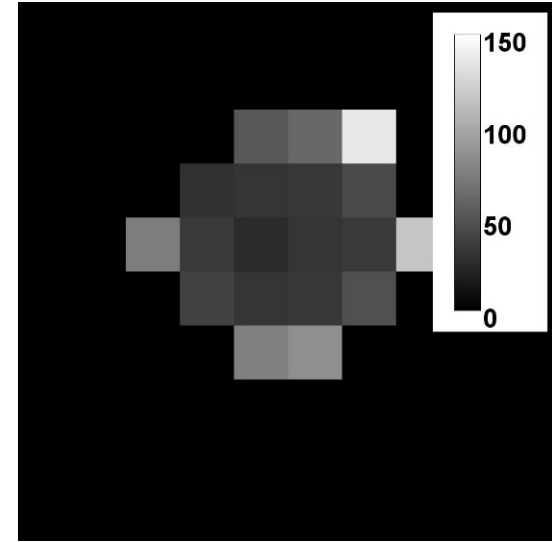
Detector calibration for accurate ToA with pulsed UV LED



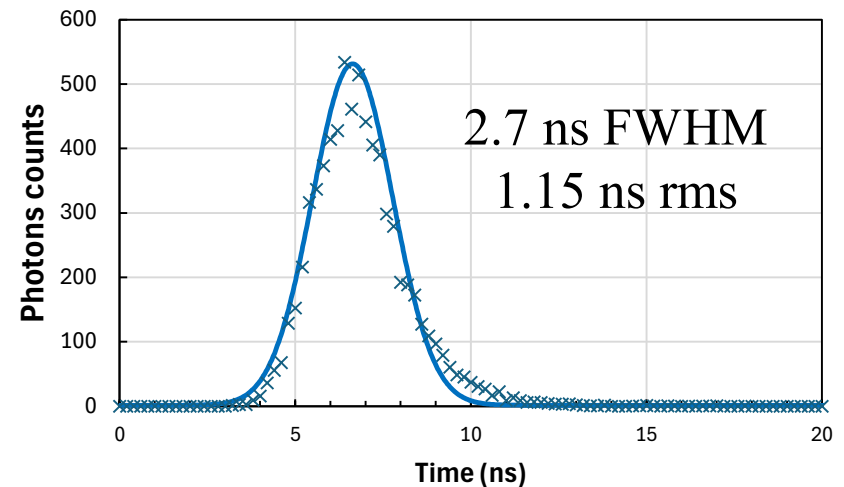
UV LED focused to a small area on the detector



ToT values for a single photon



ToA values for a single photon





Soft X-ray counting for pump-probe experiments at extremely high input fluxes

MCP saturation - extracted charge needs to be replenished

Can MCP be “switched ON/Off” in ~ns time?

In collaboration with

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C. Schüßler-Langeheine², N. Pontius²

¹Freie Universität Berlin

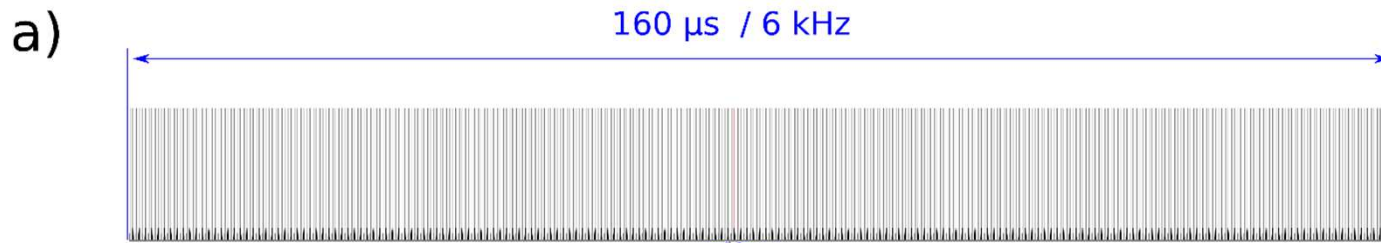
²Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (BESSY II)



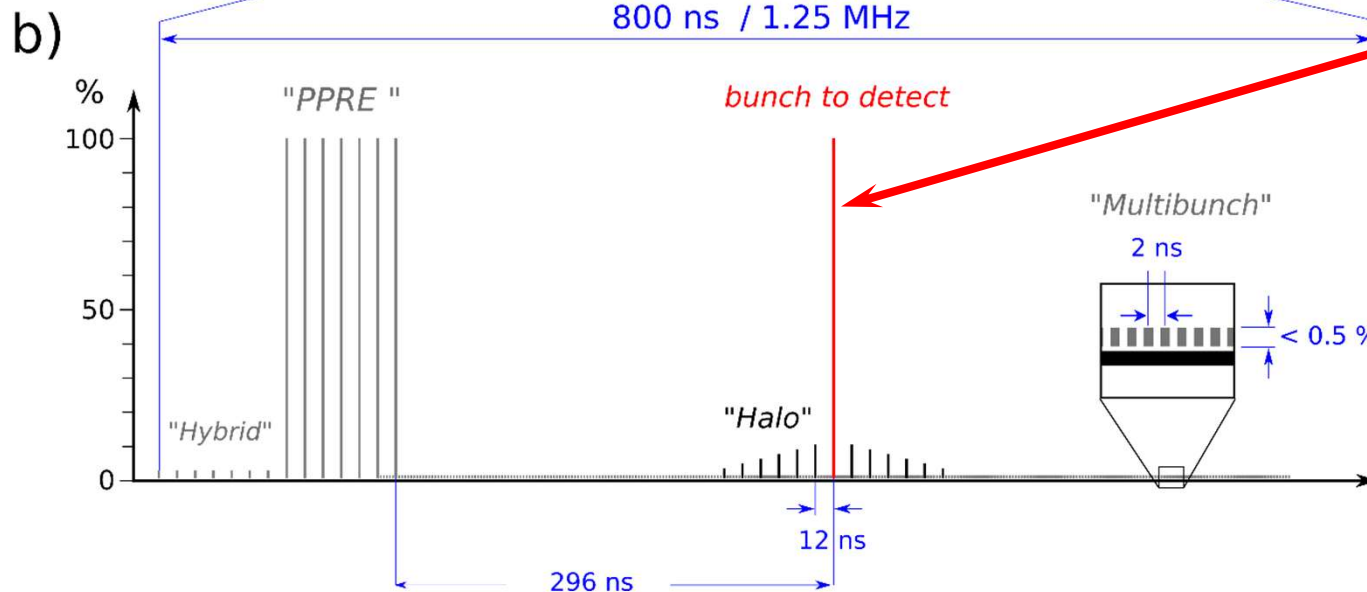
Soft X-ray counting for pump-probe experiments at extremely high input fluxes

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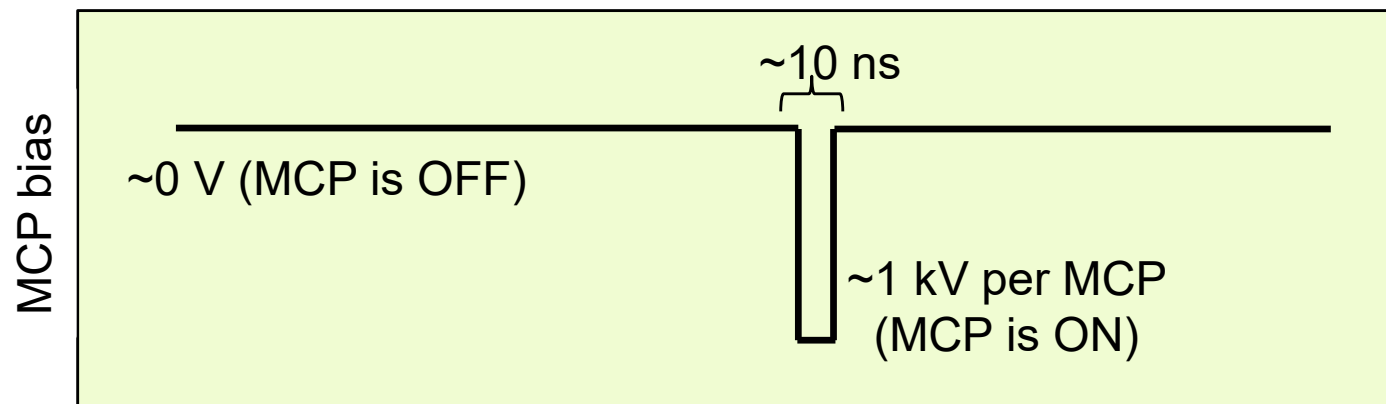
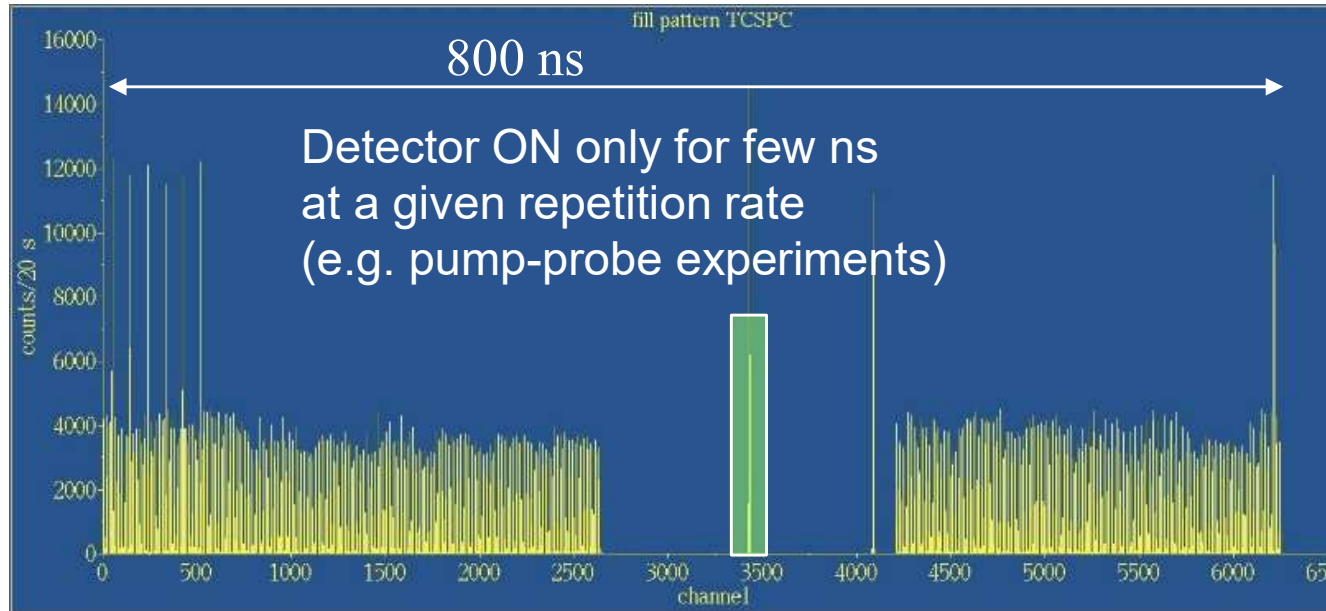
Detect only one short pulse, rest of the time detector is OFF





Solution: gating the MCP accelerating bias

Beam intensity vs. time

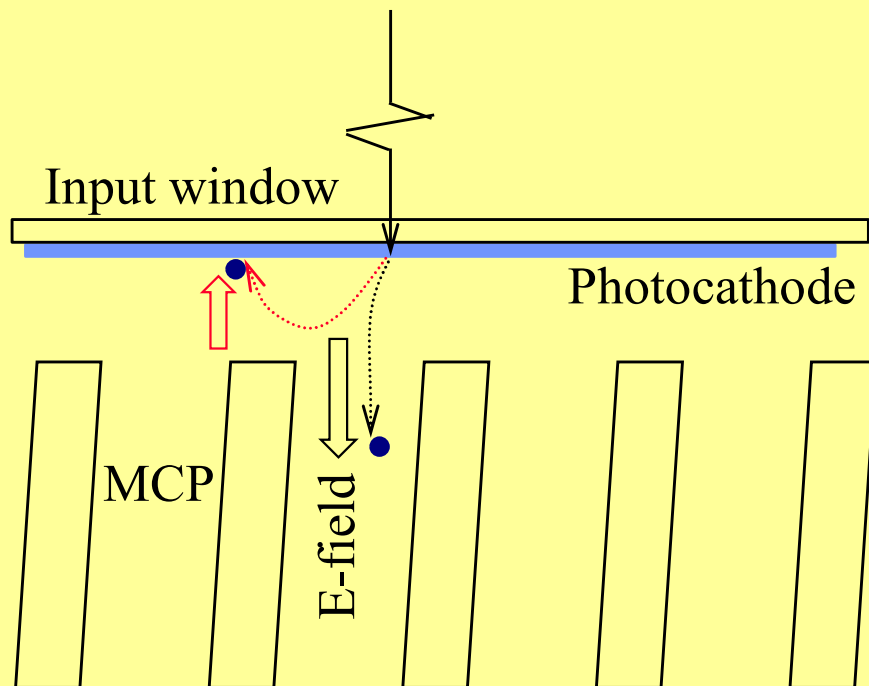




Time gating in MCP detectors

Image intensifiers (visible photons):

photocathode is gated at \sim ns scales.
Photoelectrons have \sim eV energies, easy to
stop them by reversing the electric field
(<100 V bias steps, almost no current)



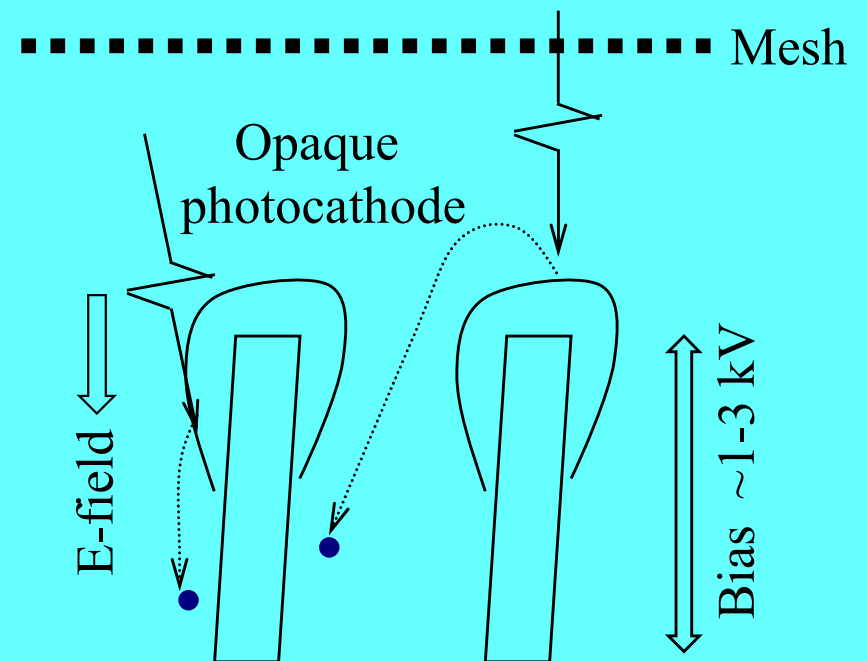
Soft X-ray detectors with opaque photocathodes:

need to turn the MCP OFF (bias \sim kV scale)
large strip currents (tens of μ A)



Electron repelling mesh

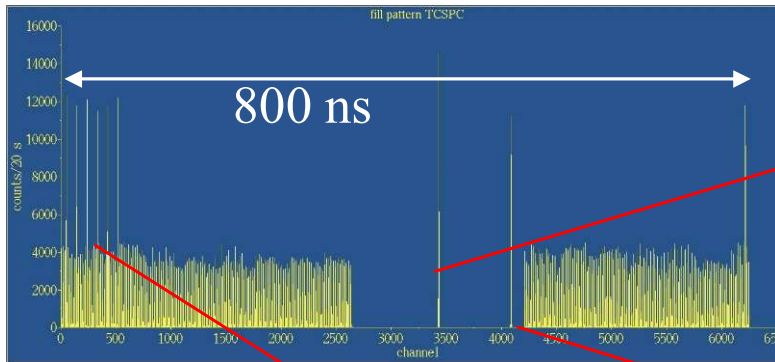
Photocathodes deposited directly
on MCP



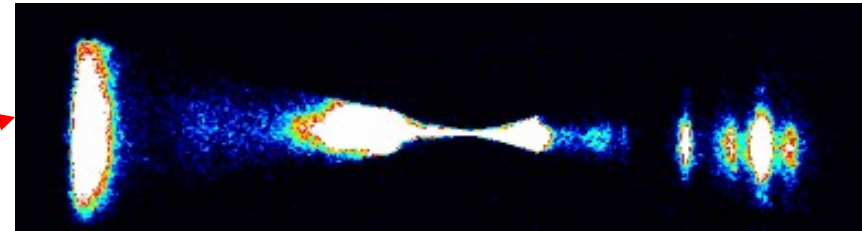


Images at different phases of the ring

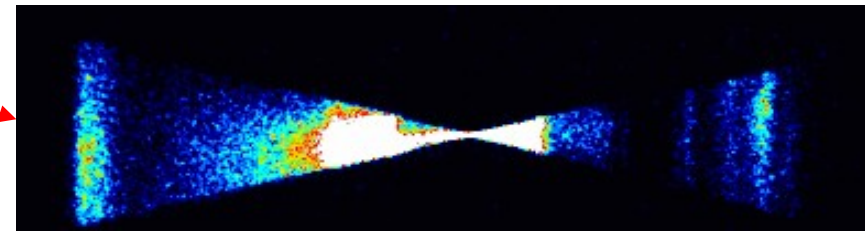
Beam intensity vs. time



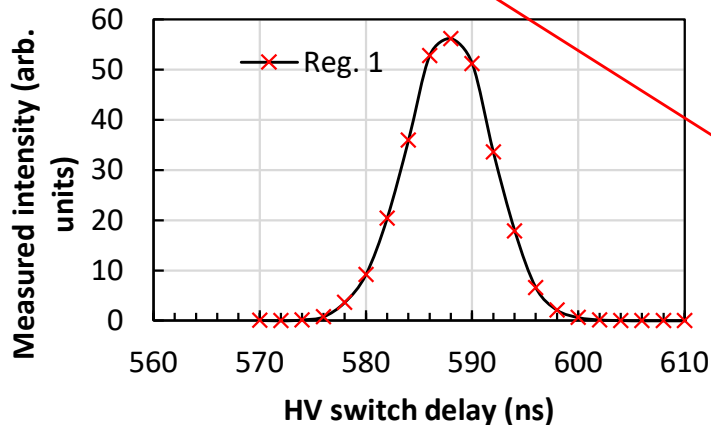
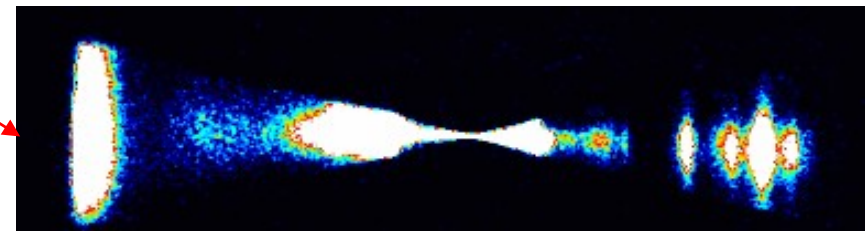
T = 588 ns



T = 672 ns



T = 966 ns



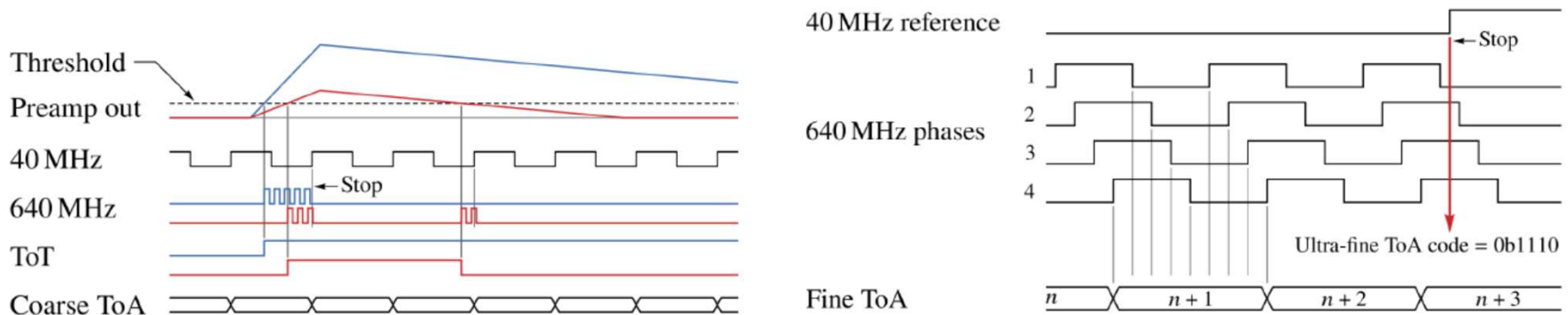
Intensity distribution is different for different phases of the storage ring cycle.

Can image them independently from each other, all in one measurement.



Sub-ns timing resolution with Timepix4

		Timepix3	Timepix4
Technology		130nm – 8 metal	65nm – 10 metal
Pixel Size		55 x 55 μm	55 x 55 μm
Pixel arrangement		3-side buttable 256 x 256	4-side buttable 512 x 448
Sensitive area		1.98 cm^2	6.94 cm^2
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA
		Event Packet	48-bit
		Max rate	0.43x10 ⁶ hits/mm ² /s
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)
		Frame	Zero-suppressed (with pixel addr)
		Max count rate	~0.82 x 10 ⁹ hits/mm ² /s
TOT energy resolution		< 2KeV	< 1KeV
TOA binning resolution		1.56ns	195ps
TOA dynamic range		409.6 μs (14-bits @ 40MHz)	1.6384 ms (16-bits @ 40MHz)
Readout bandwidth		$\leq 5.12\text{Gb}$ (8x SLVS@640 Mbps)	$\leq 163.84\text{ Gbps}$ (16x @10.24 Gbps)
Target global minimum threshold		<500 e ⁻	<500 e ⁻





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Pixel arrangement		3-side buttable 256 x 256	4-side buttable 512 x 448	
Sensitive area		1.98 cm^2	6.94 cm^2	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	
		Event Packet	48-bit	64-bit
		Max rate	0.43x10 ⁶ hits/mm ² /s	3.58x10⁶ hits/mm²/s
	Max Pix rate	1.3 KHz/pixel	10.8 KHz/pixel	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)
Max count rate		~0.82 x 10 ⁹ hits/mm ² /s	~5 x 10 ⁹ hits/mm ² /s	
TOT energy resolution		< 2KeV	< 1KeV	
TOA binning resolution		1.56ns	195ps	
TOA dynamic range		409.6 μs (14-bits @ 40MHz)	1.6384 ms (16-bits @ 40MHz)	
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With the knowledge of MCP/Timepix3 detector timing resolution we are confident in getting to sub-ns timing resolution with

High spatial resolution,

High counting rates,

Large dynamic range

Many simultaneous particles



MCP/Timepix detectors enable particle counting with

- High spatial resolution ($\sim 6 \mu\text{m}$)
- High time resolution ($\sim 2 \text{ ns}$ is now, $\sim 200 \text{ ps}$ coming)
- High counting rates ($> 100 \text{ MHz}$)
- High dynamic range
- Many simultaneous particles (hundreds to thousands)
- Large format detectors become possible with Timepix4

Thank you for your attention!

This work was supported in part by US Department of Energy and NASA.

The work on MCP/Timepix detector was done within the Medipix collaboration.