Detectors for the European X-ray Free Electron LASER

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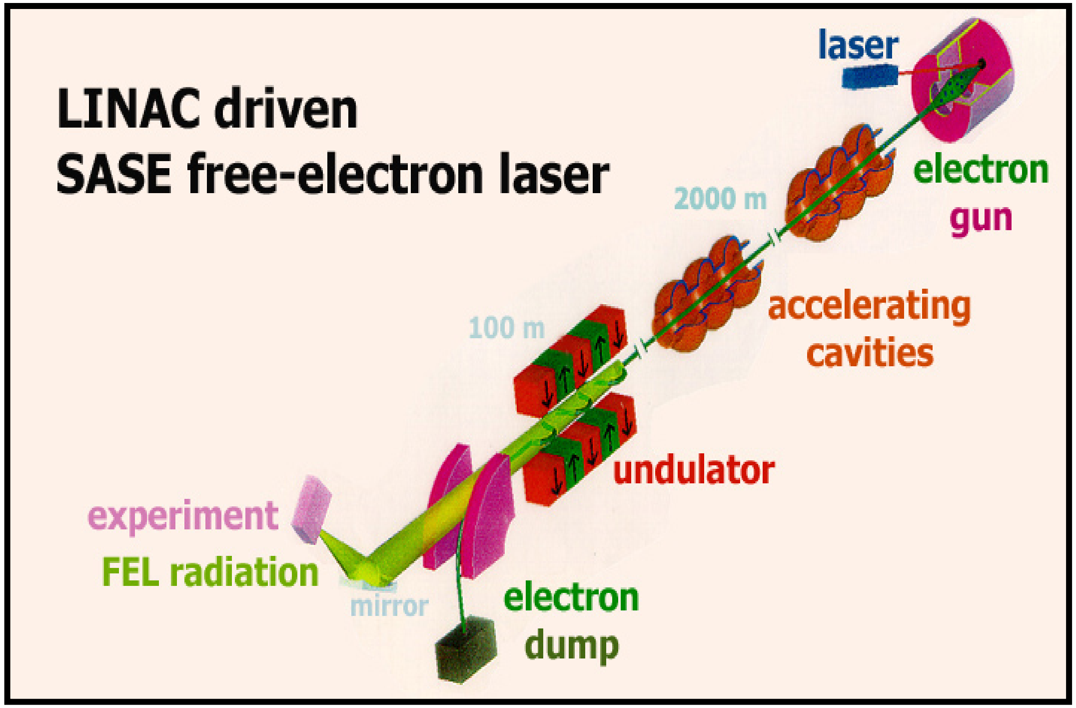
IWORID-8

XFEL
X-Ray Free-Electron Laser

Detectors for XFEL

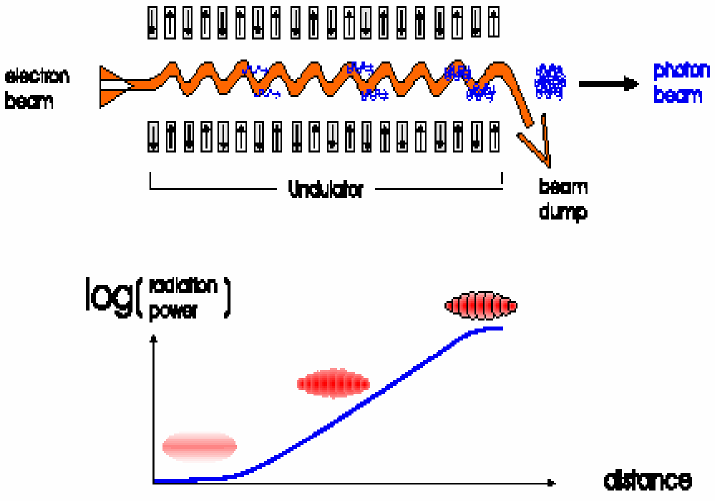
- The XFEL project
- Status.
- Science and the first set of imaging detectors.
- Beam monitoring and other detectors.
- Challenges.
- Questions.

FEL: Free electron LASER. An overview.



3 main components.

- Bunch production
- Acceleration
- SASE LASER



Photon peak power in saturation ~ 10 GW

What does an FEL deliver that is special

- Very short pulse width ~100fs
- Very high flux ~kW
  - 100s uJ per pulse.
  - Pulse rates of 10s MHz.
- High level of coherence.

FLASH (VUV FEL) at DESY

Objective: lasing at λ ~ 6 nm

(2006-2007)

Lasing at 32nm achieved in Jan 2005

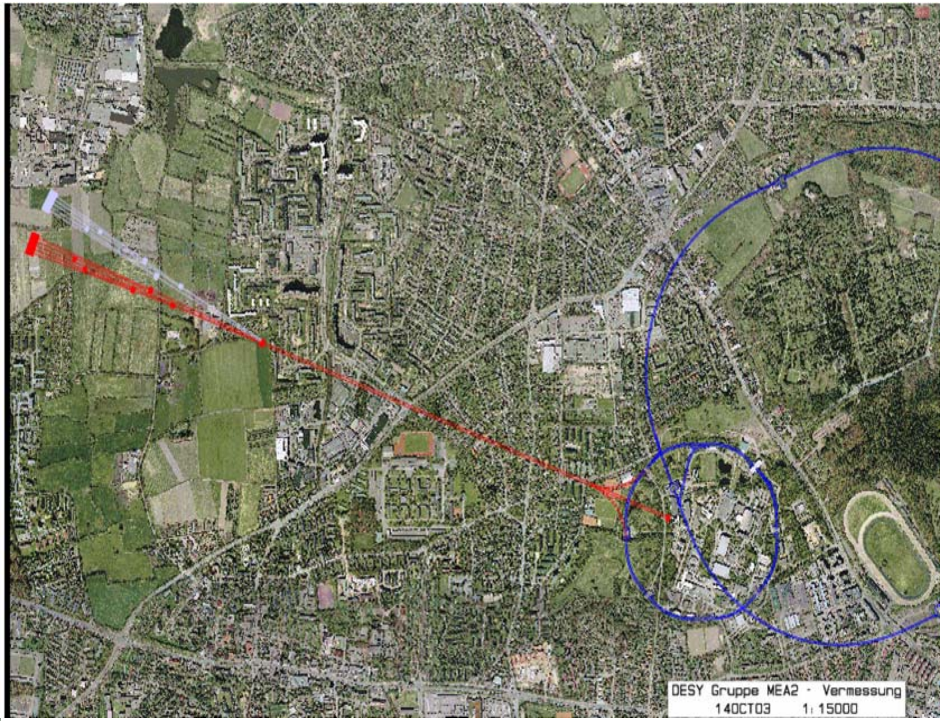
Present status :

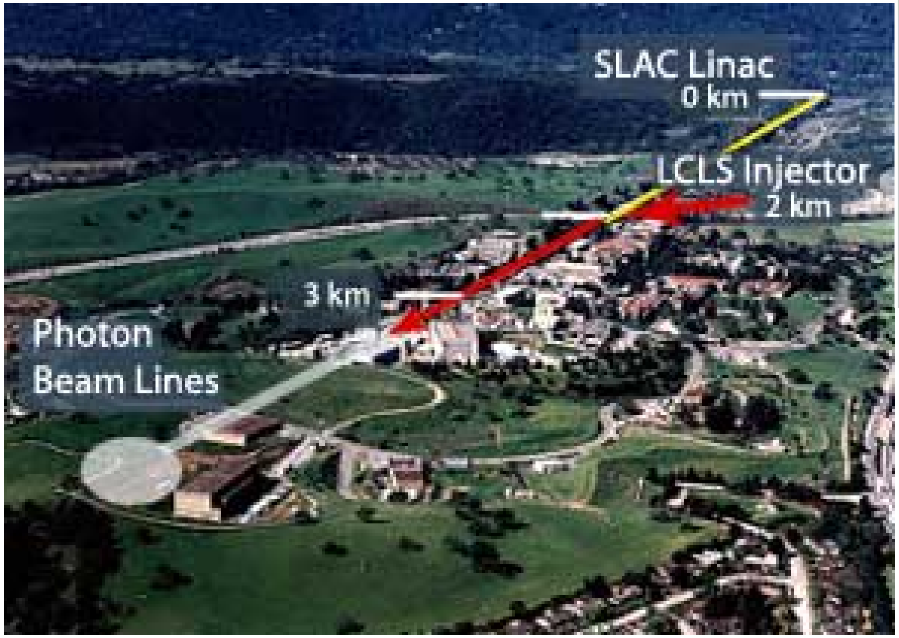
Now lasing at 13nm!

User operation started on 5 exp.stations (Aug. 2005)

Linac-based X-ray Free-electron Lasers

European XFEL Project, Hamburg →



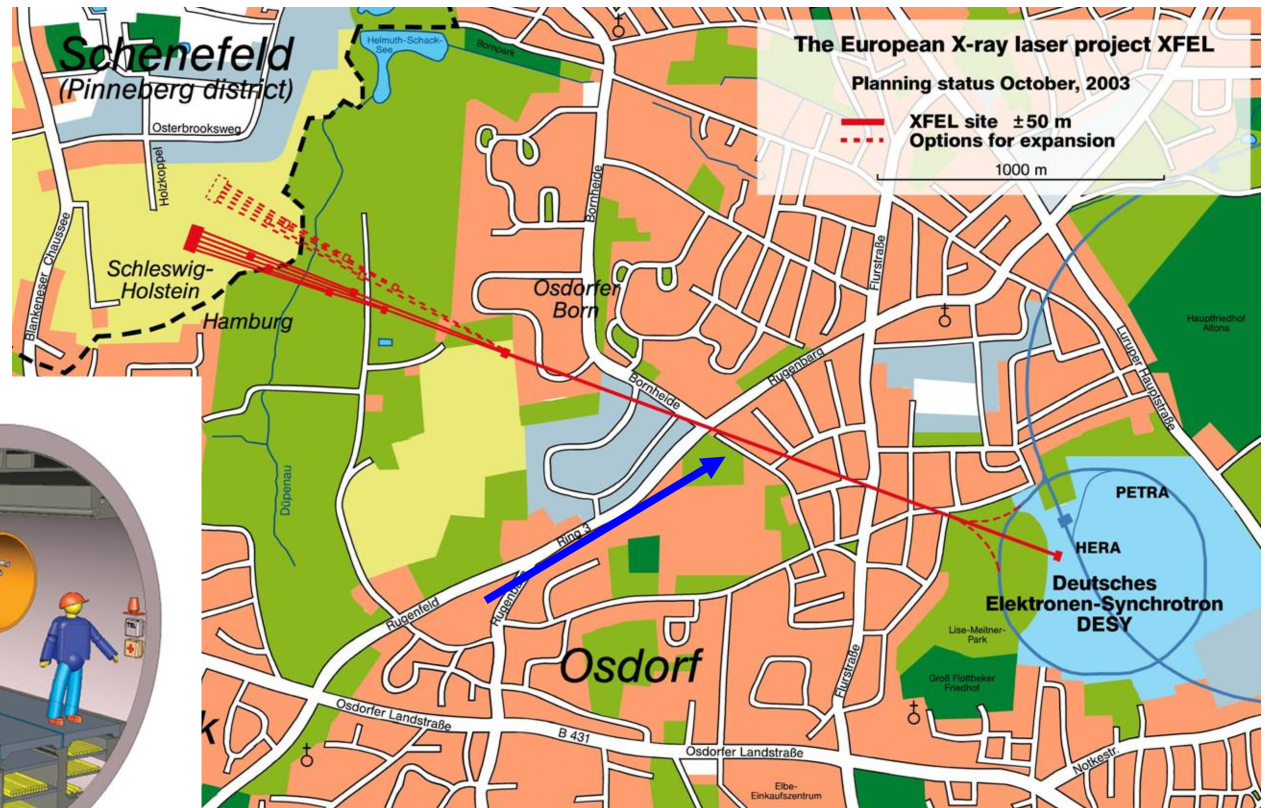


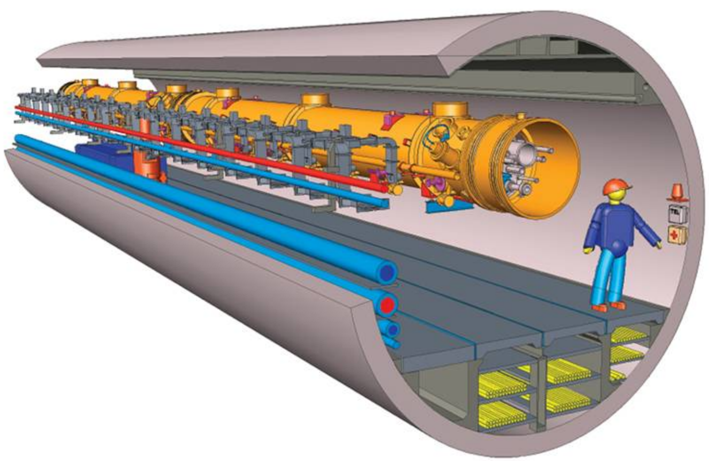
← Linear Coherent Light Source, SLAC, Stanford

XFEL
X-Ray Free-Electron Laser
DESY

European XFEL project
Site based near DESY – Hamburg.

3.4km





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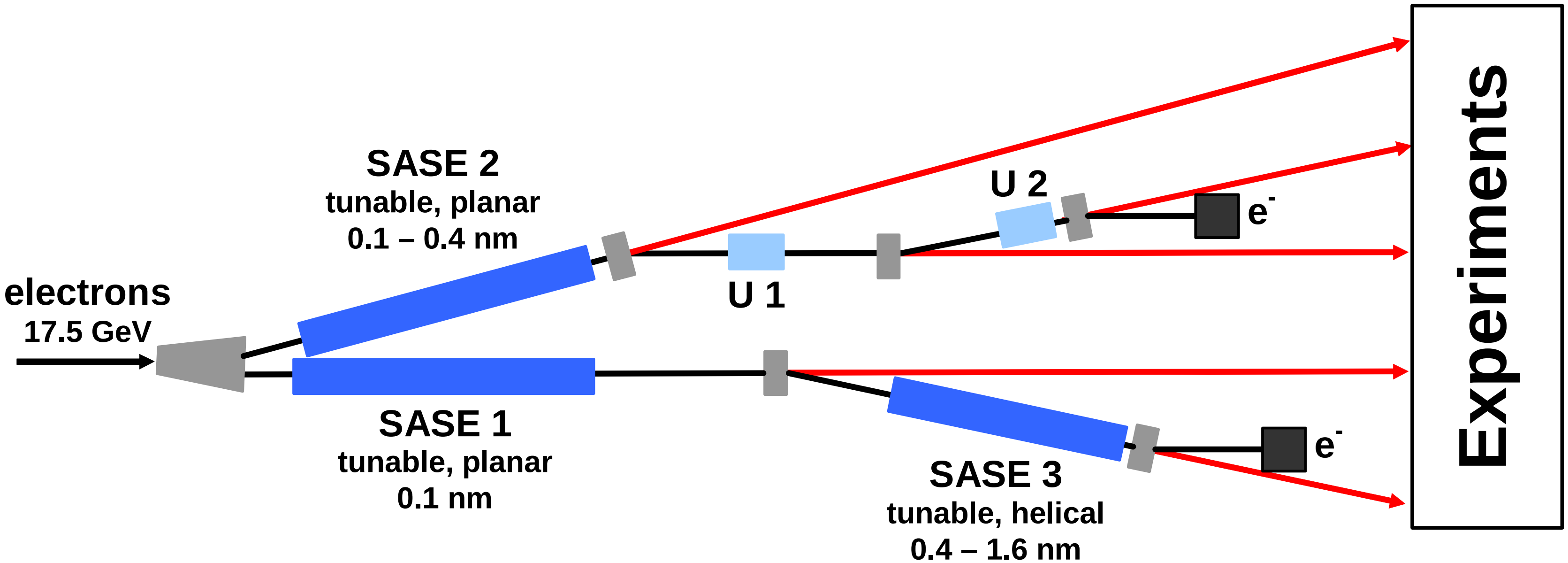
X-Ray Free-Electron Laser

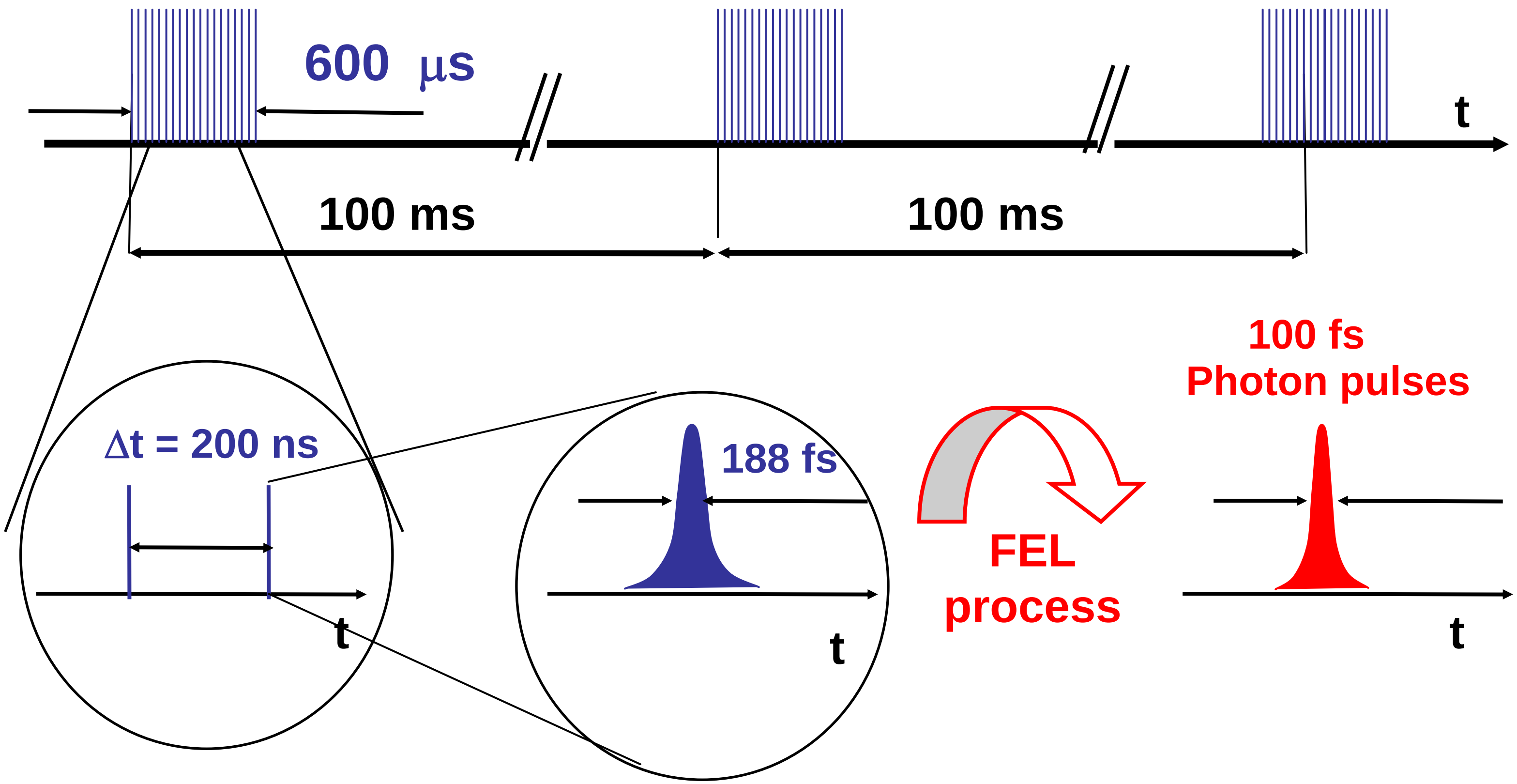
Undulator and Beamline Layout



Distribution of the 5 beamlines, with 2 experimental stations each

Time Structure

Electron bunch trains
(with up to 3000 bunches à 1 nC)



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SASE Source characteristics

Parameter	Unit	SASE 1	SASE 2		SASE 3		
Electron energy	GeV	17.5	17.5	17.5	17.5	17.5	10.0**
Wavelength	nm	0.1	0.1	0.4	0.4	1.6	6.4
Photon energy	keV	12.4	12.4	3.1	3.1	0.8	0.2
Peak power	GW	20	20	80	80	130	135
Average power*	W	65	65	260	260	420	580
Photon beam size (FWHM)	µm	70	85	55	60	70	95
Photon beam divergence (FWHM)	µrad	1	0.84	3.4	3.4	11.4	27
Coherence time	fs	0.2	0.22	0.38	0.34	0.88	1.9
Spectral bandwidth	%	0.08	0.08	0.18	0.2	0.3	0.73
Pulse duration	fs	100	100	100	100	100	100
Photons per pulse	#	10^{12}	10^{12}	1.6×10^{13}	1.6×10^{13}	1.0×10^{14}	4.3×10^{14}
Average flux	#/s	3.3×10^{16}	3.3×10^{16}	5.2×10^{17}	5.2×10^{17}	3.4×10^{18}	1.4×10^{19}
Peak brilliance	B	5.0×10^{33}	5.0×10^{33}	2.2×10^{33}	2.0×10^{33}	5.0×10^{32}	0.6×10^{32}
Average brilliance*	B	1.6×10^{25}	1.6×10^{25}	7.1×10^{24}	6.4×10^{24}	1.6×10^{24}	2.0×10^{23}

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SR (Spontaneous) characteristics

Parameter			
photon energy [keV]	20	50	200
peak power [MW]	15	126	81
average power [W]	59	504	324
photon beam size (FWHM) [µm]	84	83	83
photon beam divergence (FWHM) [µrad]	3.5	2.9	2.5
pulse duration (FWHM) [fs]	100	100	100
number photon per pulse [x10^8]	3.3	2.8	1.1
average flux of photons [x10^13/s/0.1%]	1.3	1.1	4.4
peak brillance [x10^28]*	1.4	2.9	1.4
average brillance [10^19]*	5.8	1.2	56

Timescales

- Completion of preparation : 2006/07.
- Construction phase starts 2007.
- Initial construction complete ~2012/13.
- Operation starts ~2014.

- LCLS : Starts 2009/10. (120Hz)
- SCSS (Japan) : Starts after 2010. (60Hz)

Instruments

- New area of research
- New science areas and techniques.

- Vast array of new instrumentation required, for example...
  - Optics.
  - Sample handling.
  - Detectors.

Detectors for XFEL

- Approach
  1. Define initial flagship techniques
  2. Define initial detector requirements.
  3. Develop and agree formal specifications.
  4. Initiate construction ASAP.

  5. Identify key areas of necessary R&D.
  6. Identify other key detection areas.
  7. Execute ‘parallel’ development programme.

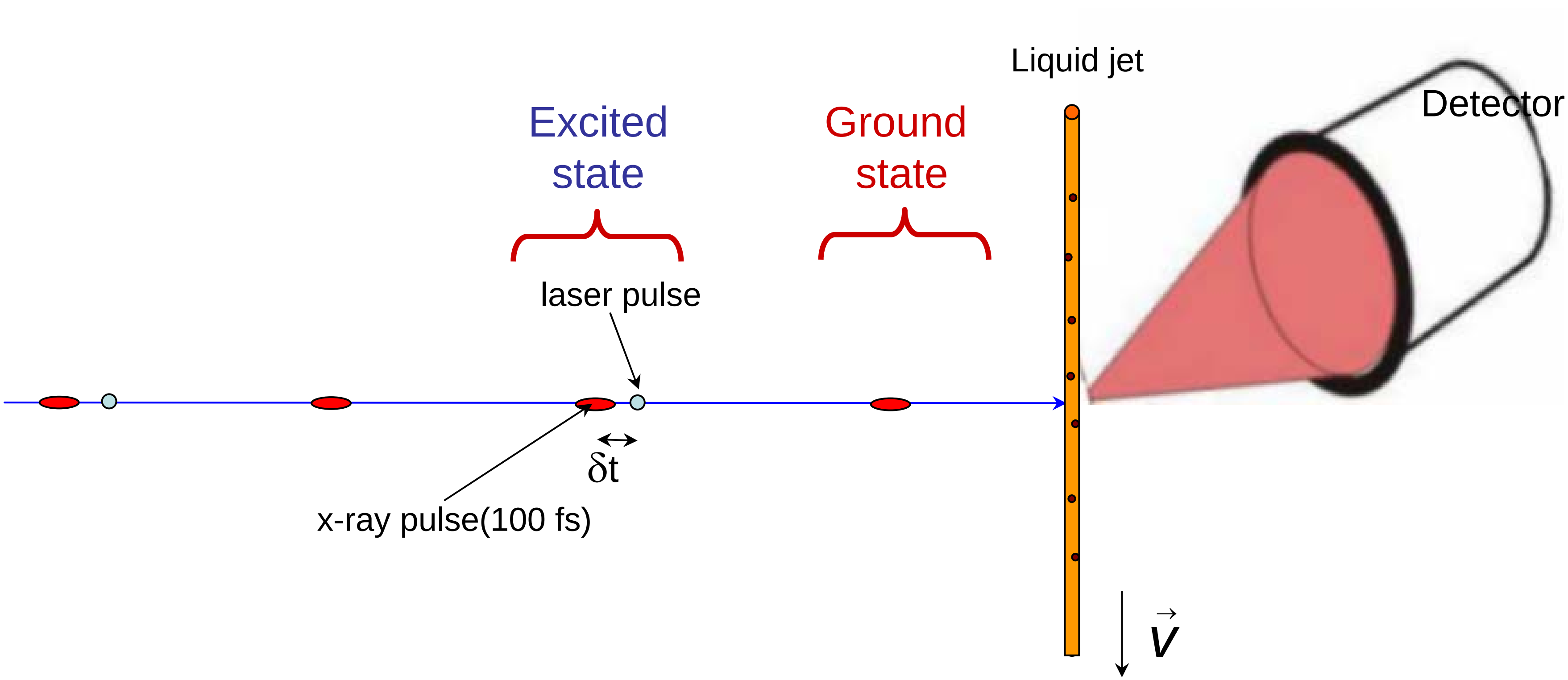
- UK(CCLRC) and XFEL presently working together on 2-3 and 5-6.

Science

- 5 flagship science techniques.
  - Pump probe Non-crystalline diffraction.
  - Pump probe diffraction.
  - Coherent imaging.
  - Single particle imaging.
  - X-ray photcorrelation spectroscopy.

- Overview of science.
- Review of initial imaging detector spec's.

Area/Experiment 1: Pump-Probe on non-crystalline material.



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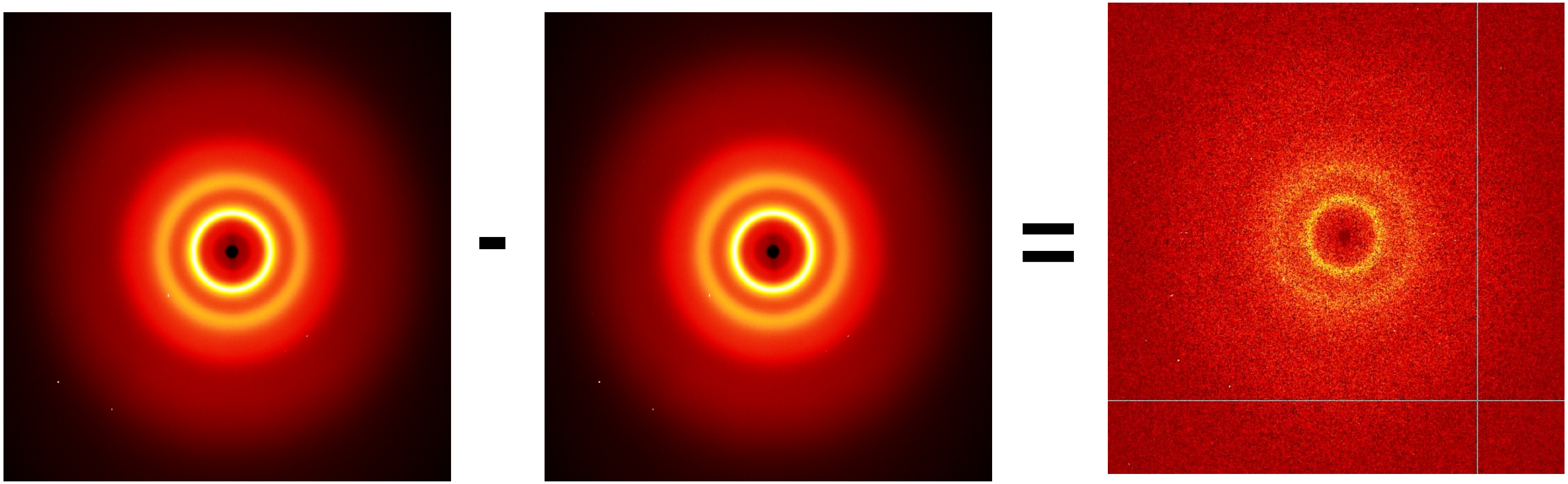
Area/Experiment 1: Pump-Probe on non-crystalline material (Wulff)



Excited state - **Ground state** = **Difference**

XFEL
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DESY

Area/Experiment 1: Pump-Probe on non-crystalline material (Wulff)

Detector size or angular range:

Q_{max} = 4πsinθ/λ = 10 $Å^{-1}$; λ=1Å ➔ 2θ_{max} = +/- 100 degrees

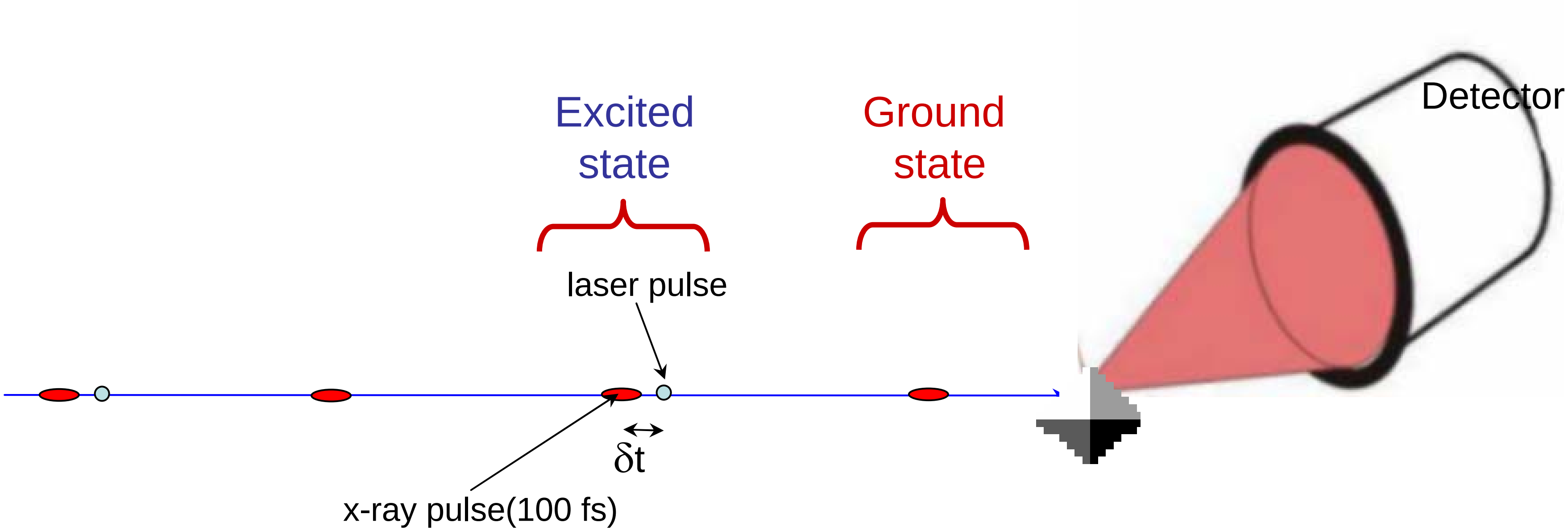
Pixel size or angular resolution:

5-10 oscillations; ➔ 2x safety margin=20 oscillations max
➔10 sampling points per oscillation ➔ 200 pixels
➔500 pixels for +/- 100 degrees

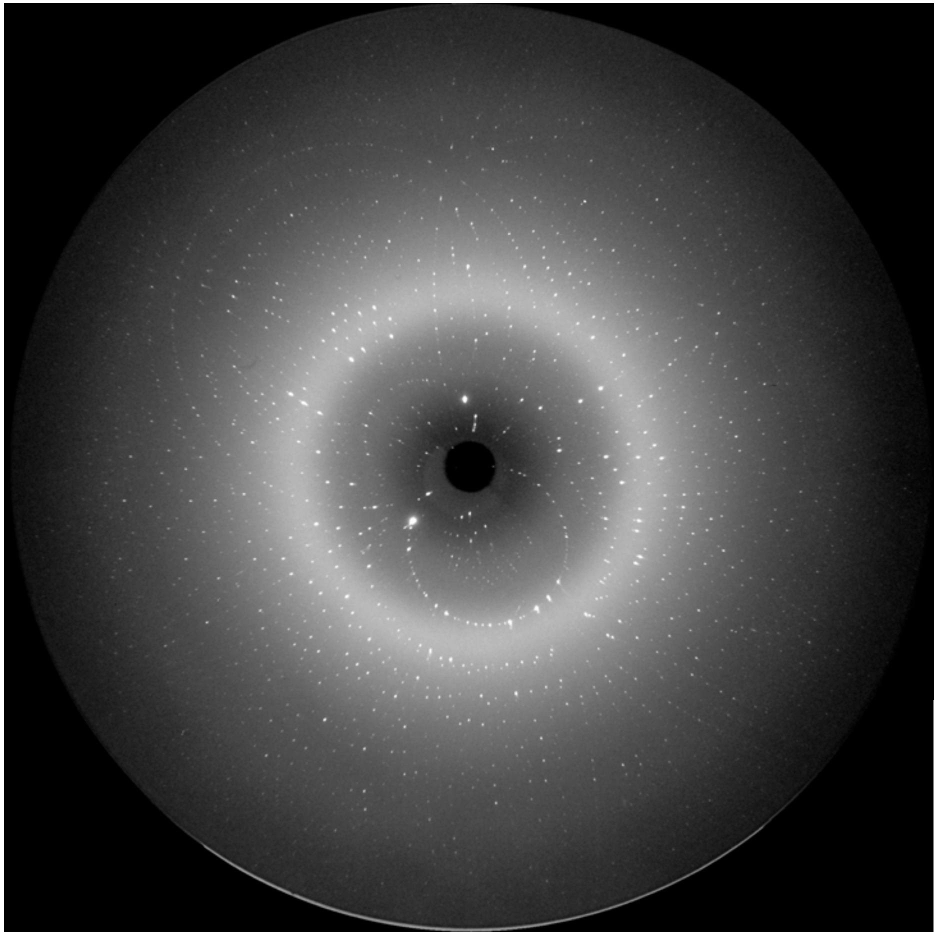
Area/Experiment 1: Pump-Probe on non-crystalline material (Wulff)

	Detector I: Pump Probe, Non-Crystalline	
XFEL radiation source	SASE-1 (and U1)	
Photon energy range	8 – 12	keV
Energy resolution	None	eV
Quantum efficiency	>0.8	
Radiation hardness	10^{16}	12 keV X-ray ph/pixel
Total angular coverage	200	degrees
Angular resolution or pixel size	7	mrad
Number of pixels	500 x 500	
Acceptable tiling constraints	<20% dead area, no circular features	
Maximum local rate	5×10^4	ph/pixel/100fs pulse
Maximum global rate	3×10^7	ph/100fs pulse
Timing	minimum 10	Hz (but see below)
Flat field response	1%	
Dark current	*<0.01 eq X-ray photon*	per pixel per exposure
Read-out noise	*<0.01 eq X-ray photon*	per pixel
Linearity	1%	
Point spread function	<1 pixel FWHM	1 pixel = 7 mrad!
Image latency	< 1/1000	in subsequent image
Operating environment	Ambient	
Vacuum compatibility	No	
Maintenance	See below.	
Other requirements	Central hole	

Area/Experiment 2: Pump-Probe on crystalline material.



Area/Experiment 2: Pump-Probe on crystalline material



Area/Experiment 2: Pump-Probe on crystalline material (Wulff)

Detector size or angular range:

2dsinθ = λ = 1 Å; d=1Å ➔ 2θ_{max} = +/- 60 degrees

1000 diffraction spots; 300 μm FH1%M ➔ 300 mm

Pixel size or angular resolution:

1000 diffraction spots, ➔ 3000 pixels of 100 μm

	Detector II: Pump Probe Crystalline	
XFEL radiation source	SASE-1 (and/or U1)	
Photon energy range	12	KeV
Energy resolution	No	eV
Quantum efficiency	>0.8	
Radiation hardness	10^{16}	12 keV X-ray ph/pixel
Total angular coverage	120	degrees
Angular resolution or pixel size	100	μm
Number of pixels	3000 x 3000	
Acceptable tiling constraints	<10% dead area	
Maximum local rate	3×10^6 (10^3)	ph/pixel/100fs pulse
Maximum global rate	10^7 (10^5)	ph/s
Timing	10	Hz
Flat field response	1%	
Dark current	<0.01 eq X-ray photon	per pixel per exposure
Read-out noise	<0.01 eq X-ray photon	per pixel
Linearity	1%	
Point spread function	100 um (300 um)	FWHM (FW1%M)
Image latency	10^{-6}	Subsequent images
Operating environment	ambient	
Vacuum compatibility	No	
Maintenance	See below	
Other requirements	Central hole	

Area/Experiment 3/4: Single Particle & Coherence Imaging (Hajdu & Robinson)

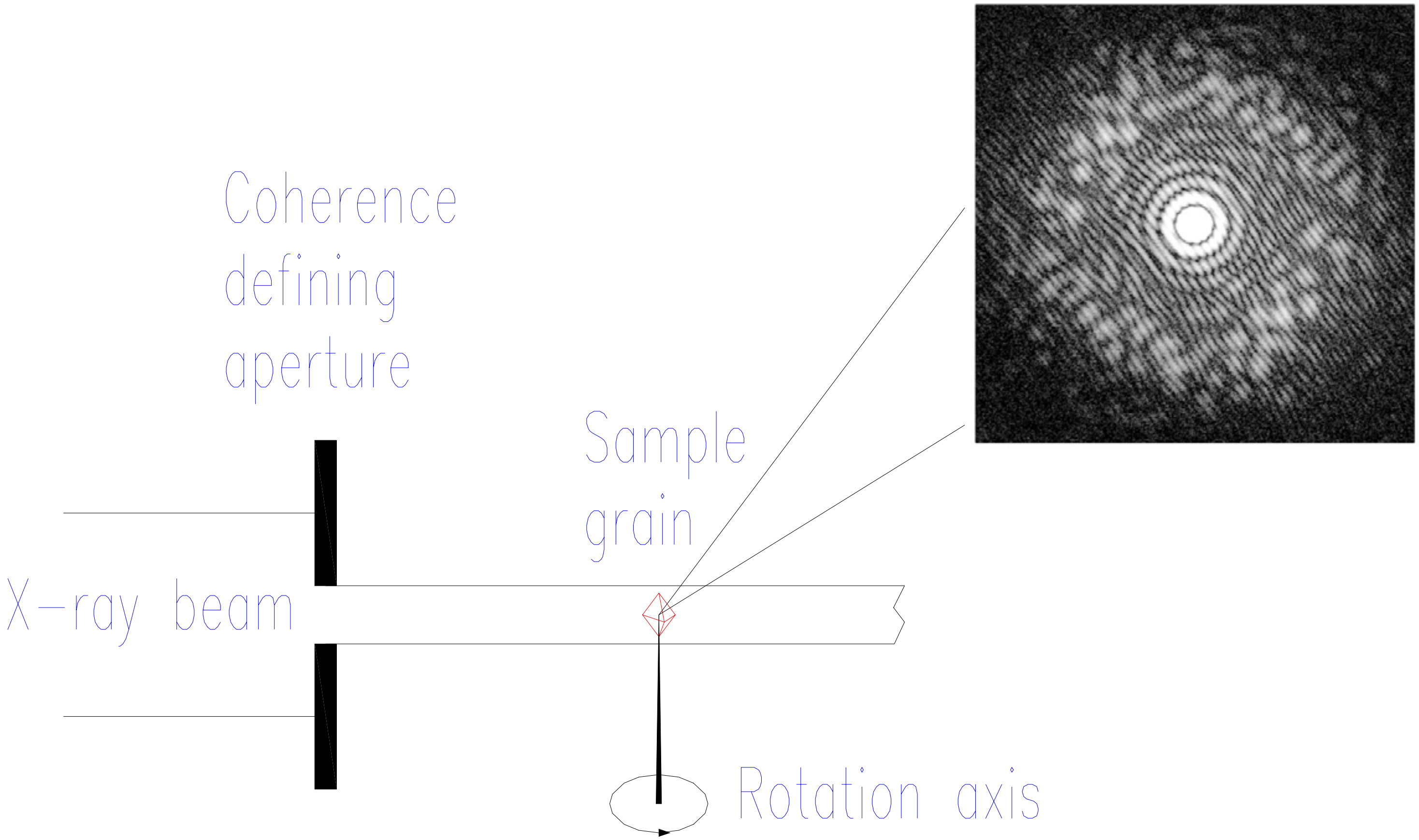


Image reconstructed from an ultrafast FEL diffraction pattern

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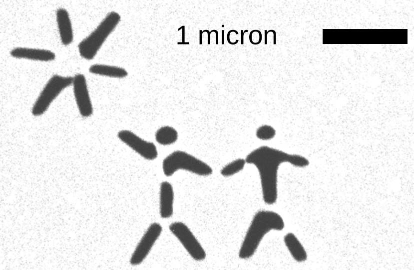
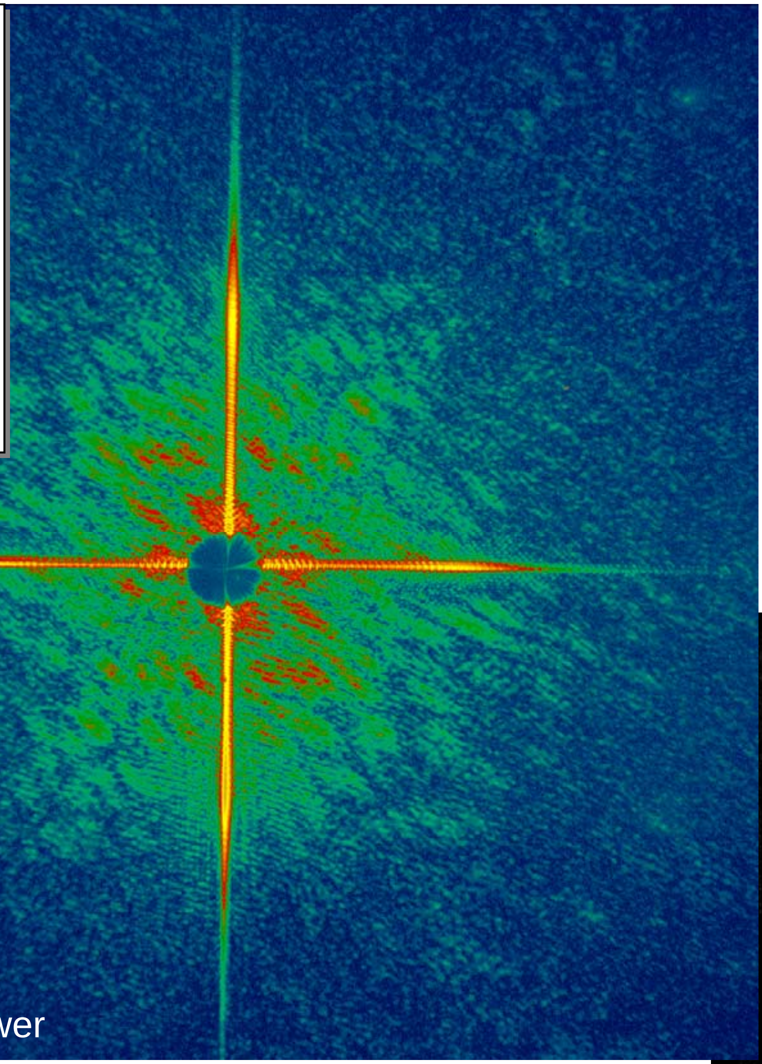
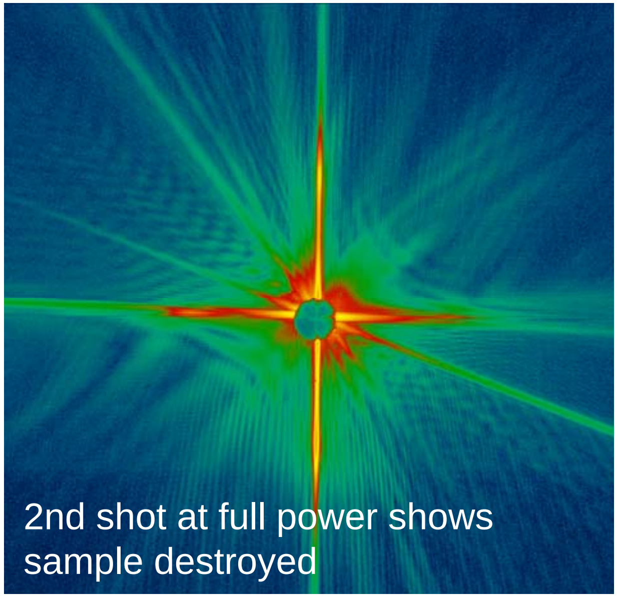
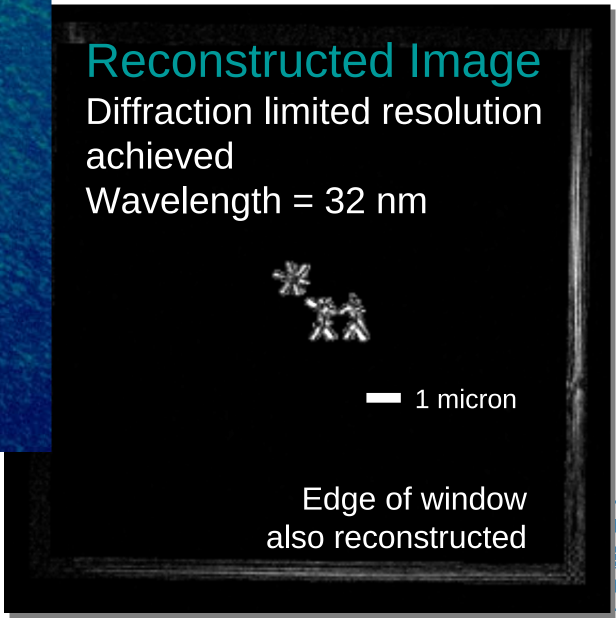
Starting Image



SEM of structure etched into silicon nitride membrane







Reconstruction by A.Barty, 14 Feb 2006

Area/Experiment 3/4: Single Particle Imaging (Hajdu & Robinson)

Detector size or angular range:

Atomic resolution (=1 Å); λ= 1Å ➔ $2\theta_{max}$ = +/- 60 degrees

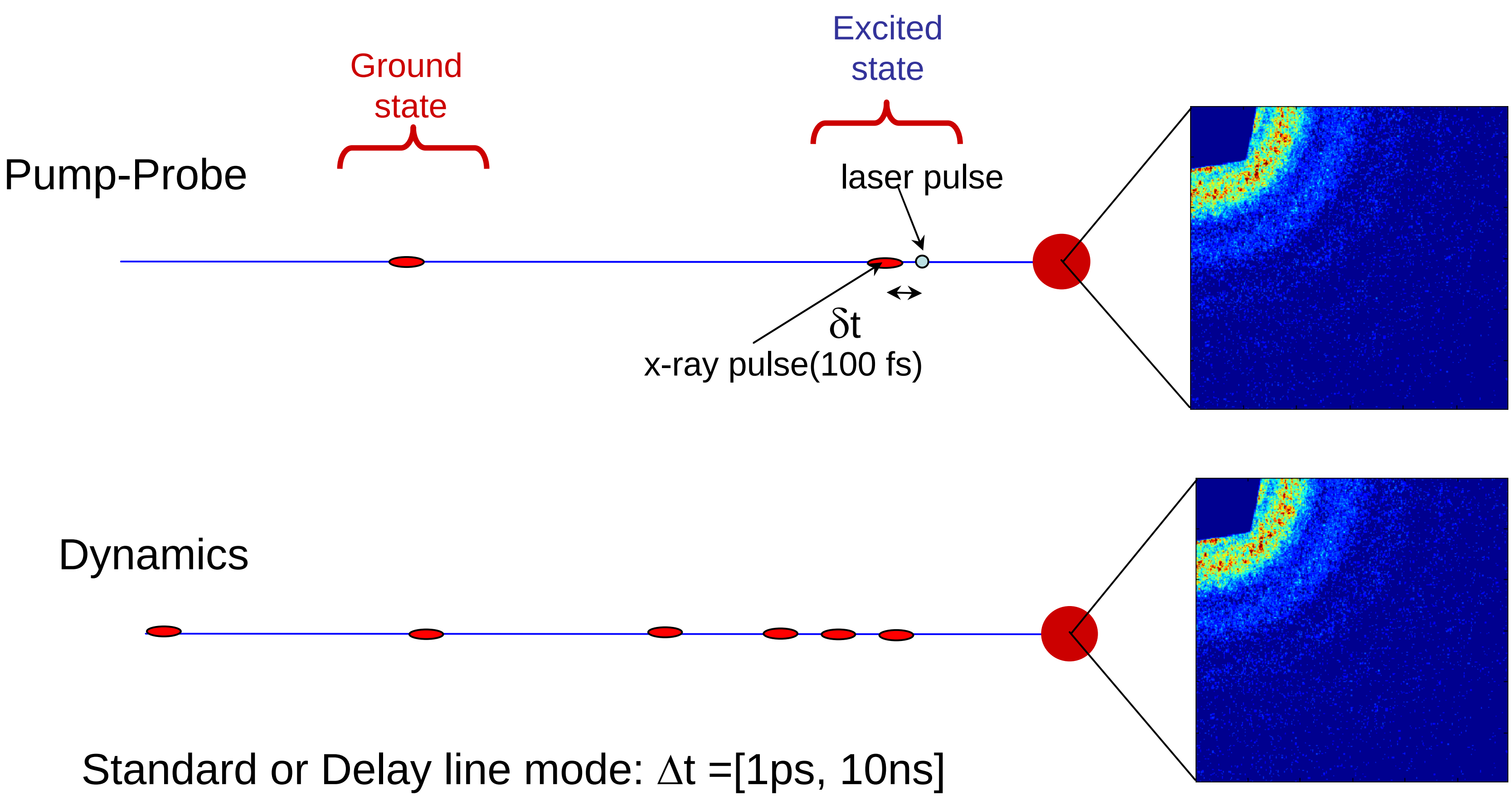
Pixel size or angular resolution:

1000 Å particle (Virus) } ➔ 2000 points; +/- 2θ

Sample with 1Å resolution } ➔ 4000 points

	Detector III: Coherent Diffraction Imaging		Detector IV: Single Particle Imaging	
XFEL radiation source	SASE-2 SASE-3		SASE - 1	
Photon energy range	0.8 – 3.1	KeV	12.4	KeV
Energy resolution	No	eV	No	eV
Quantum efficiency	>0.8		>0.8	
Radiation hardness	$2\ 10^{14}$	12 keV X-ray ph/pixel	10^{16}	12 keV X-ray ph/pixel
Total angular coverage	120	degrees	120	degrees
Angular resolution or pixel size	0.1	mrad	0.5	mrad
Number of pixels	20k x 20k (!)		4000 x 4000	
Acceptable tiling constraints	See text		Minimal tiling required	
Maximum local rate	10^4	ph/pixel/100fs pulse	10^4	ph/pixel/100fs pulse
Maximum global rate	10^7	ph/s	10^7	ph/s
Timing	Up to 5MHz		10	Hz
Flat field response	1%		1%	
Dark current	<0.01 eq photon	Per pixel per frame	<0.01 eq X-ray photon	Per pixel per exposure
Read-out noise	<0.01 eq photon	Per pixel	<0.01 eq X-ray photon	Per pixel
Linearity	1%		1%	
Point spread function	<1 pixel	FWHM	<1 pixel FWHM	
Image latency	<1/15000	In subsequent image	<1/1000	
Operating environment	Ambient		ambient	
Vacuum compatibility	Yes		yes	

Area/Experiment 5: X-ray Photon Correlation Spectroscopy (Grübel)



Standard or Delay line mode: Δt =[1ps, 10ns]

Area/Experiment 5: X-ray Photon Correlation Spectroscopy (Grübel)

Pixel Size or Angular Resolution:

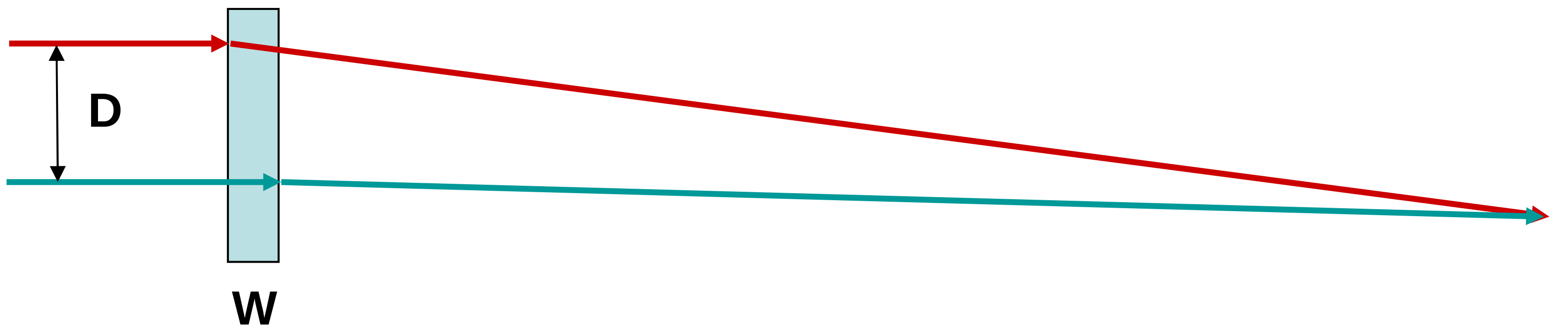
pixel size $\leq$ speckle-size = $(\lambda/d)\bullet L$ = (1Å/25 µm= 4 µrad) x 20 m = 80 µm

speckle-size = beamsize➔ pixelsize: $(\lambda\bullet L)^{1/2}$ = 45 µm (1 Å, 20m)

$PLD = 2W \sin^2(\theta) + D\sin(2\theta)$

Area/Experiment 5: X-ray Photon Correlation Spectroscopy (Grübel)

Detector Size or Angular Range:



$$PLD = 2W \sin^2(\theta) + D \sin(2\theta) < LCL = \xi_l = \lambda^2/\Delta\lambda$$

No Monochromator: $\Delta\lambda = 10^{-3}\,\lambda \rightarrow \theta_{max} = 0.10$ degrees → **1K pixels**

With Monochromator: $\Delta\lambda = 2.\,10^{-4}\,\lambda \rightarrow \theta_{max} = 0.5$ degrees → **5K pixels**

XFEL X-Ray Free-Electron Laser

Area/Experiment 5: X-ray Photon Correlation Spectroscopy (Grübel)

	Detector V: Photon Correlation Spectroscopy	
XFEL radiation source	SASE-1 (and SASE-3)	
Photon energy range	8 – 12 (0.25-3.1)	keV
Energy resolution	None	eV
Quantum efficiency	>0.8	
Radiation hardness	$2\ 10^{14}$	12 keV X-ray ph/pixel
Total angular coverage	0.2 (1.2)	degrees
Angular resolution or pixel size	4	µrad
Number of pixels	1000 x 1000 (5000 x 5000)	
Acceptable tiling constraints	<20% dead area	
Maximum local rate	10^{3}	ph/pixel/100fs pulse
Maximum global rate	10^{6} ?	ph/100fs pulse
Timing	$5\ 10^{6}$	Hz (but see below)
Flat field response	1%	
Dark current	<0.01 eq X-ray photon	per pixel per exposure
Read-out noise	<0.01 eq X-ray photon	per pixel
Linearity	1%	
Point spread function	<1 pixel FWHM	1 pixel = 4µrad
Image latency	< 1/1000	in subsequent image
Operating environment	Ambient	
Vacuum compatibility	No	
Maintenance	See below.	
Other requirements	Central hole	

Timeline for phase 1 detectors

- Timeline
  - Agree requirements.
  - Develop firm specifications.
  - **Deadline to submit EoI's: 30 September 2006**
  - Evaluation of EoI's: 15 October 2006
  - Decision by XFEL PT: 31 October 2006
  - Invitations to submit full proposals: 15 November 2006
  - Deadline to submit full proposals: 15 February 2007
  - Evaluation of proposals: 15 March 2007
  - Start of projects: 1 May 2007

What to do!

- Contact Heinz Graafsma for Expression of Interest documentation.

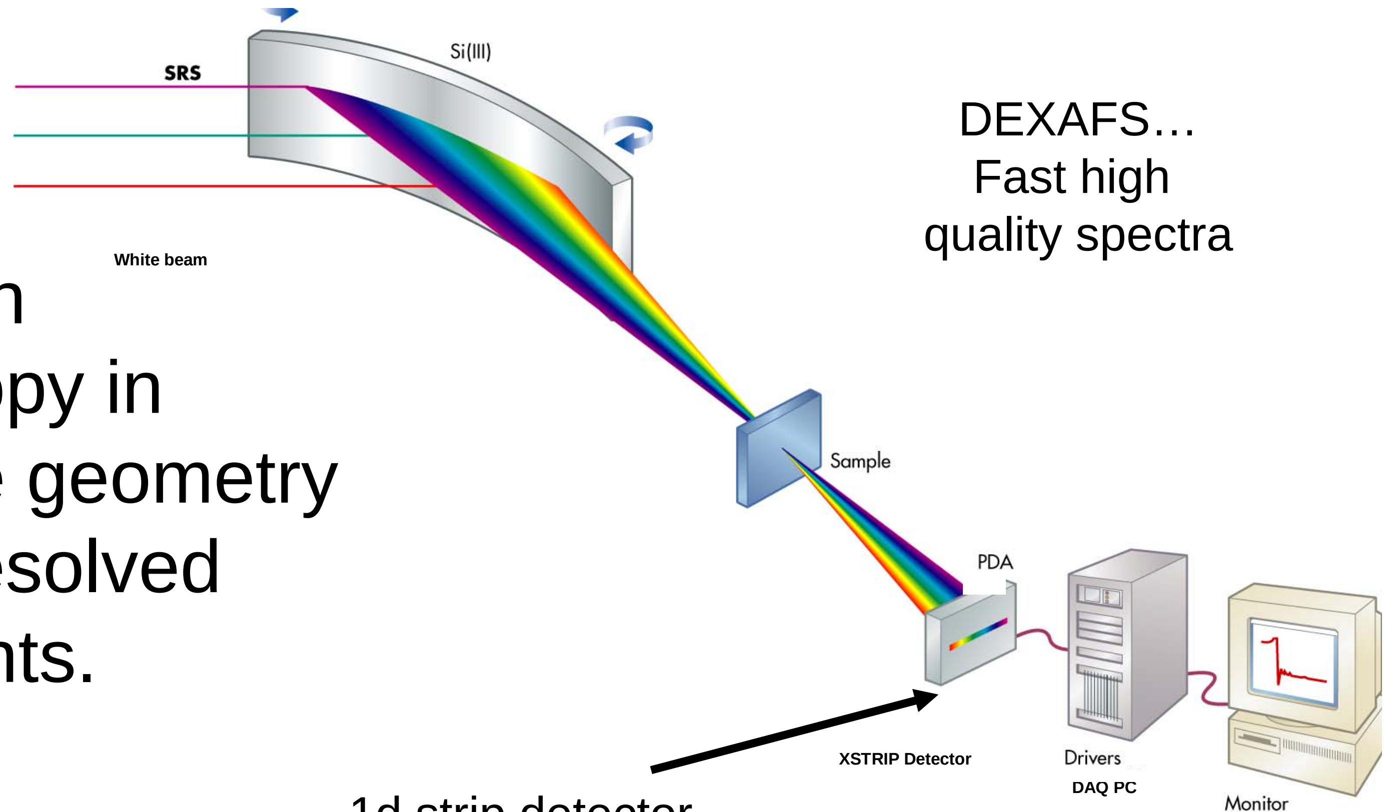
Other XFEL detector areas

- Photon beam monitoring.
  - Gas detectors / Diamond / ??
  - Position, energy, size, intensity etc.
- Photon absorption spectroscopy. *0d/1d.*
- Temporal measurements. *Streak cameras.*
- Particle (electron and ion) imaging / timing.

All require specification and development.

Subjects of future EXFEL calls.

Spectroscopy on XFEL?

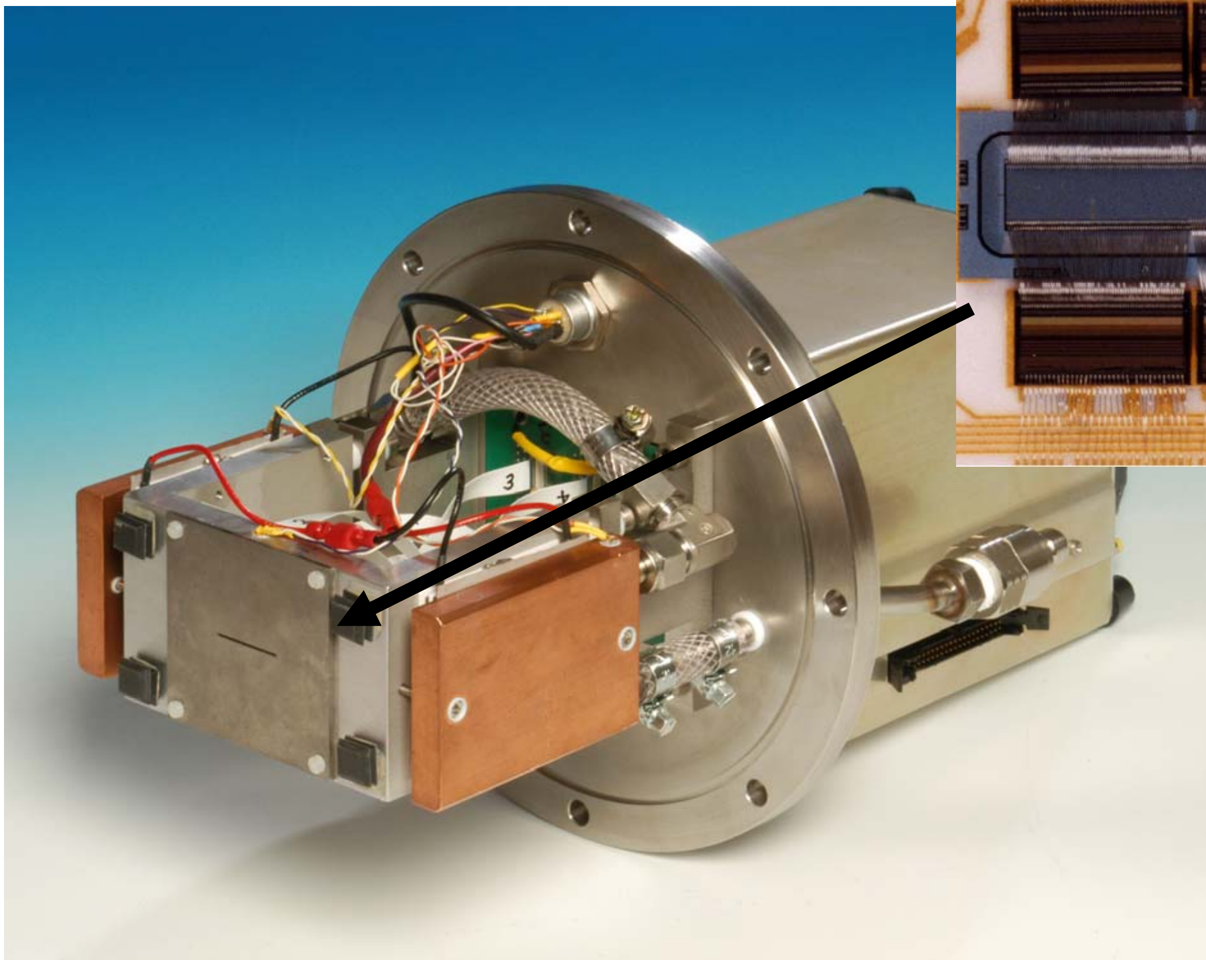


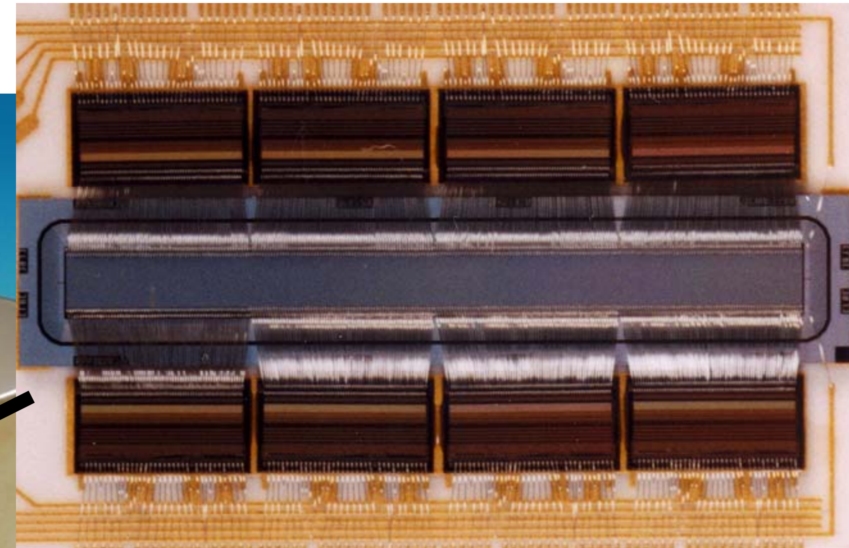
DEXAFS…
Fast high
quality spectra

- Absorption spectoscopy in dispersive geometry for time resolved experiments.

1d strip detector
XSTRIP

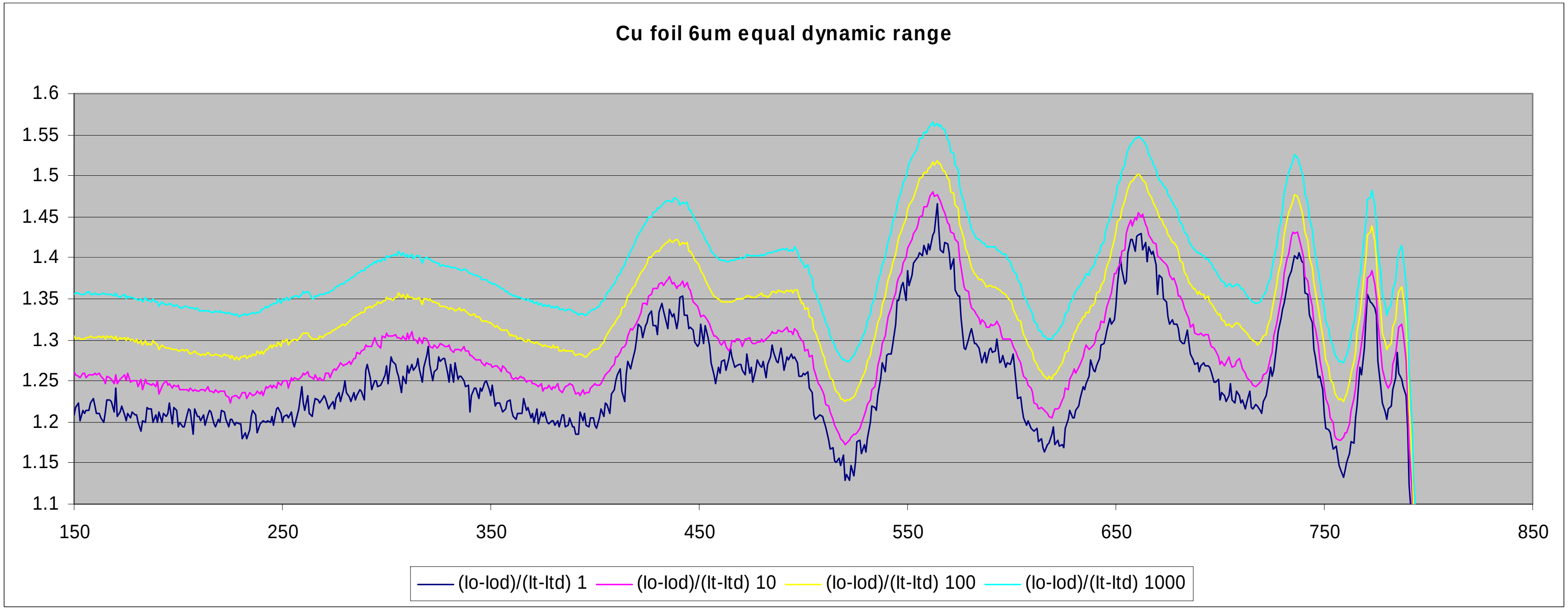
XSTRIP





XSTRIP.
1024 strips. 25um pitch.
8 fast readout ASICs.
10us frame rate.
1us minimum integration.
14 bit DNR
Maximum 10^{12} x-rays per second.

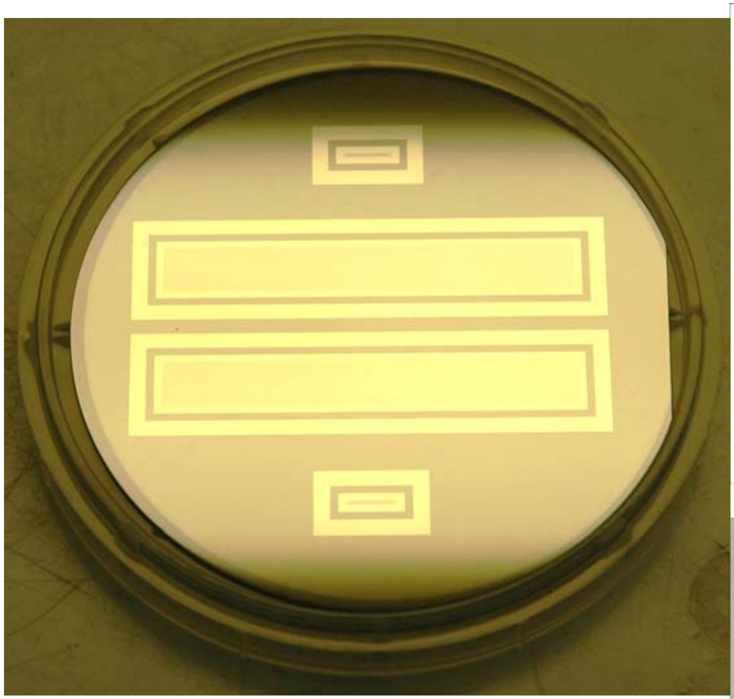
SR Detectors – XSTRIP

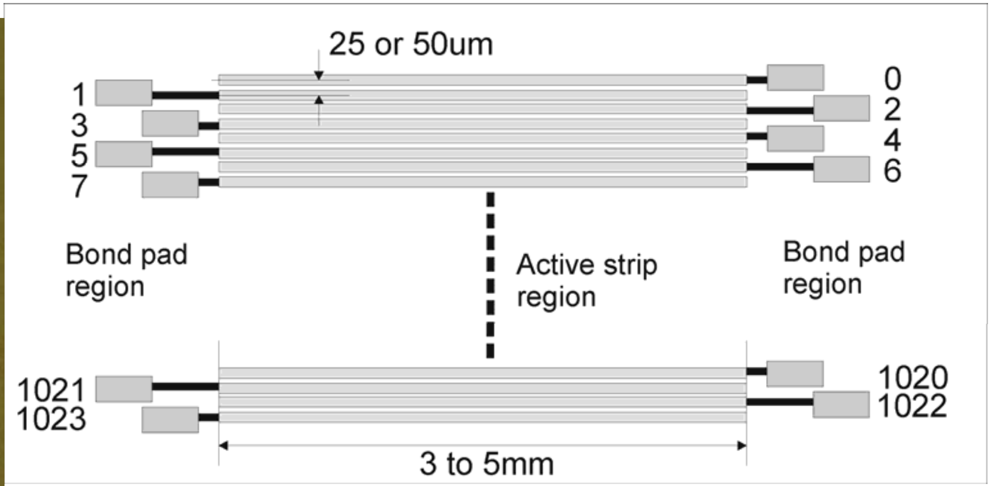


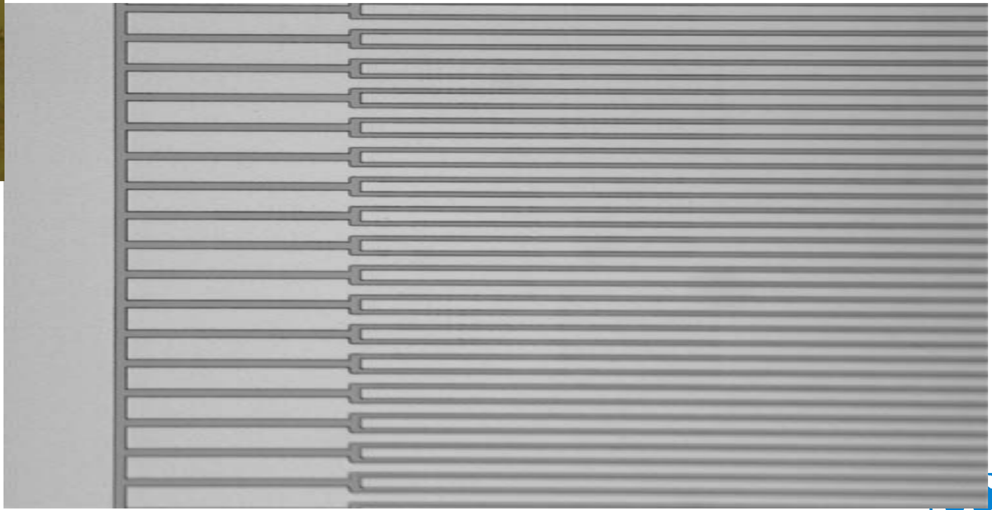
DEXAFS at 50us integration time.

Also scans taken with single bunch of electrons.

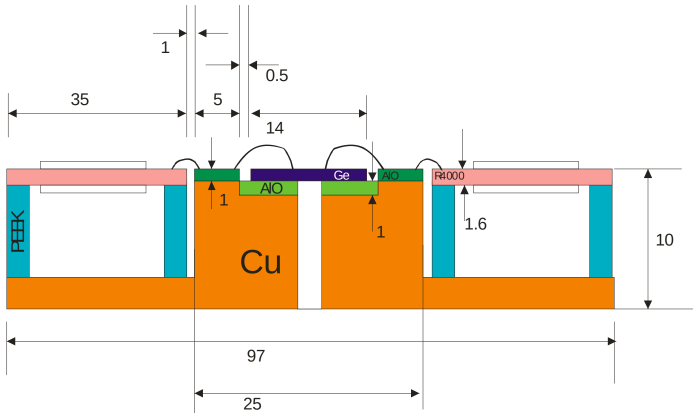
XSTRIP : XH : One solution.

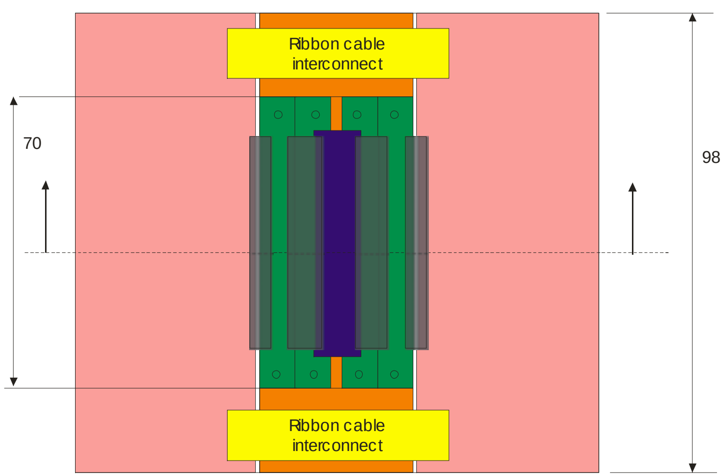


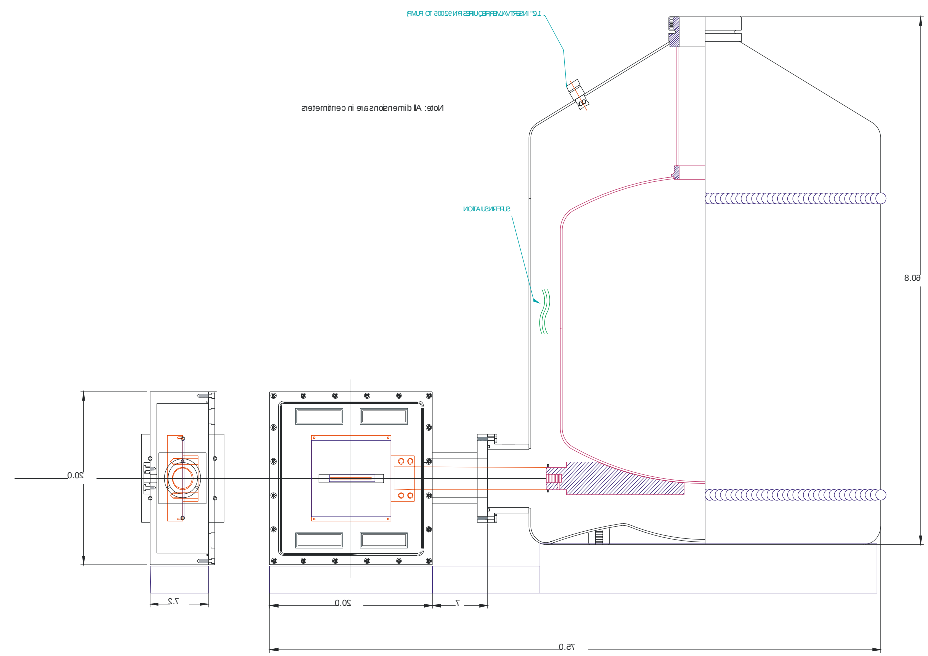




XSTRIP : XH







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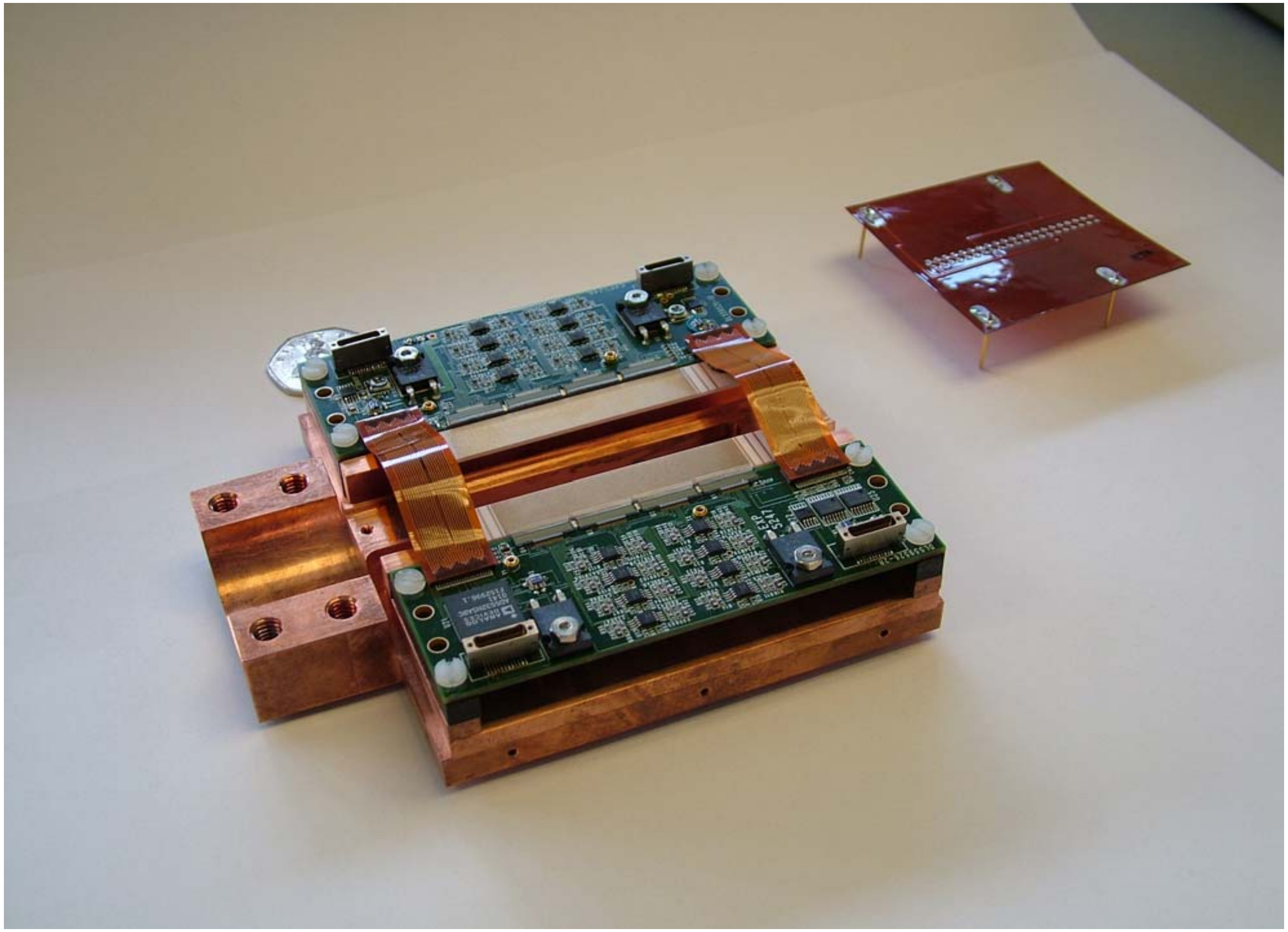
XSTRIP : XH electronics

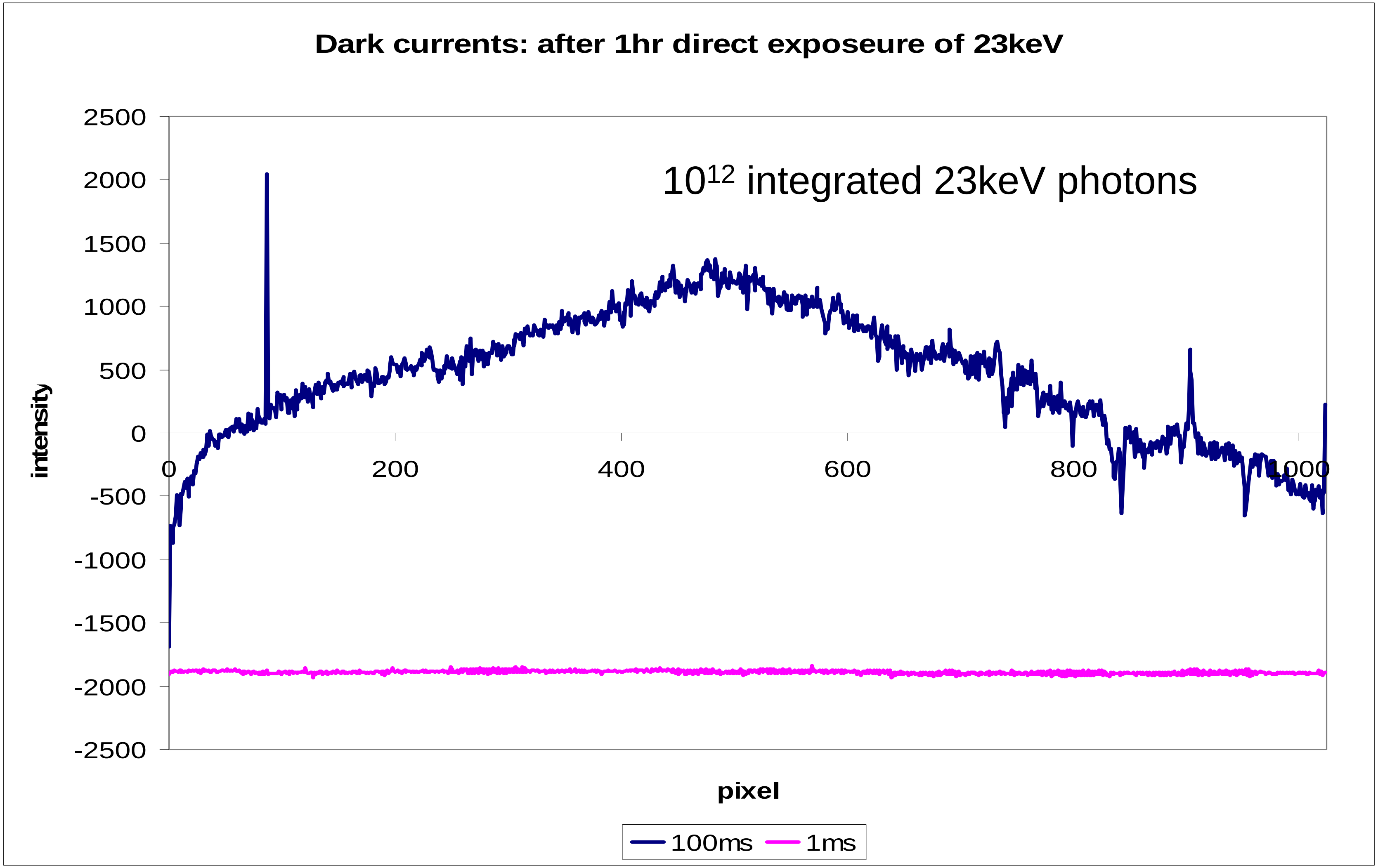


Challenges : Detector R&D

- Materials :
  - Silicon / gas / other.
  - Speed *<100ns - faster in some cases.*
  - Radiation damage (& electronics). *10^{16}*
  - ‘Field’ saturation. *$3x10^{6}$ph = 1uC pulse!.*
  - Manipulation. *Central hole. Tiling.*
  - Interconnection.
  - Windows. *Vacuum?*

  Beam monitoring !!

XFEL X-Ray Free-Electron Laser


Dark currents: after 1hr direct exposeure of 23keV
10^{12} integrated 23keV photons
intensity
pixel
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0
200
400
600
800
1000
100ms
1ms

Challenges : Detector R&D

- Front end readout :
  - Integrating only?.
  - Dynamic range. *10^7 ph.*
  - Speed. *10Hz….but 20k x 20k!!*
  - Data volume / transmission / selectivity.
  - Robust (industrial environment).
- Back end data acquisition.
  - Data volume and storage. *Gb s^{-1}*
  - Data analysis.
  - Reliability.
  - Lifetime.

Challenges : Detector R&D.

- Experimental integration.
  - Pump probe. ~fs.
  - Sample handling and manipulation.

- Other challenges.
  - Other experimental requirements : time / energy / phase
  - Detector cost.
  - Limited number of projects/detectors.
  - Multiple configurations.
  - Maintenance and support.
  - Known, stable, characterised performance.

Conclusions

- European XFEL will deliver extremely interesting and challenging science..but will require very high quality detectors.
- First phase of detectors are proposed NOW and partners/suppliers are being sought.
- Further developments and calls for later phase detectors will also occur.
- R&D activities are already underway in some areas. These will continue and expand.

Acknowledgements

Thanks to…

- Heinz Graafsma / Massimo Altarelli. DESY.
- Michael Wulff / Janos Hajdu / Ian Robinson / Gerhard Gruebel : Science.
- Masaharu Nomura / Yasuhiro Inada. PF AR.
- John Evans / Trevor Rayment / Cyril Ponchut.
- Detector teams at DL and RAL.

- You for your attention!!

Questions

XFEL
X-Ray Free-Electron Laser

Possible solutions?

- Hybrid pixel detectors?
  - LAD.
  - Medipix.
  - Pilatus.
- CMOS sensor detectors?
  - PAD.
  - Startracker.
- Others – Gas counters?