The Development of the Large Pixel Detector at RAL

Marcus French

Science and Technology Facilities Council

Rutherford Appleton Laboratory

European XFEL

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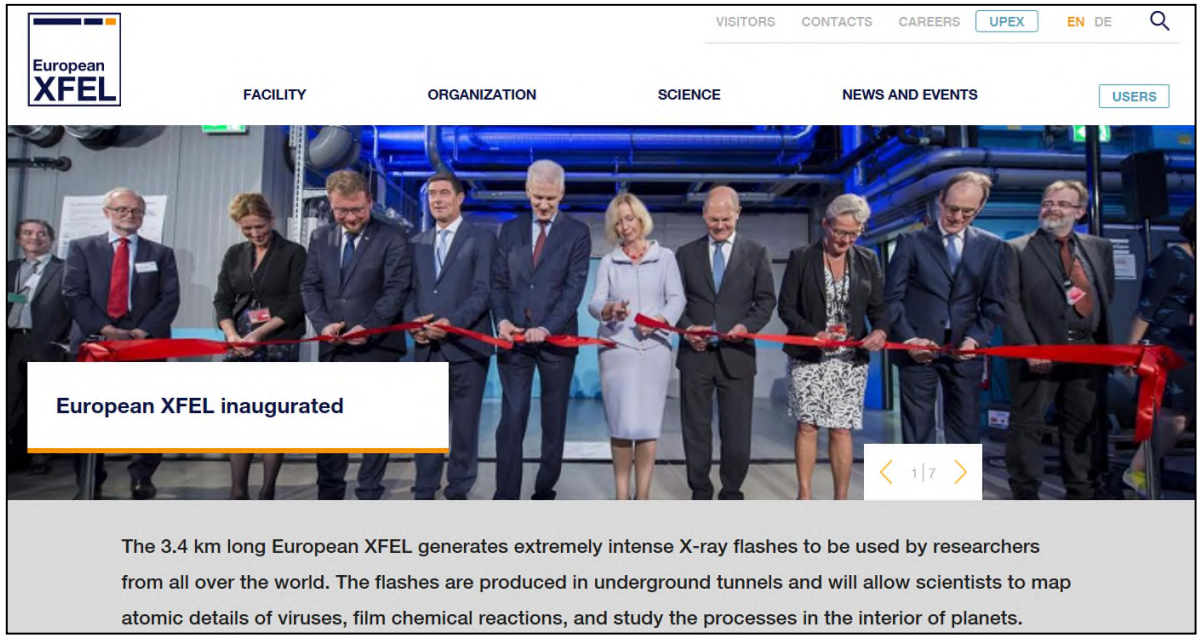
XFEL Inauguration 1st Sep 2017

- Now open for first users
- LPD is now delivered and installed on FXE Beamline
- LPD commissioning is currently ongoing
- It is confirmed that UK now becoming full partner!! ☺

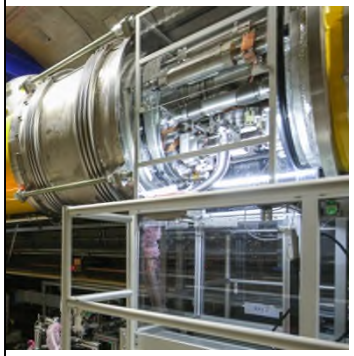


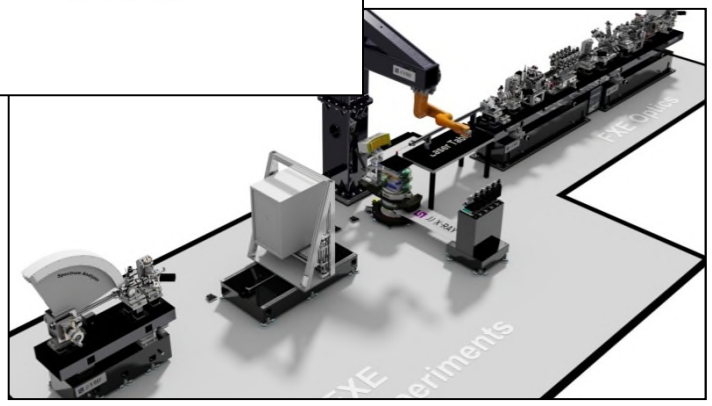
XFEL Inauguration 1st Sep 2017

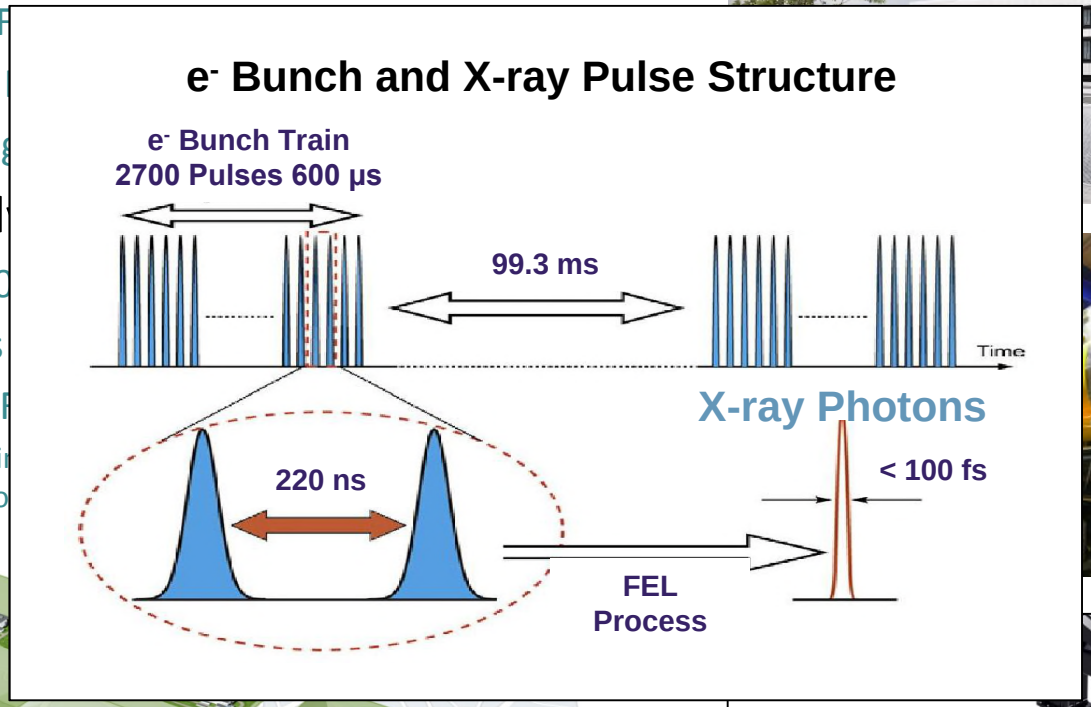
- BBC News article http://www.bbc.co.uk/news/science-environment-41117442

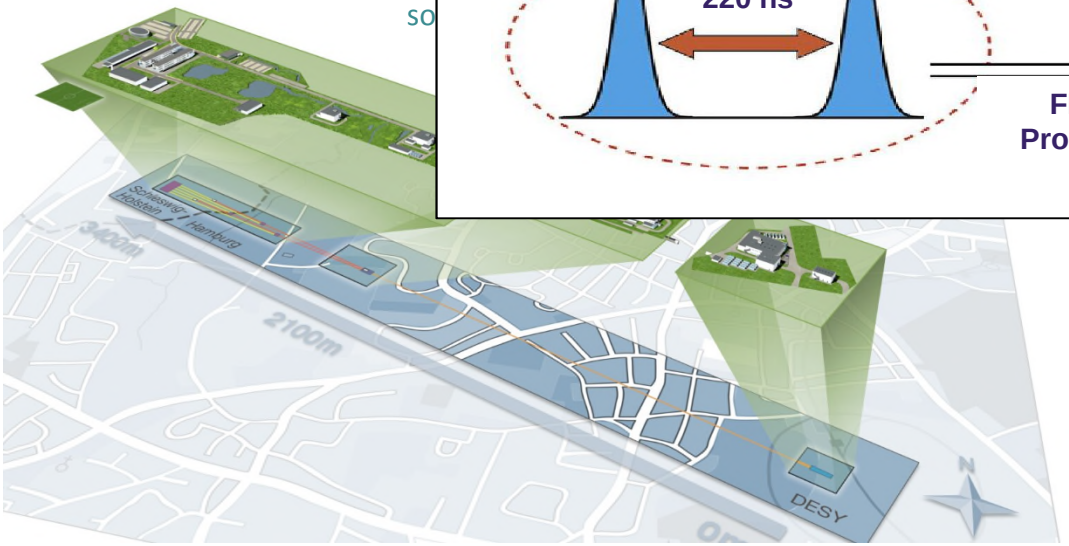
XFEL Introduction

- The European XFEL
  - X-ray F
  - DESY, (
  - First lig
- Extremel
  - 27,000
  - Bursts
  - FXE – F
    - Ti
      so

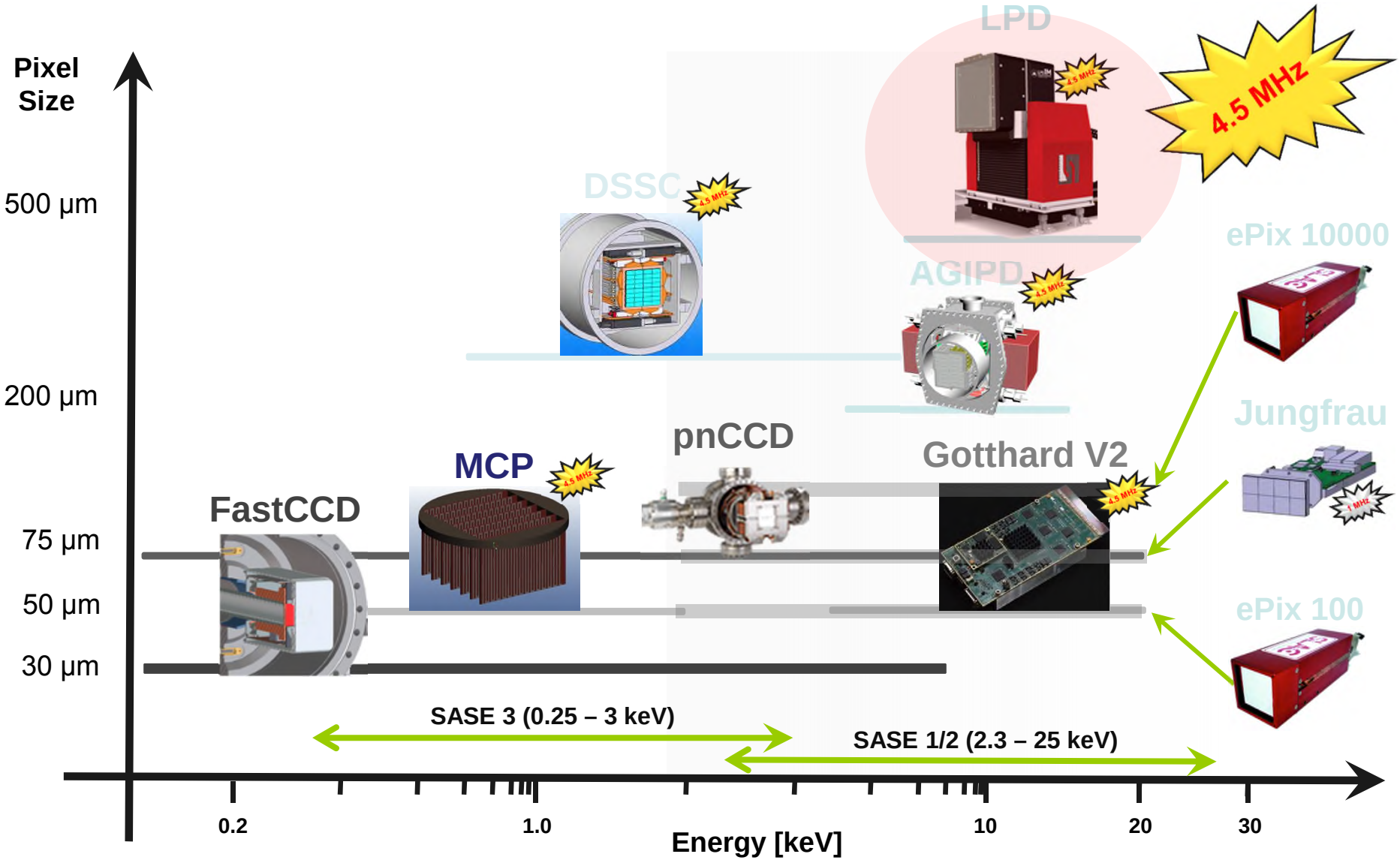








LPD is one of several projects…



LPD: From First Ideas to User Operation: 2006 - 2017

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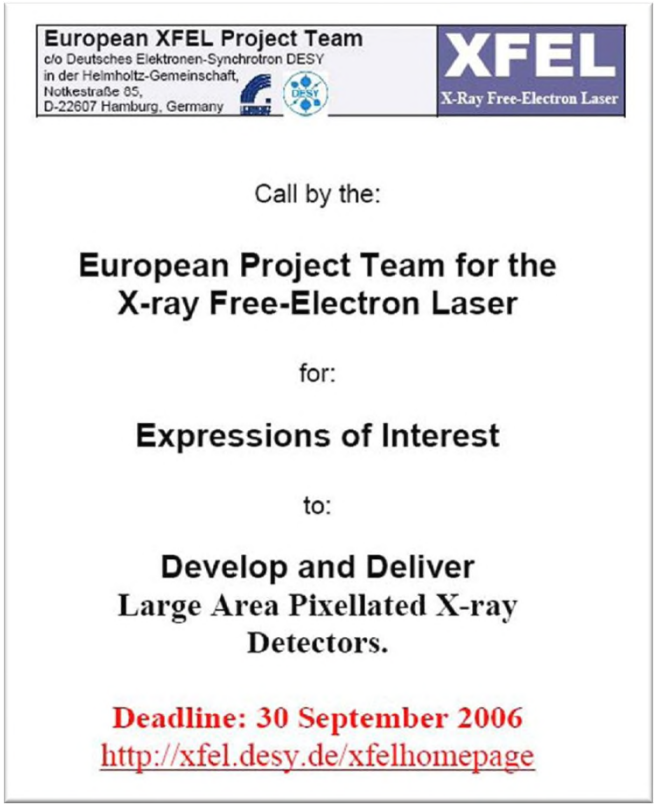
The initial Call



European XFEL Project Team
c/o Deutsches Elektronen-Synchrotron DESY
in der Helmholtz-Gemeinschaft,
Notkestraße 85,
D-22607 Hamburg, Germany

XFEL
X-Ray Free-Electron Laser

Call by the:

European Project Team for the X-ray Free-Electron Laser

for:

Expressions of Interest

to:

Develop and Deliver Large Area Pixellated X-ray Detectors.

Deadline: 30 September 2006
http://xfel.desy.de/xfelhomepage

- The European XFEL pulse structure poses strict constraints on detectors (e.g. intensity and time structure)
- No commercial imaging detectors available
- Call for expression of interest launched in 2006
- 3 project proposals were selected with the goal to finally have at least one fast 2D imaging detector

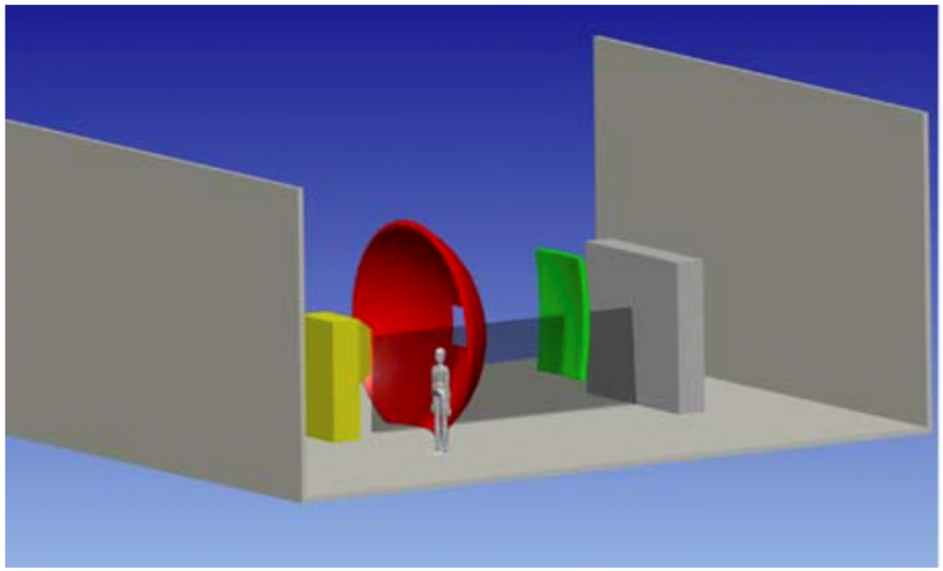
Selected proposals:

i. Adaptive Gain Integrating Pixel Detector
ii. The Large Pixel Detector
iii. DEPFET Sensor with Signal Compression

Initial Thoughts

- Key Features
  - Pixel size 1 mm x 1 mm
  - 16 tiles (16 mm x 64 mm) organized in super modules (128 mm x 128 mm)
  - Two detection planes at 2 m and 4 m sample distance
  - Total sensitive area 12 m2
  - 3000 image storage capacity
  - All in vacuum!

The Really Large Pixel Detector



LPD: Towards a full proposal

- April 24th, 2007 Invitation to present the LPD proposal at the 2nd XDAC, A. Schwarz to M. French, H. Graafsma, R. Feidenhans'l, M. Altarelli, I. Gembalies,, N. van Bakel, M. Campbell, N. Allison, P. Delpierre, P. O'Connor; P. Fajardo, K.-T. Knöpfle et al.

Dear Marcus,

you are cordially invited to present your proposal to develop the

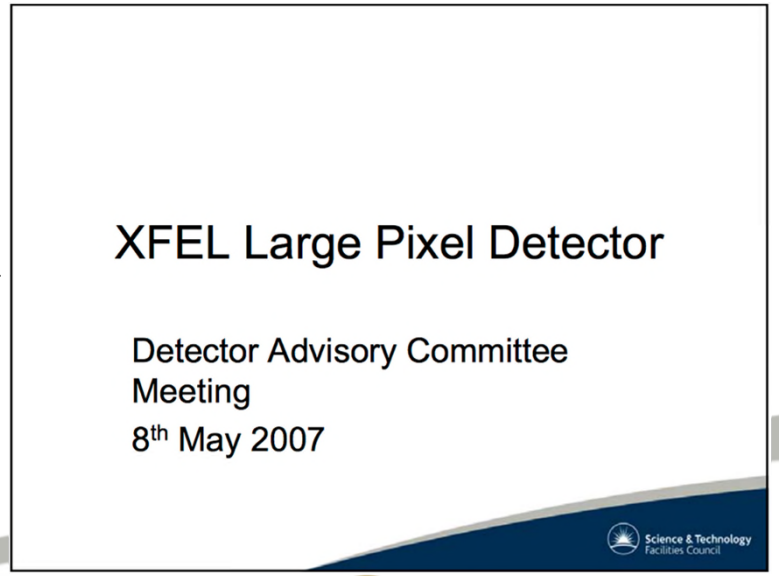
XFEL Large Pixel Detector (LPD)

for the XFEL at the 2nd meeting of the XFEL Detector Advisory Committee, which will take place

May 8th to May 9th, 2007 at DESY, Hamburg
The presentation for your consortium has been scheduled for Tuesday, May 8th, 10:15-11:45 o'clock

Technical Team:
- STFC Rutherford and Daresbury Laboratory
- Glasgow University
- Surrey University

Science Team:
- UCL
- Daresbury
- others



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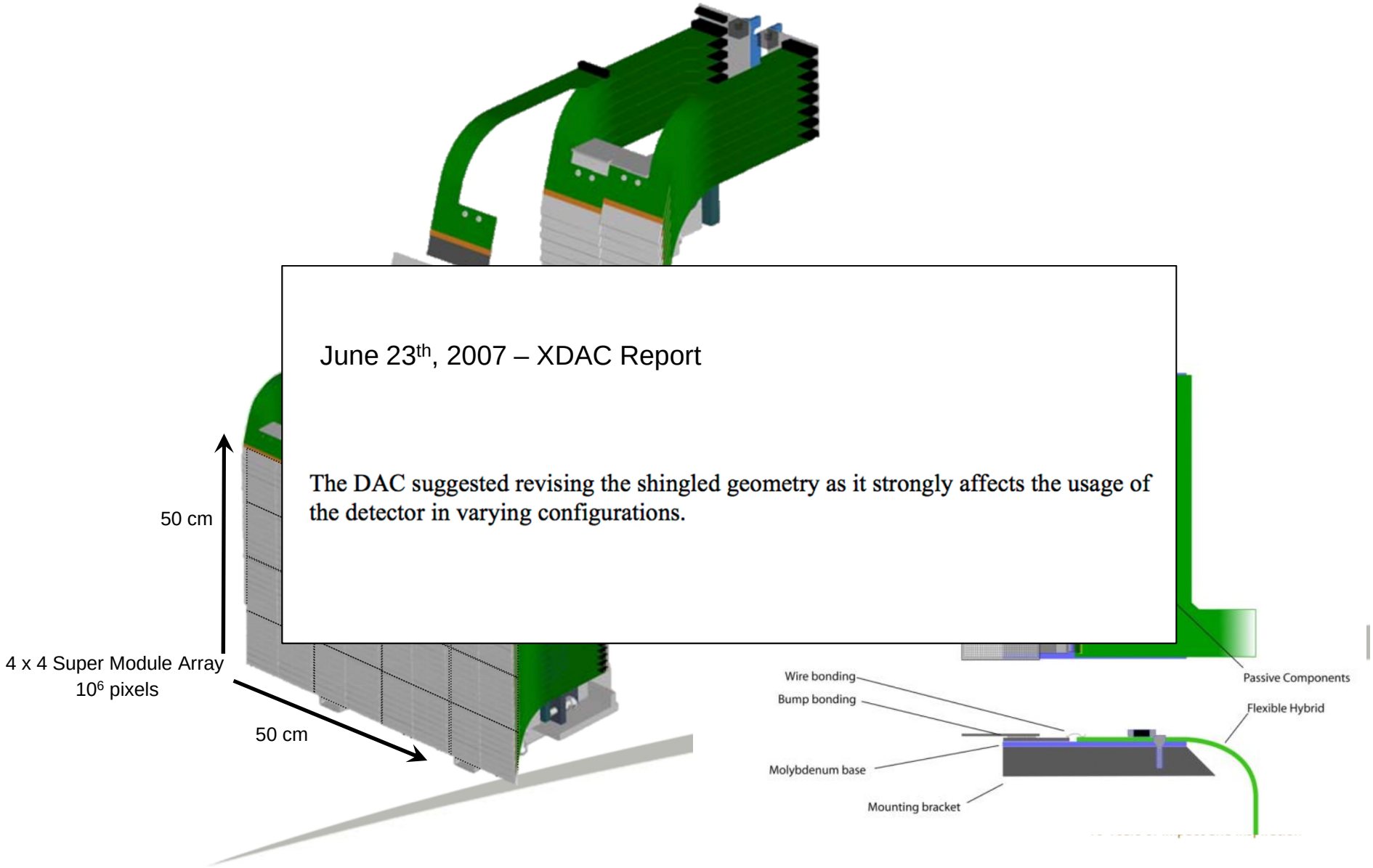
Initial Concept: May 2007



June 23th, 2007 – XDAC Report

The DAC suggested revising the shingled geometry as it strongly affects the usage of the detector in varying configurations.

The LPD Today

LPD Key Parameters

Large Pixel Detector

- Built by STFC for the European XFEL
- **1 Megapixel** - 500um pixels
- **4.5MHz frame rate**
- **Dynamic range**, 1 to 1x10^5 photons per pixel per pulse. Using parallel gain stages.
- **512 frame memory depth** continuously stores all three gains, overwriting whenever a veto is received.
- Output data rate ~**10GByte/s** per megapixel

The LPD megapixel detector.

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LPD Tour – Front View

LPD Tour – Front View

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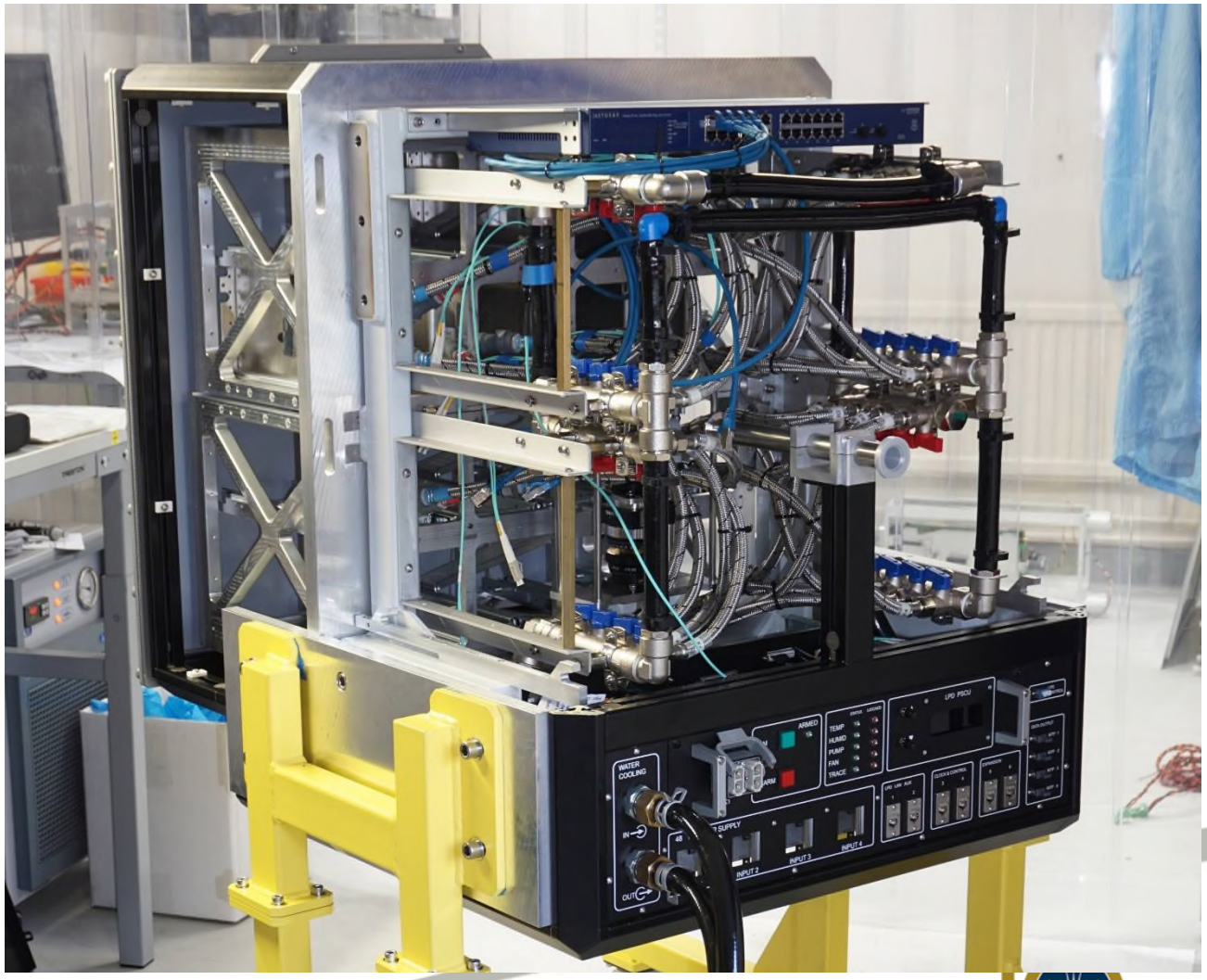
LPD Tour – Rear View



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LPD Tour – Rear View

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LPD Tour – Detector Control

System monitoring and interlocks only allow power up of the front end systems when safe

Housekeeping power supplies

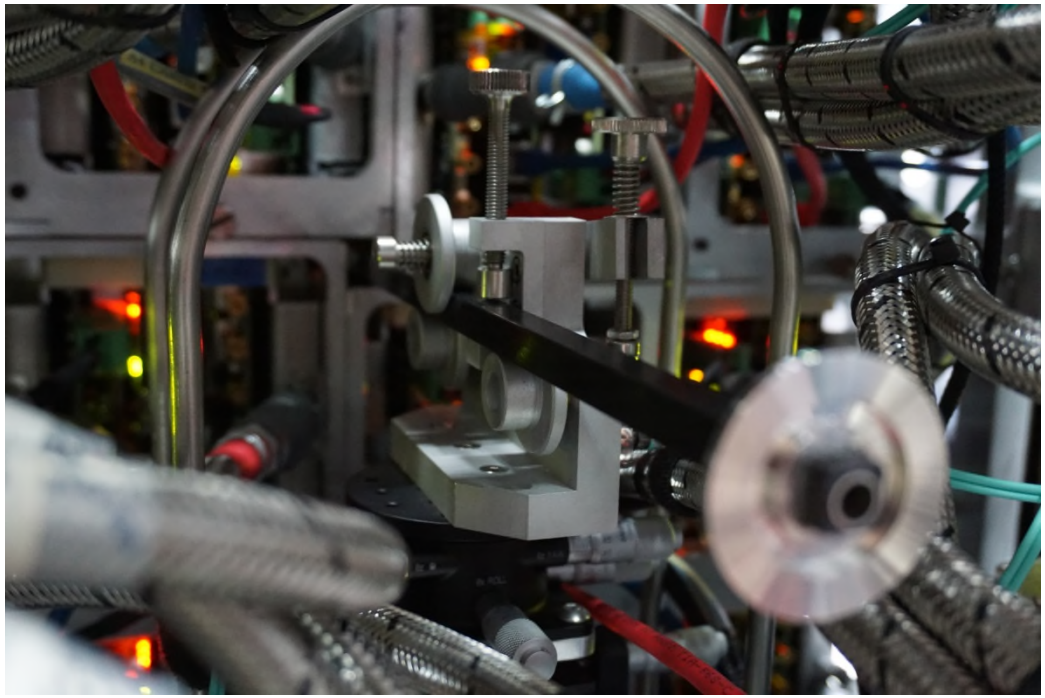
On-board PC for remote access

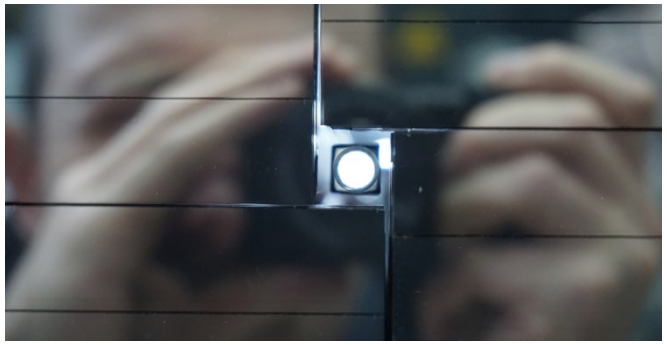
Hard wired interlock logic

Information screen: Status and alerts

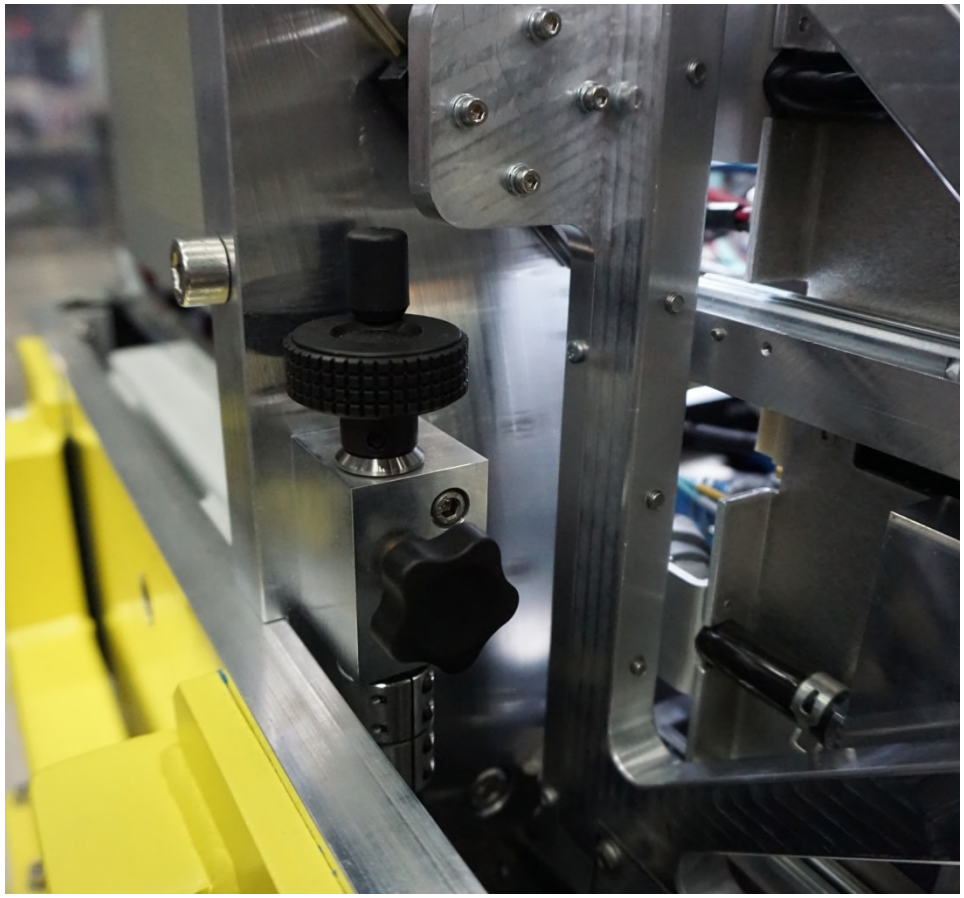
If conditions deteriorate then power is shut down and the failure state latched for inspection prior to rearming the system

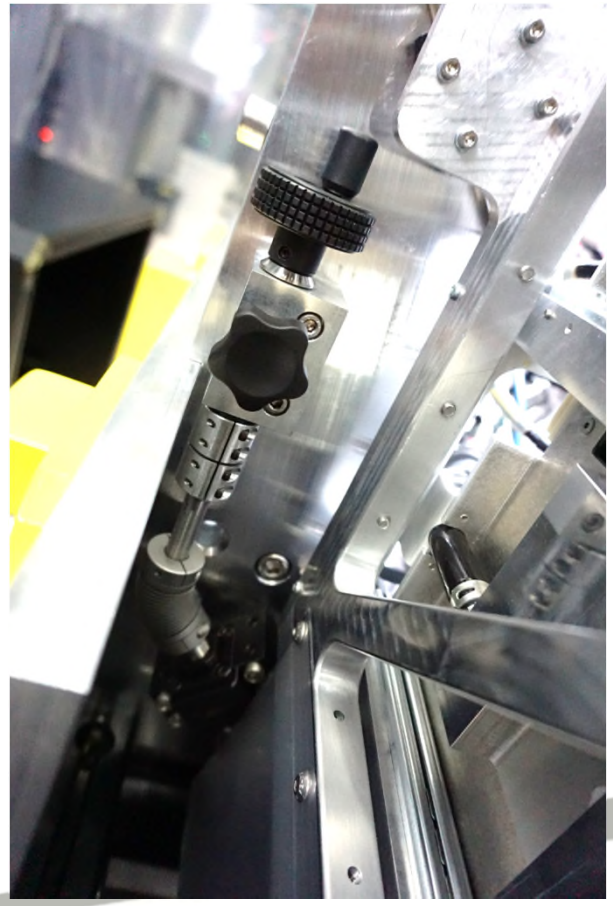
Added Beam Flight Tube



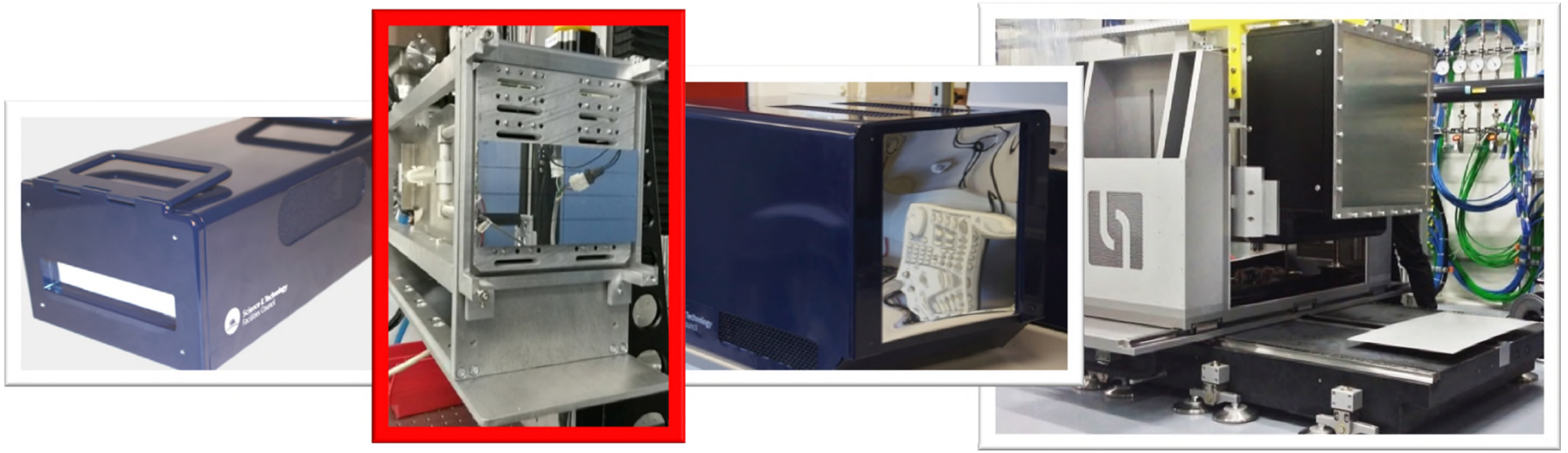


Central Hole Adjustment





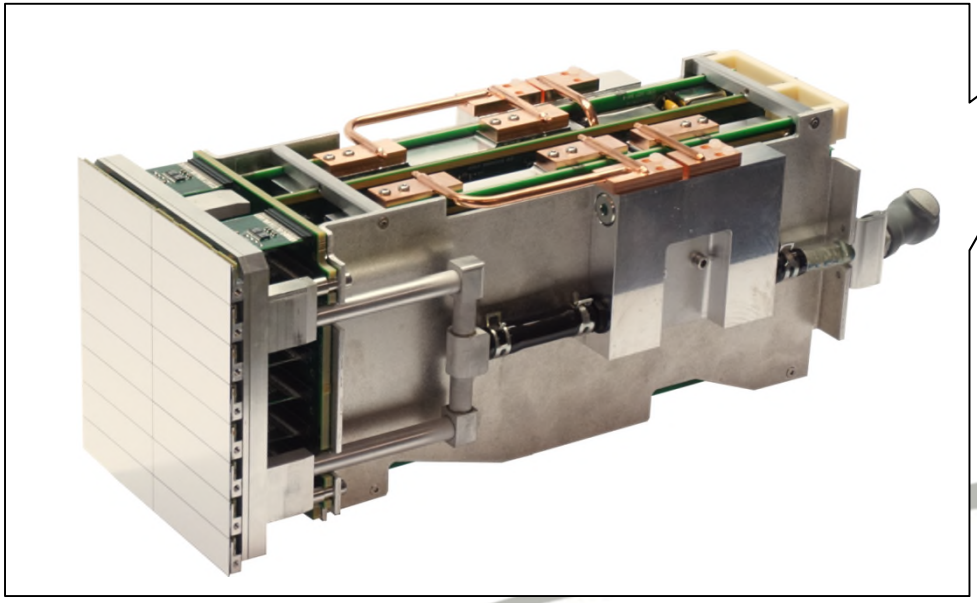
LPD Detector Family

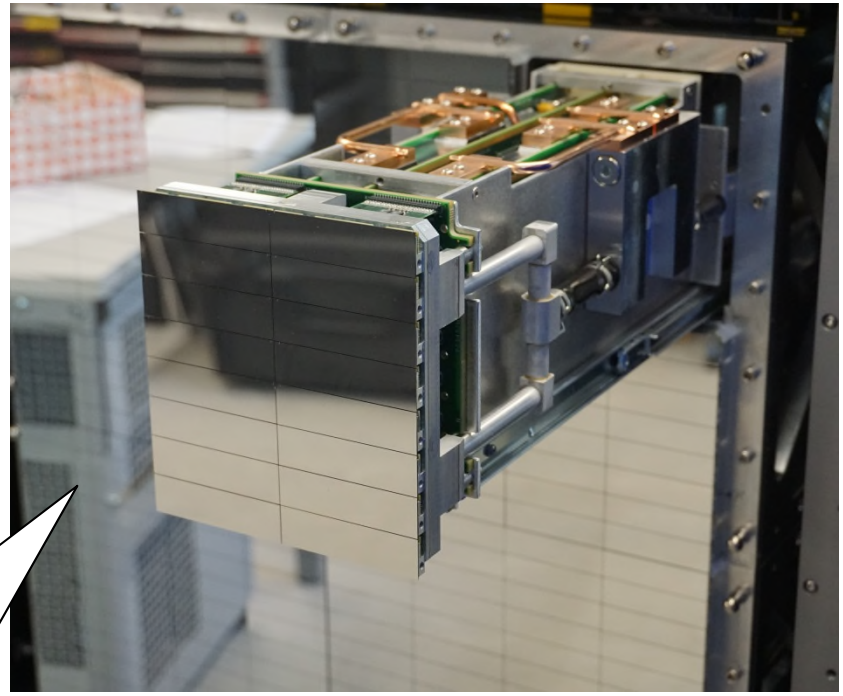


Two-Tile System	Super-Module	¼ Megapixel Detector	1 Megapixel Detector
Small flexible test system (32 x 256 pixels) Firmware tests Early beamline tests and calibration Veto system tests First 4.5 MHz images at FXE	Small flexible test system (256 x 256 pixels) 1/16th of the 1 Mpixel detector Early beamline tests and calibration measurements	Test system at XFEL.EU (512 x 512 pixels) Mechanical concept and integration concept for 1 Mpixel detector	Final system (1024 x 1024 Pixels) Installation at photon beamline Scientific experiments at FXE

LPD Super-Module

- Front end system segmented into 16 Supermodules
- Each easily swappable for servicing and maintenance





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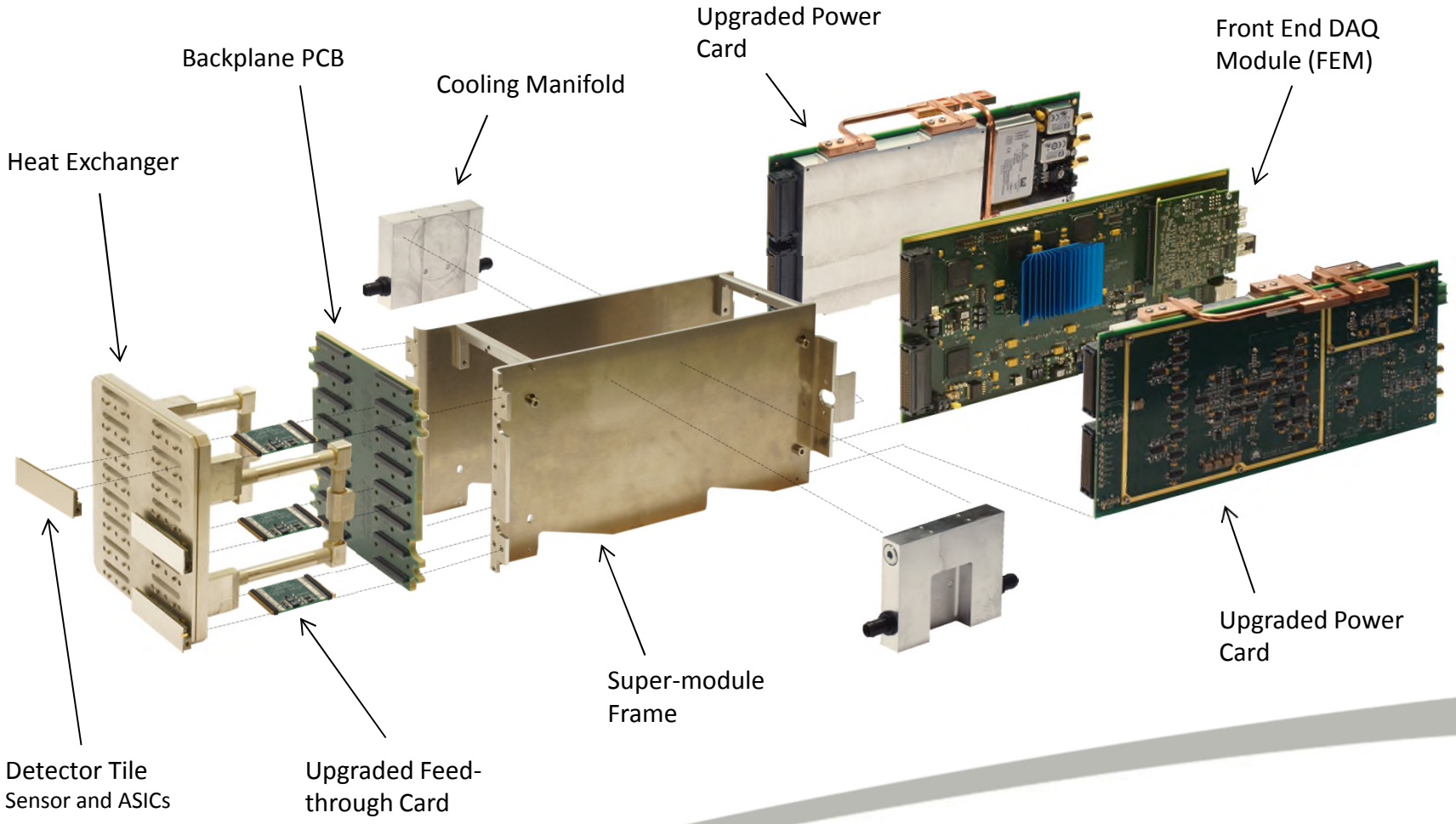
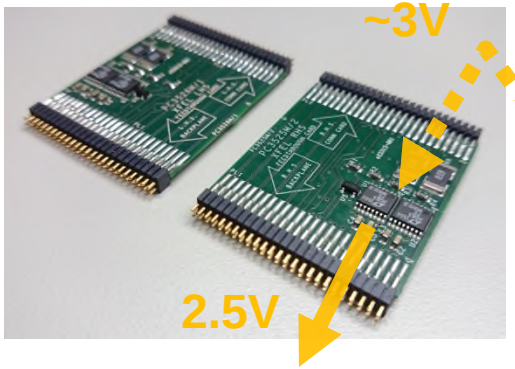
Super Module Components

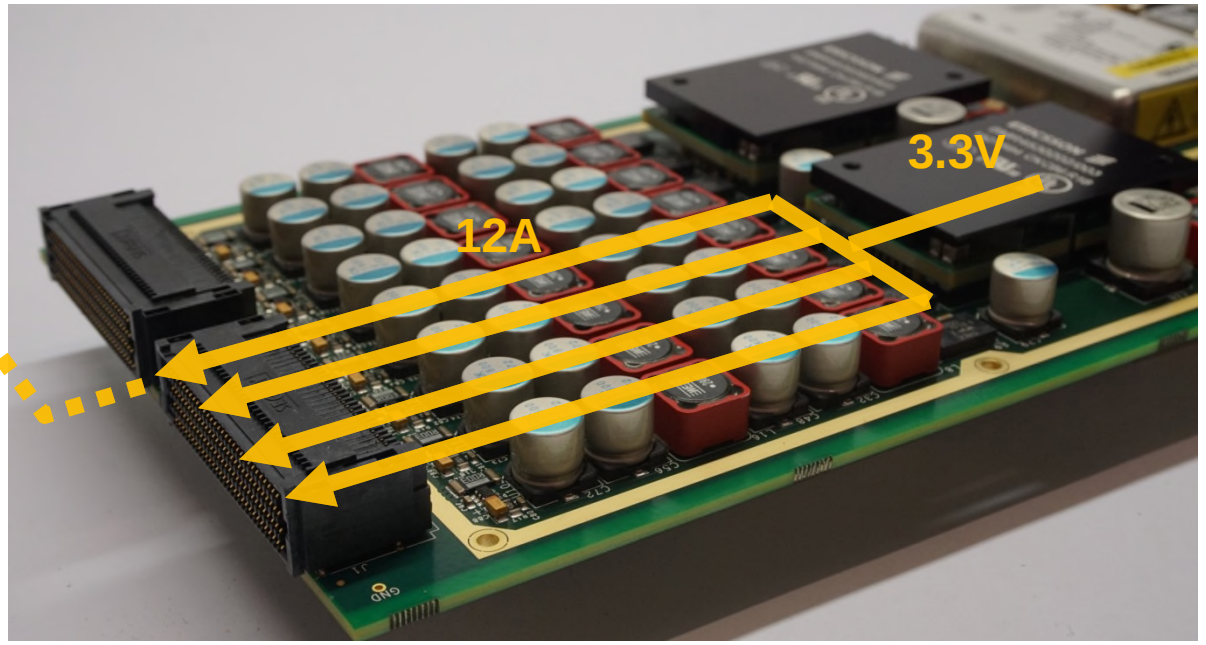


Delivering the Power

Front end low drop out regulators



Power to ASICs

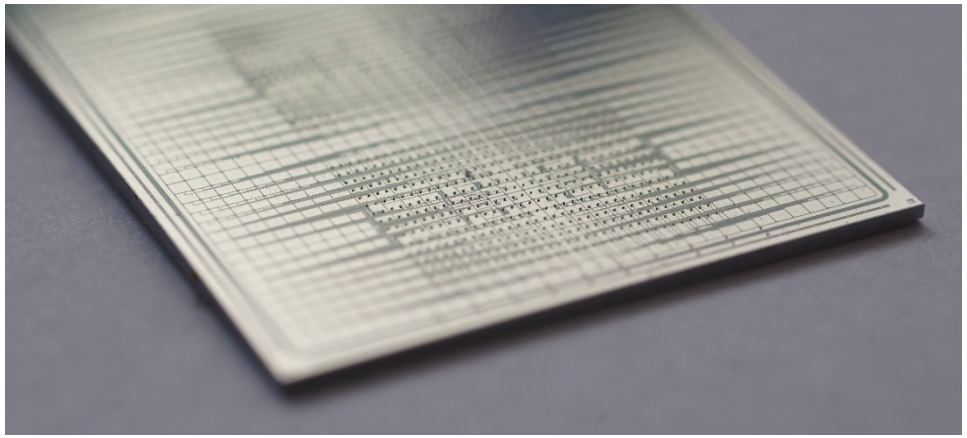


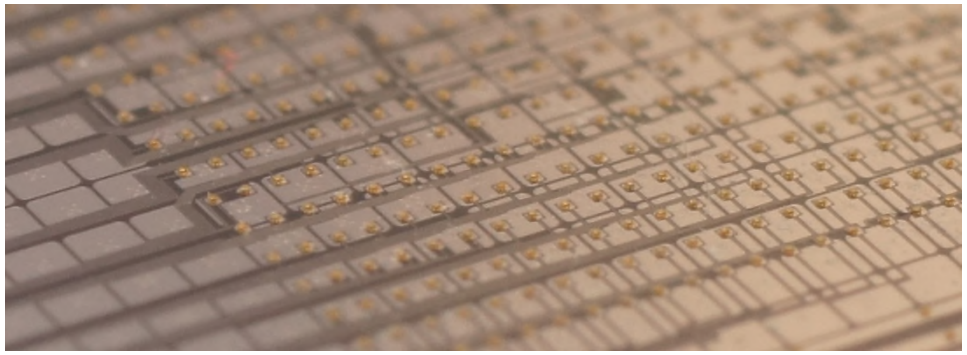
Separate filtration chain for each LPD detector tile.

- 3.3V DC-DC converters each feed 4 filtration chains
- Each chain handles up to 12A (RLCCLCC) required for each detector tile
- Closer to the tile there is further voltage regulation to deliver smooth 2.5V

LPD Sensors

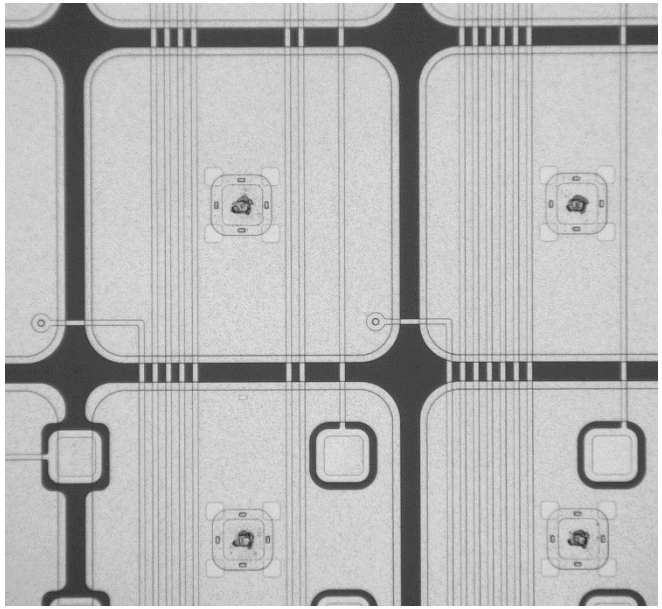
- 4096 Pixels (32 x 128)
- 500um pixels tracked to a finer pitch bump bond array
- 2 layer metal design



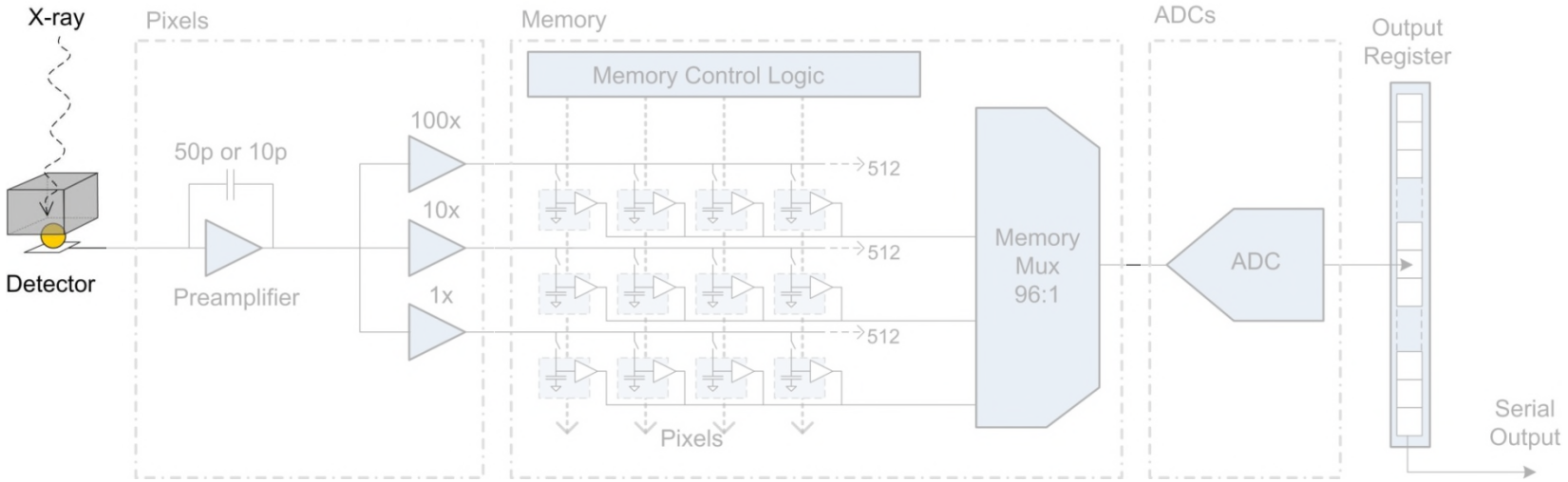


HAMAMATSU

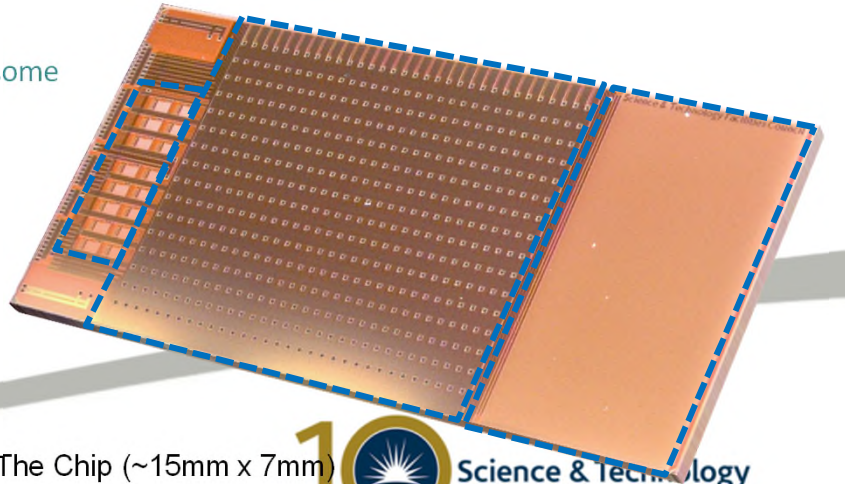
PHOTON IS OUR BUSINESS



LPD ASIC 2012



- 512 Channels
- Preamplifier with 10/50pF feedback
  - An additional high mode gives lower noise at the expense of some dynamic range.
- 100x, 10x and 1x parallel gain stages
- 512 frames of memory for each channel and gain
  - Veto System
- 16 SAR ADCs – 12 Bit
- 100MHz digital output
- IBM 130 nm



The Chip (~15mm x 7mm)

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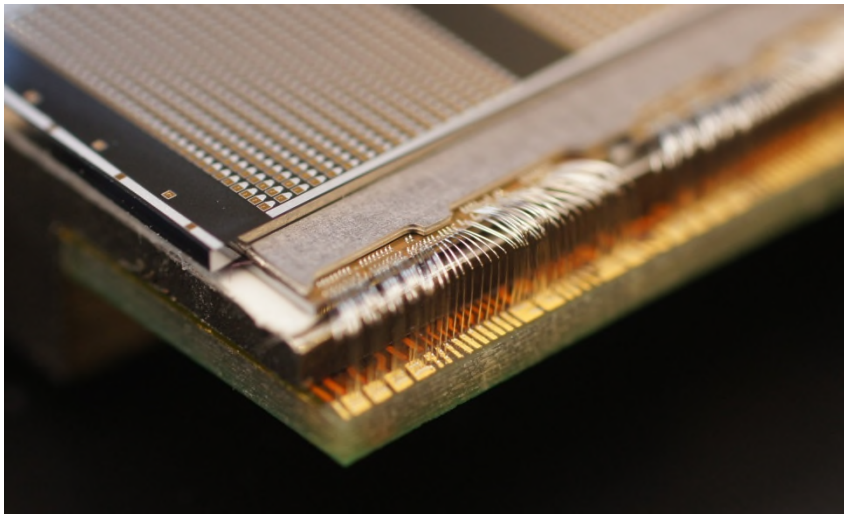
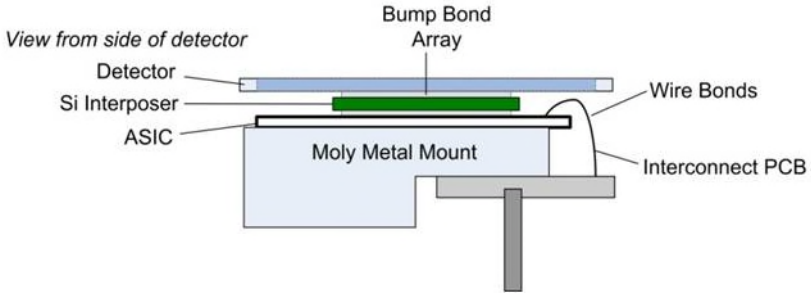
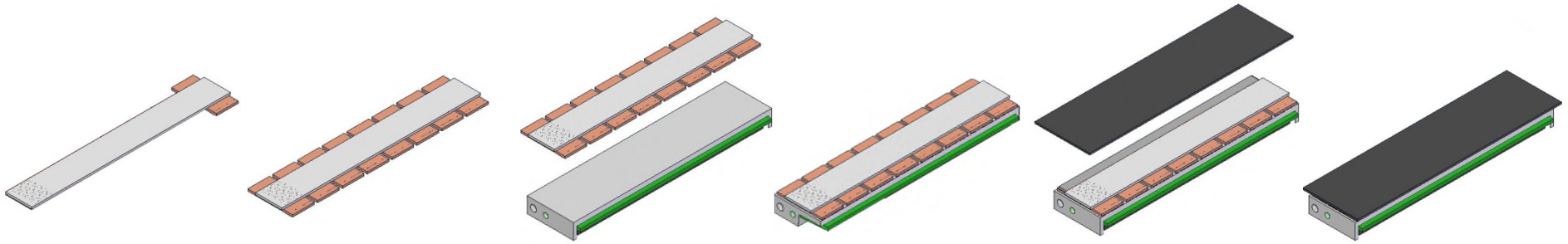
LPD Overview - Interconnect







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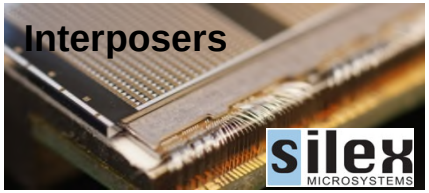
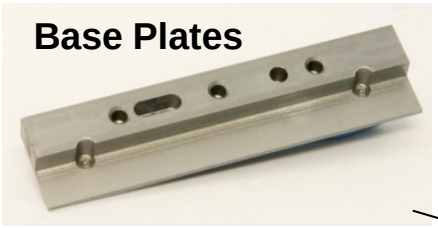
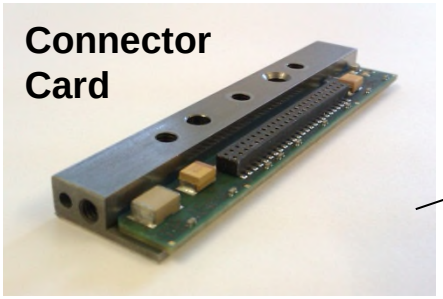
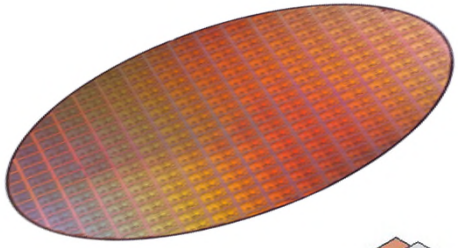
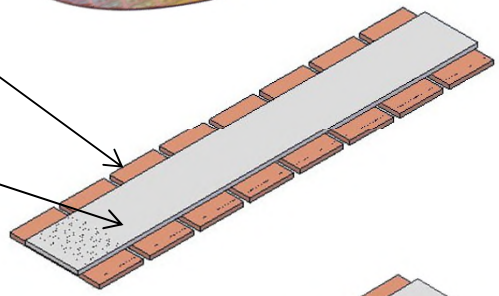
Manufacture of Modules

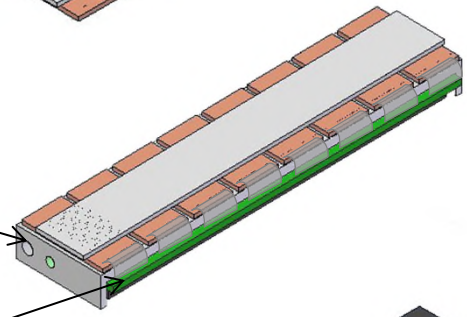


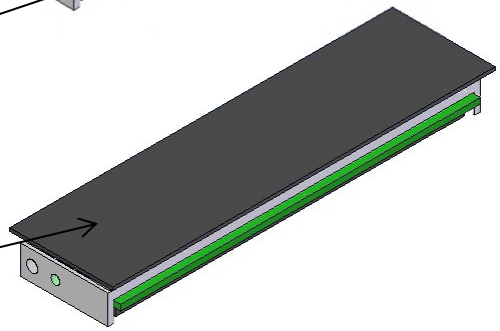












1. ASIC Wafer Processing
2. ASIC Interposer Assembly
3. ASIC Wirebonding
4. Sensor Assembly

LPD Current Data Rates

- Output data rate ~**10GByte/s** per detector
- During a 12 hour experiment this could generate ~**0.4PB of raw data**
- LPD is an integrating detector, each image could be interesting in it's own right, so all of this may be saved.
- In reality experiments are unlikely to run with such high efficiency XFEL estimate lower values for their annual disk space requirements
- **10PB per year** for long term storage (http://www.xfel.eu/research/data_handling/)

- The LPD system has 4 MTP fibre optic outputs
- Using a total of 16 pairs for data output.

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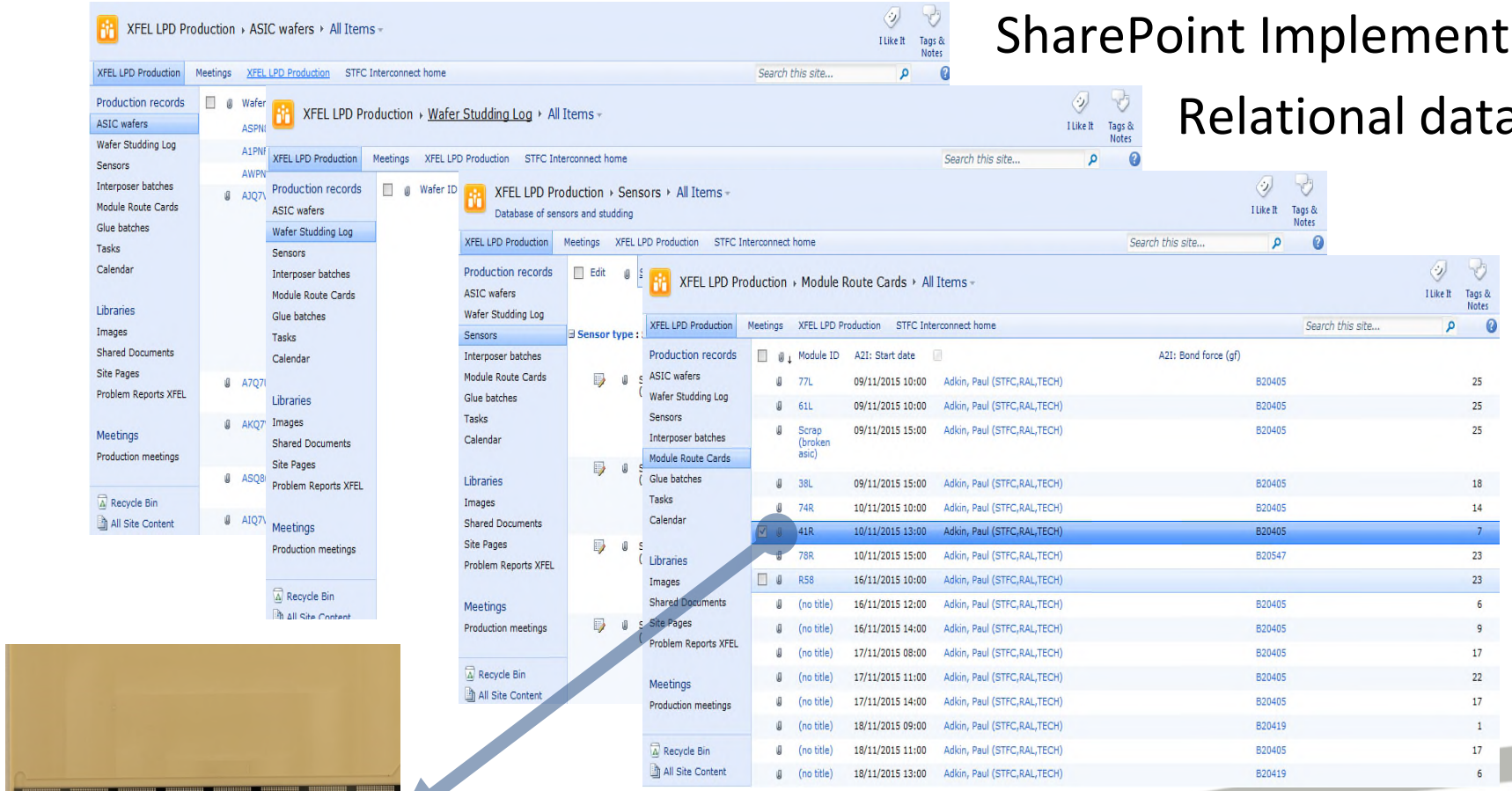
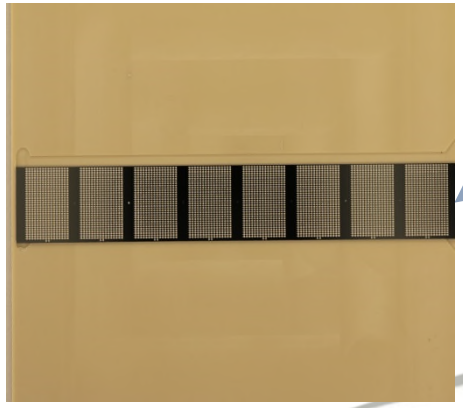
LPD Production

Traceability & configuration records





SharePoint Implementation

Relational database

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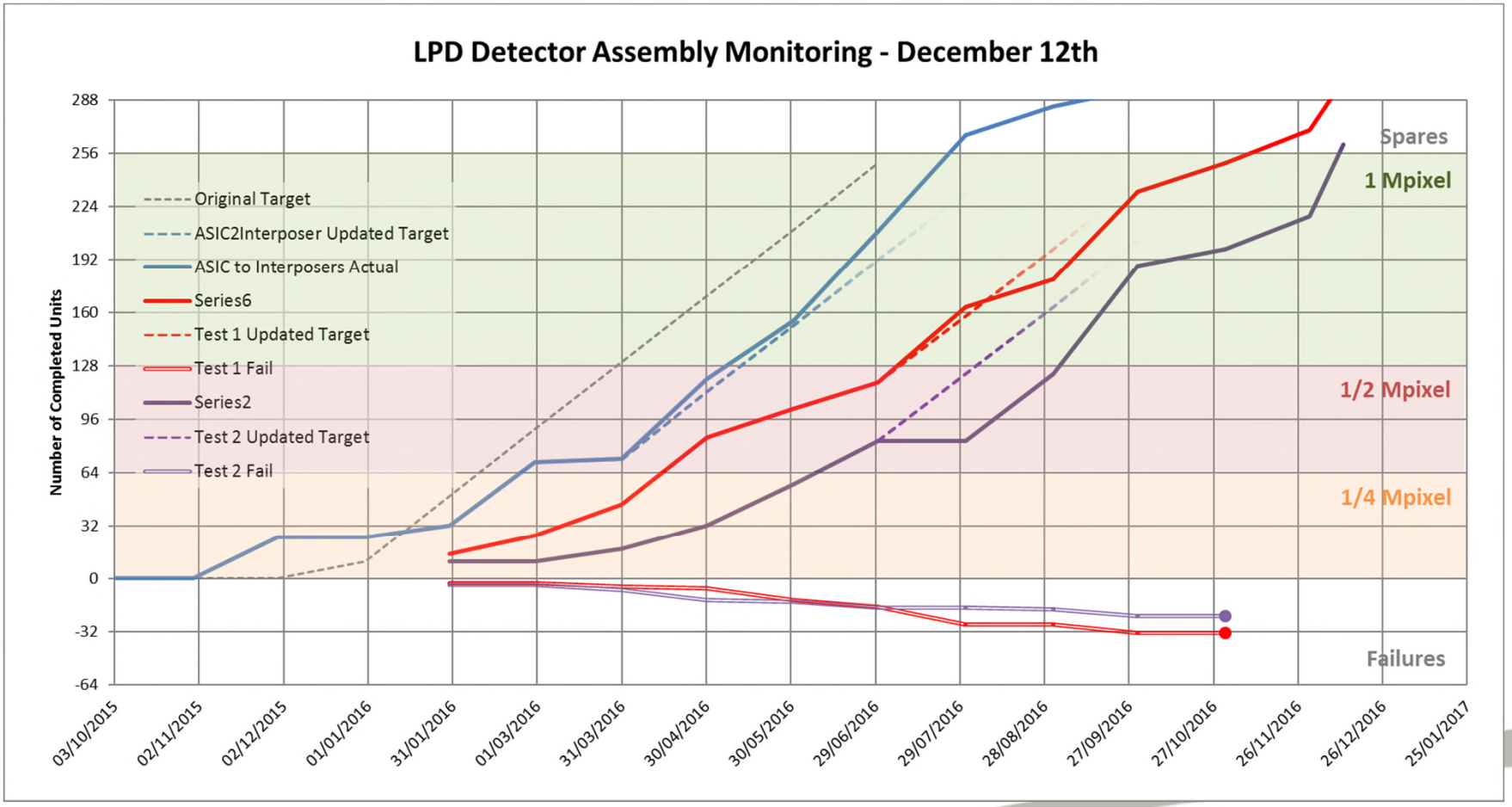
Tile manufacture tracked



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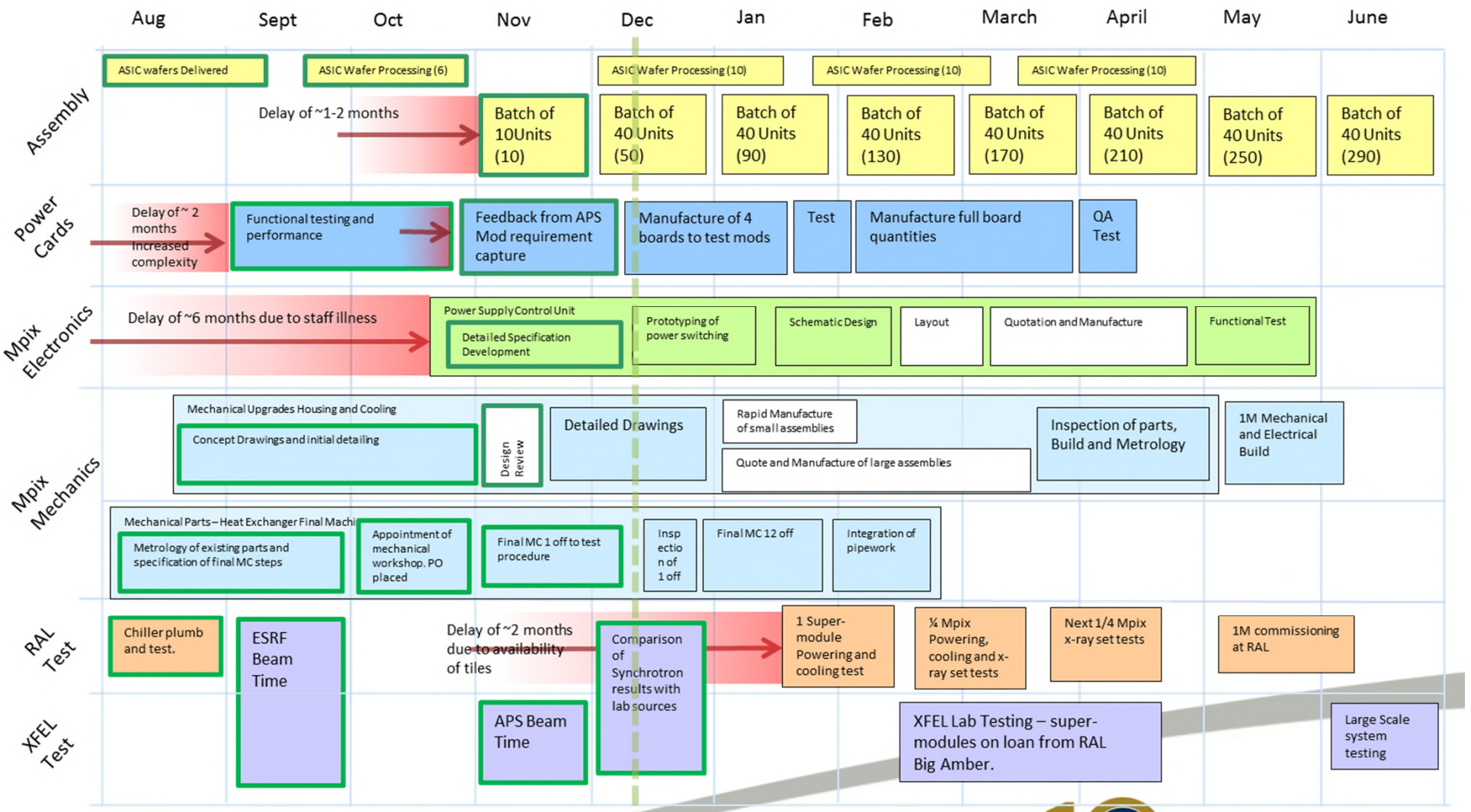
Detailed plans for all components



Note: Delay reported with reference to last XDAC

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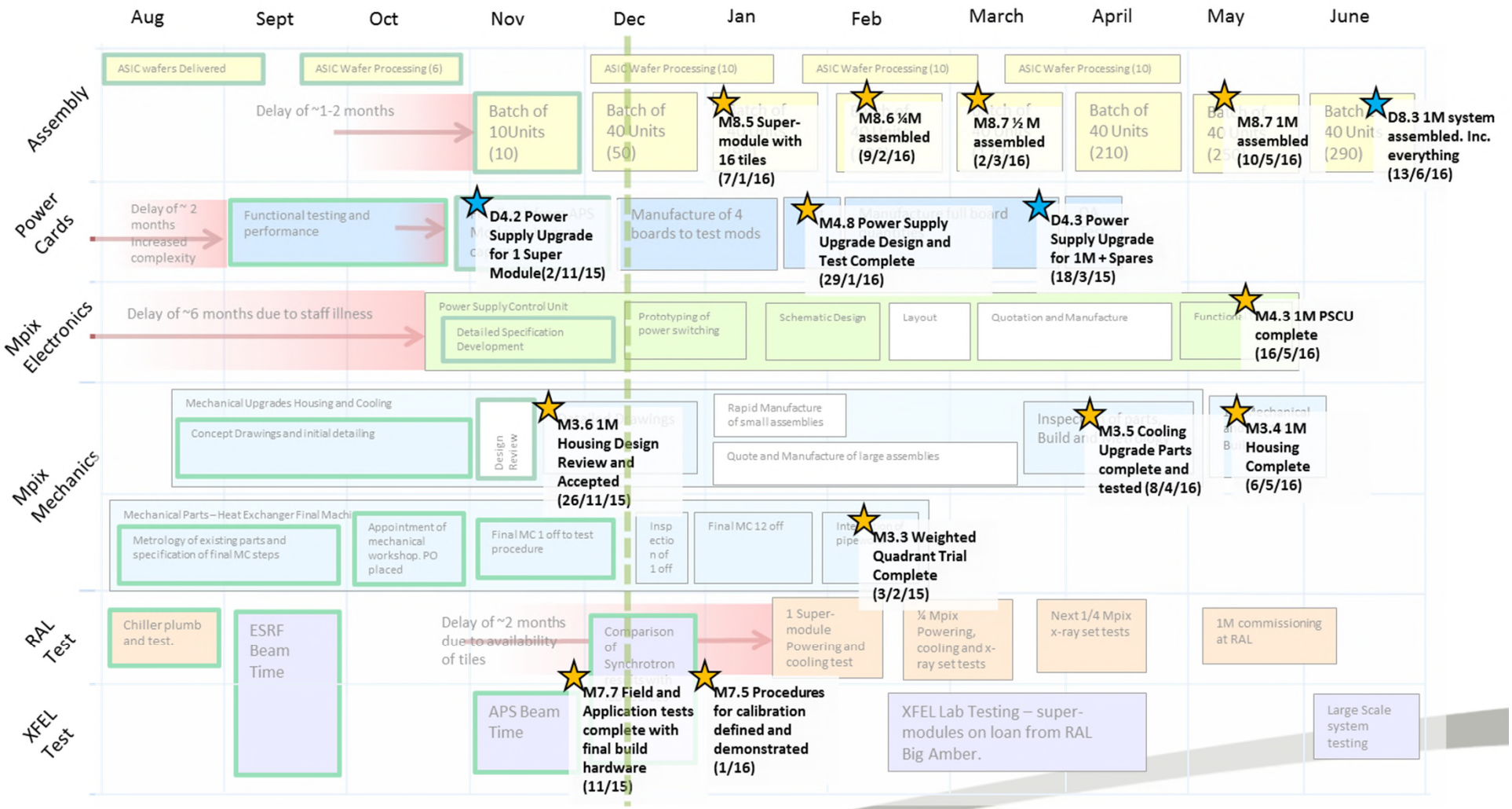
With Milestones tracked



Note: Delay reported with reference to last XDAC

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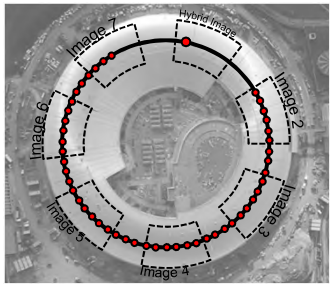
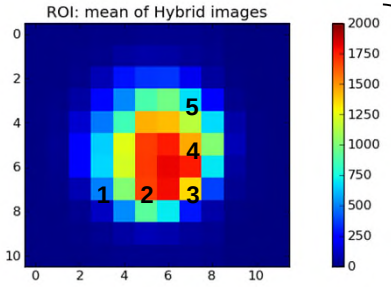
LPD Test and Callibration

LPD Test and Calibration Programme

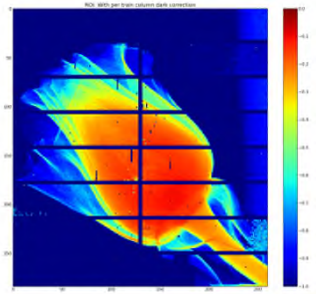
Hybrid mode at SR sources and FELs



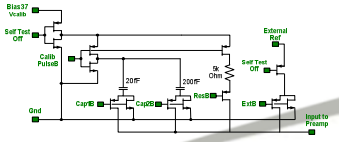
Optical/IR Lasers



X-ray set lab sources



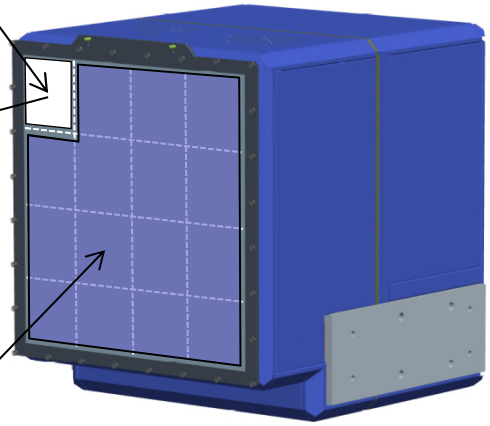
On-Chip Test Pulses



1. Obtain high quality calibration sets from synchrotron source for small scale systems

2. Compare calibration results with lab based sources to validate use with LPD

3. Extend the calibration set across the full scale system with lab based testing



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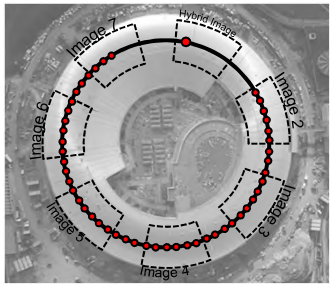
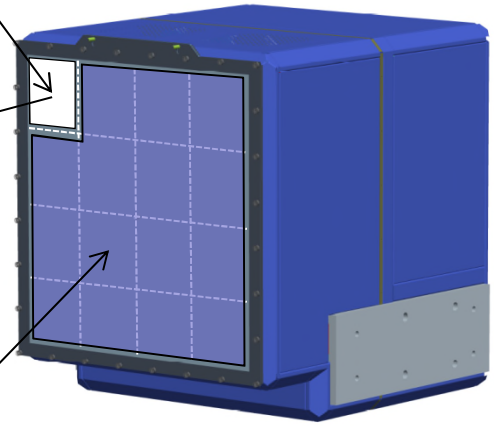
Xray Photon Sources

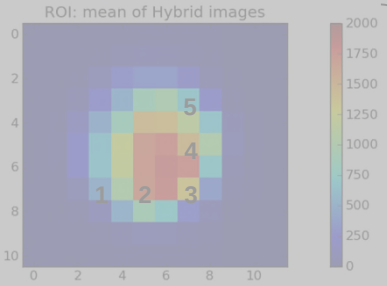
Hybrid mode at SR sources and FELs



1. Obtain high quality calibration sets from synchrotron source for small scale systems

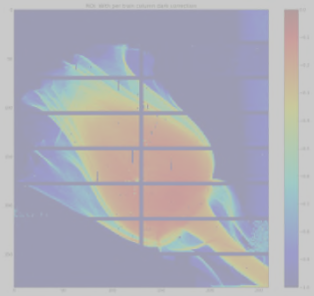


Optical/IR Lasers



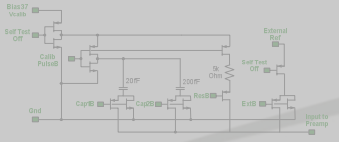
2. Compare calibration results with lab based sources to validate use with LPD

X-ray set lab sources



3. Extend the calibration set across the full scale system with lab based testing

On-Chip Test Pulses



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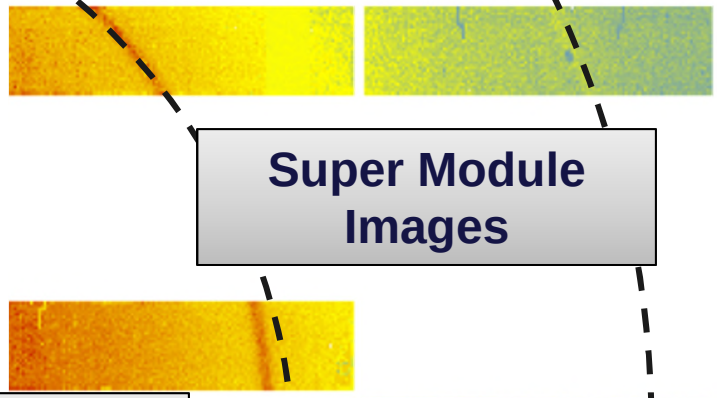
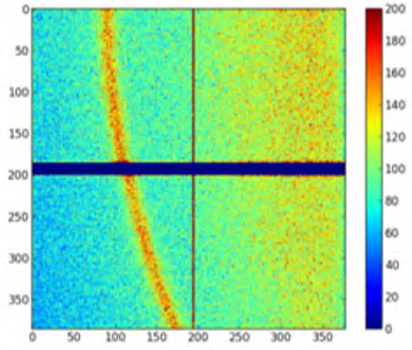
LPD First "Diffraction Experiments" at LCLS

- Photon energy 9 keV
- Sample TiO_2 on Kapton
- Detectors CSPAD and LPD Super Module

Super Module Images



CSPAD Image



LPD Super Module

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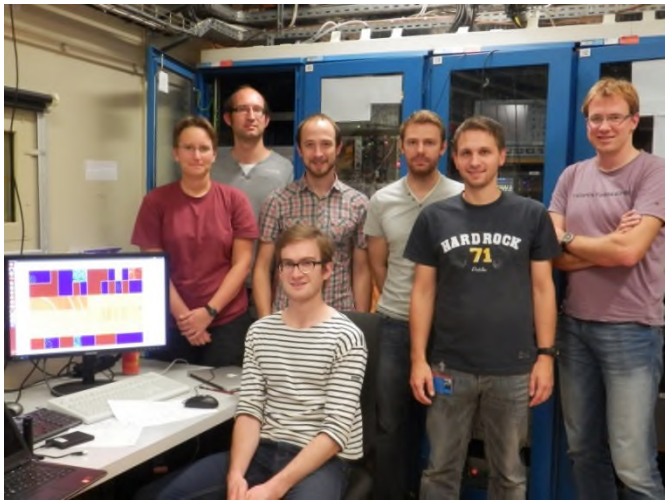
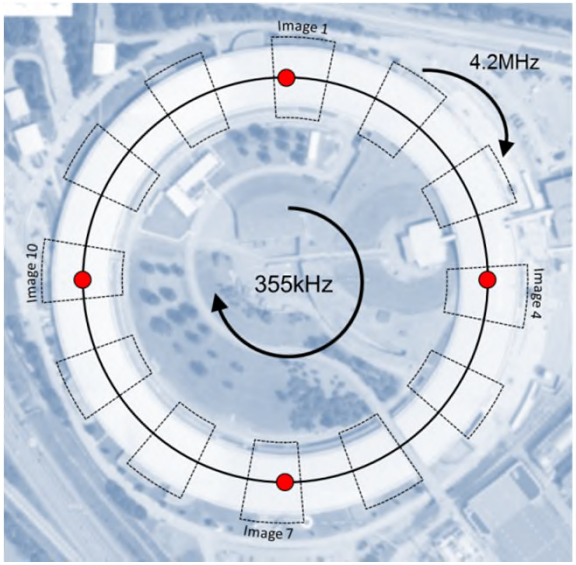
ESRF – 4 bunch mode

ESRF – Using 4 Bunch mode to mimic XFEL and FXE style experiments with liquid jets and laser pumping.

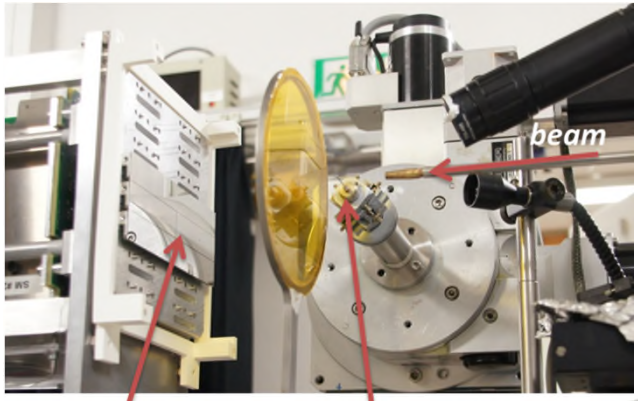
Single shot diffraction patterns



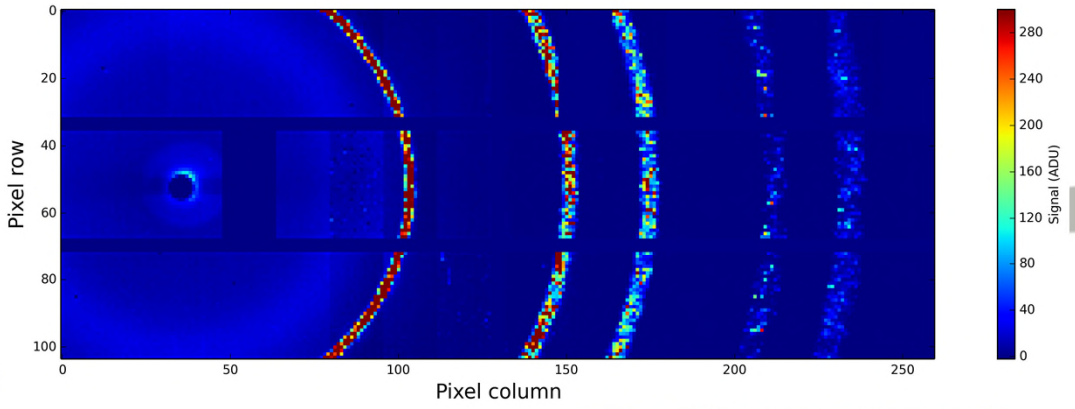
ESRF – XFEL and RAL team



ESRF Hybrid fill 4 bunch mode. Synchronized with LPD running at 4.2MHz



Si powder diffraction – Mean in x10 gain



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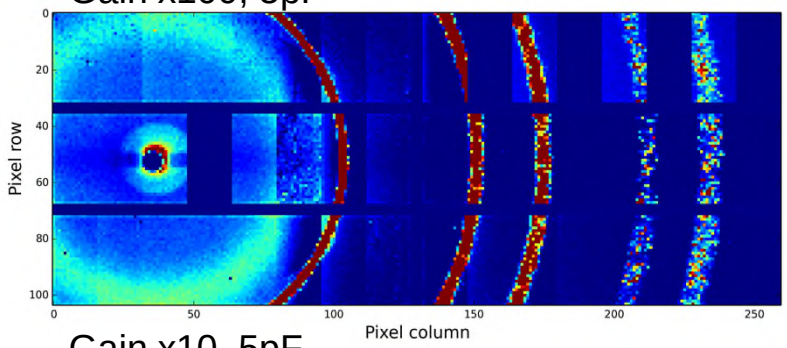
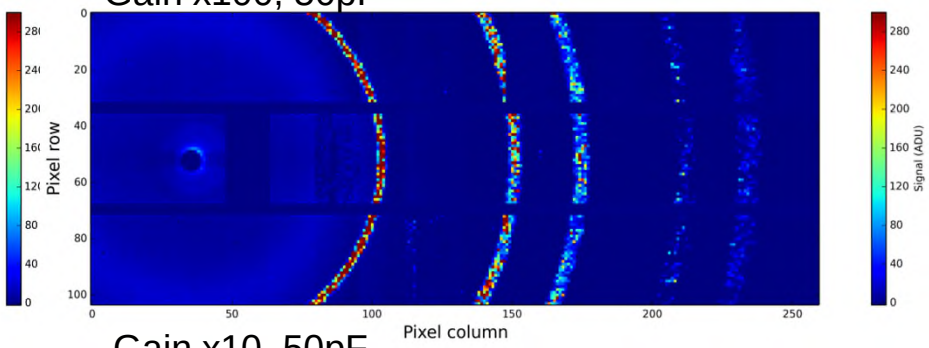
LPD – Same Diffraction Pattern at Different Gains at ESRF

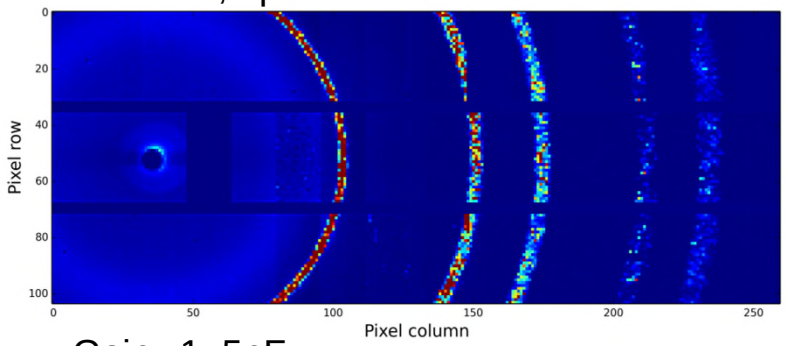
Gain x100, 5pF



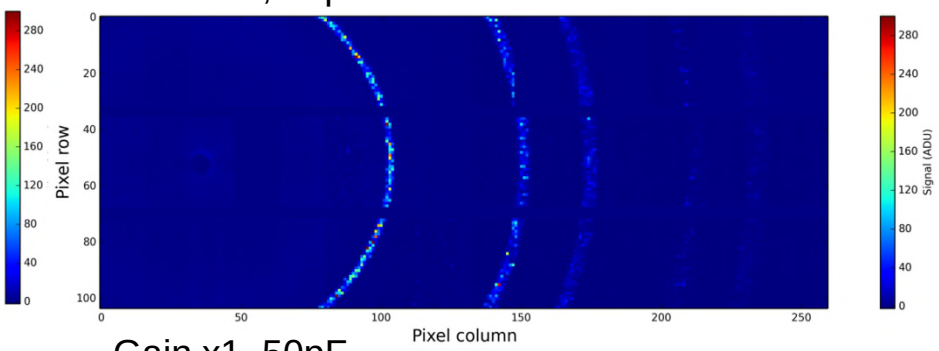
Gain x100, 50pF



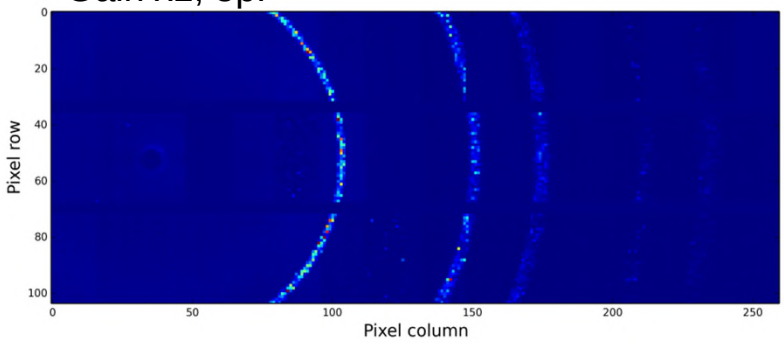
Gain x10, 5pF



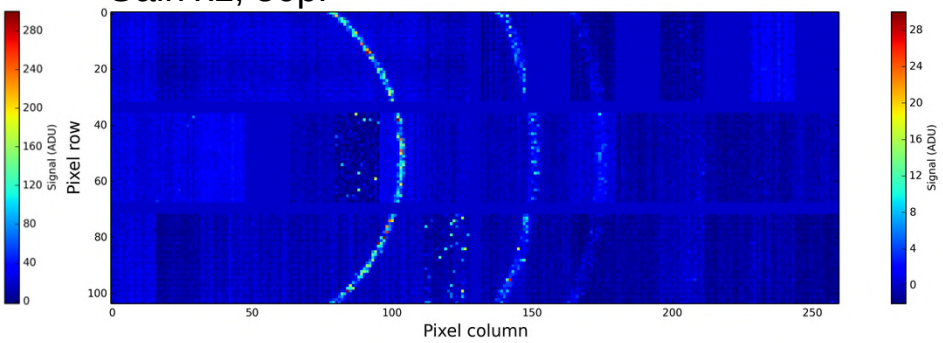
Gain x10, 50pF



Gain x1, 5pF



Gain x1, 50pF



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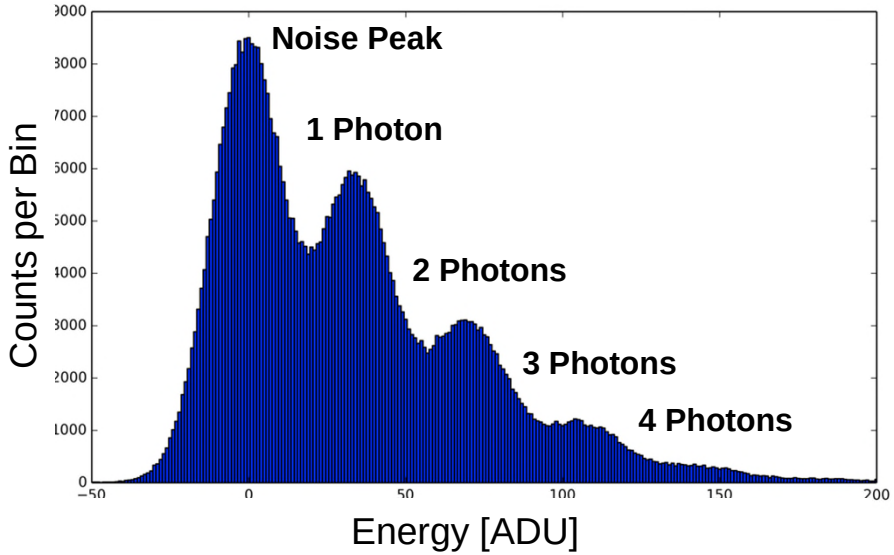
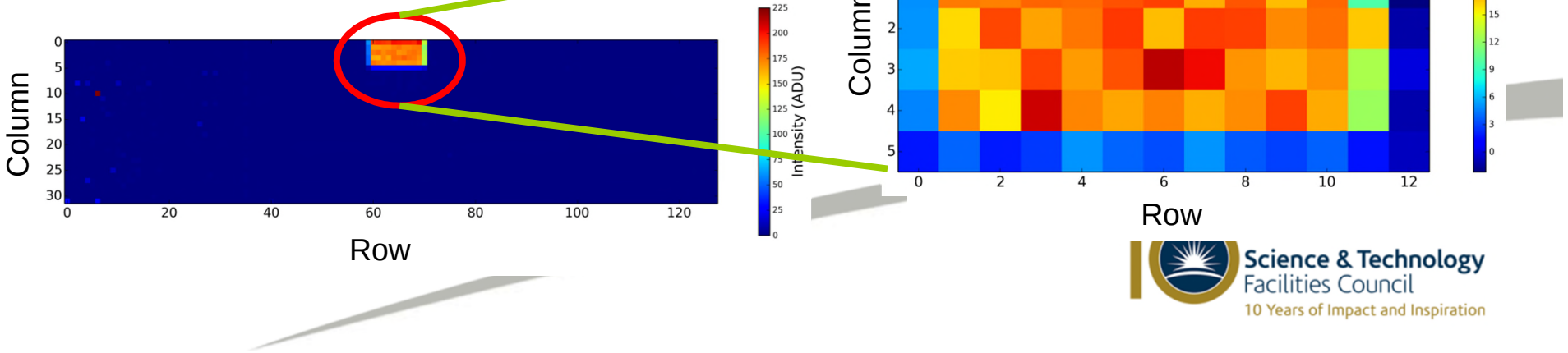
Low Intensity Performance at LCLS, PETRA III and APS

- Single photon sensitivity demonstrated down to 12 keV
- Tests with final hardware at ESRF and APS this fall



Imaging and Charge Sharing Properties



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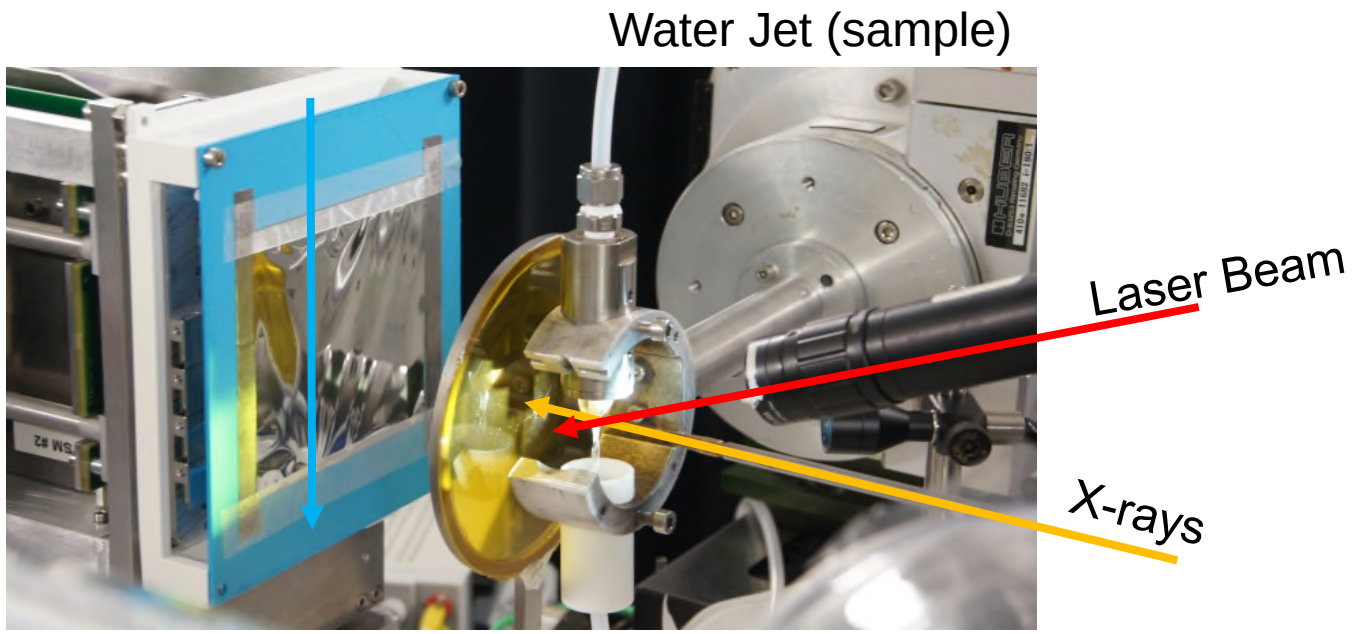
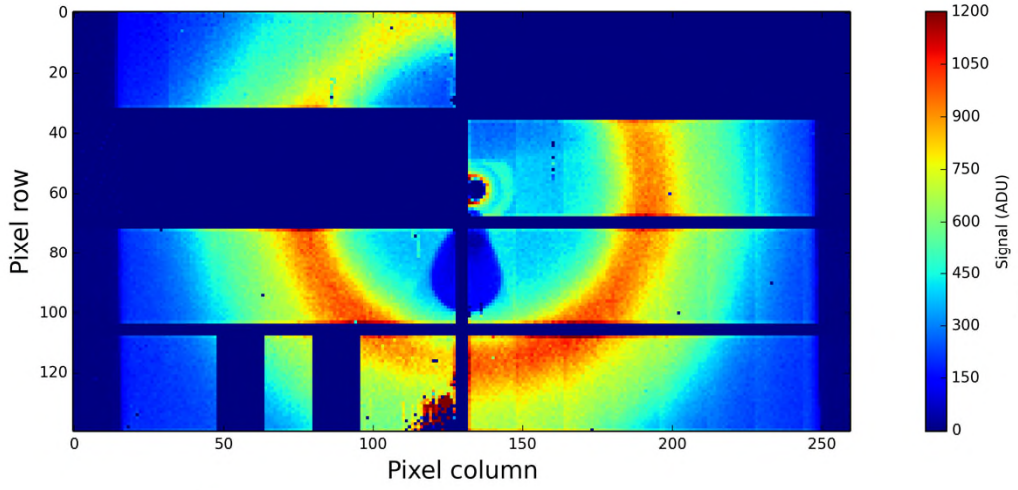
ESRF – 4 Bunch Mode





Liquid diffraction with laser pump probe conditions

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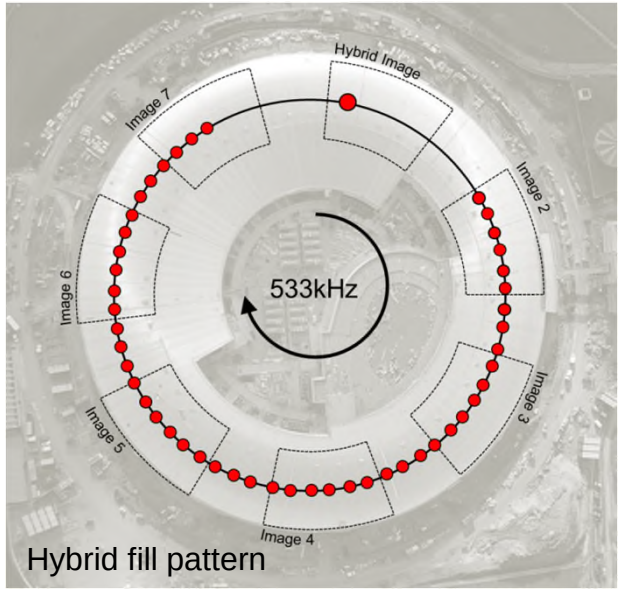
Diamond – Hybrid Mode

Diamond – Hybrid mode

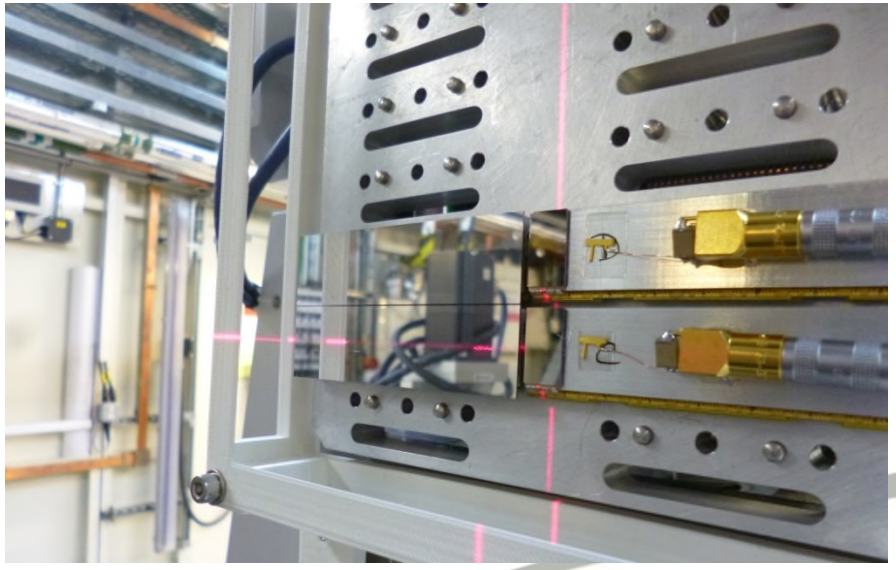
Well timed monochromatic photons for 4.5MHz imaging.

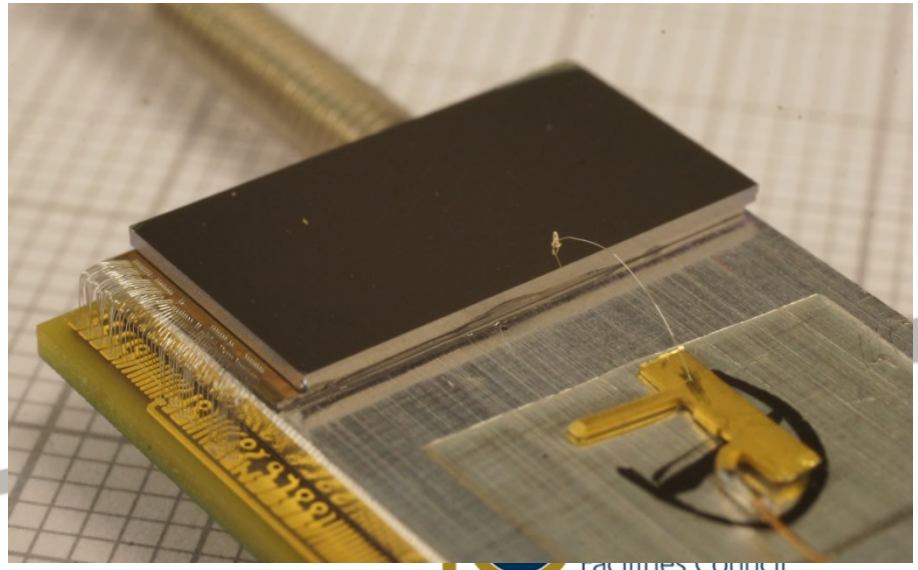
Test of a full LPD super-module with new power cards

LPD Silicon and GaAs side by side trials



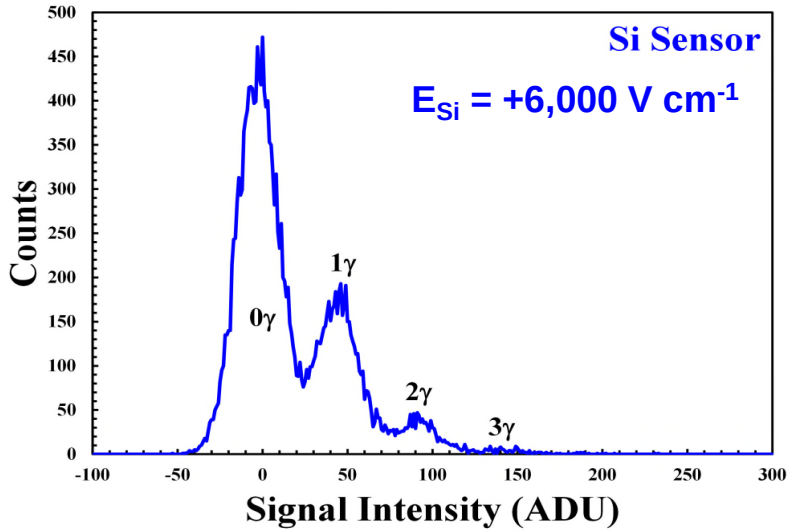
Hybrid fill pattern

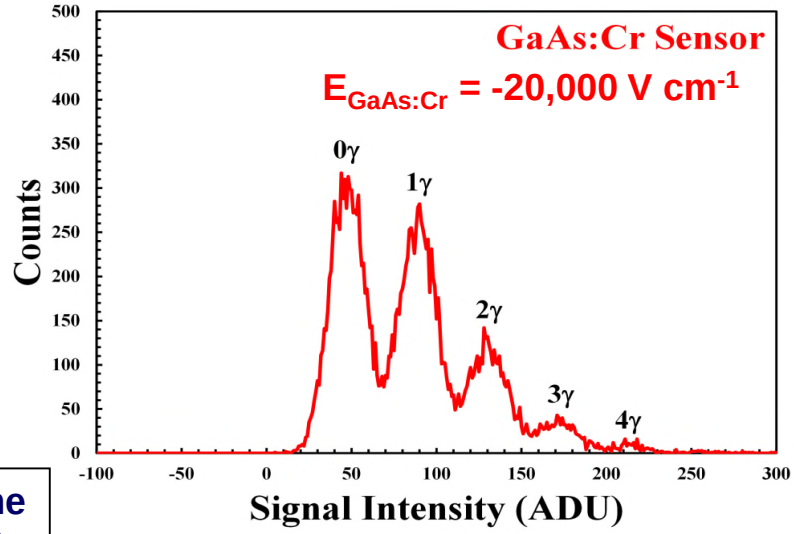

LPD Silicon and GaAs:Cr tiles operating side by side


Closeup GaAs:Cr sensor

Diamond – LPD GaAs:Cr

- Al absorber = 1.0mm
- Single photon counting
- Beam size = 0.1mm x 0.1mm
- Photon E = 20 keV
- GaAs:Cr stops 60% more events as expected.
- Noise performance in Si & GaAs:Cr limited by the ASIC.
- Evidence for polarisation…

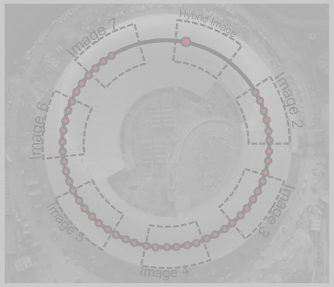




Characterisation and Development of GaAs:Cr High Frame Rate X-Ray Imaging Detectors – Dr Matthew Veale R03-5

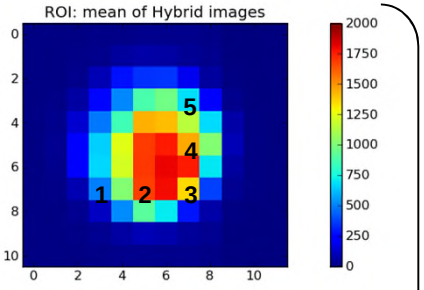
Optical/IR Lasers

Hybrid mode at SR sources and FELs

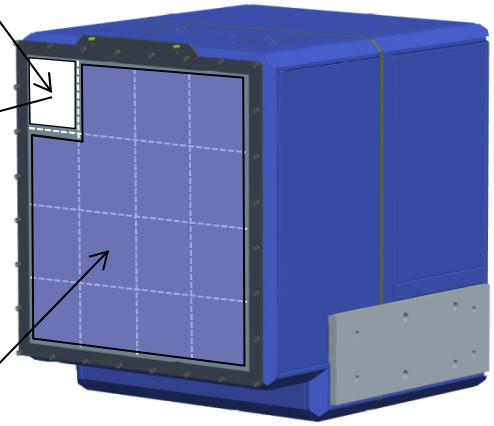


1. Obtain high quality calibration sets from synchrotron source for small scale systems

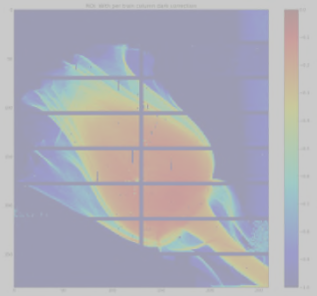
Optical/IR Lasers



2. Compare calibration results with lab based sources to validate use with LPD

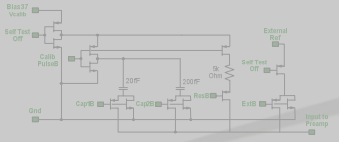


X-ray set lab sources



3. Extend the calibration set across the full scale system with lab based testing

On-Chip Test Pulses



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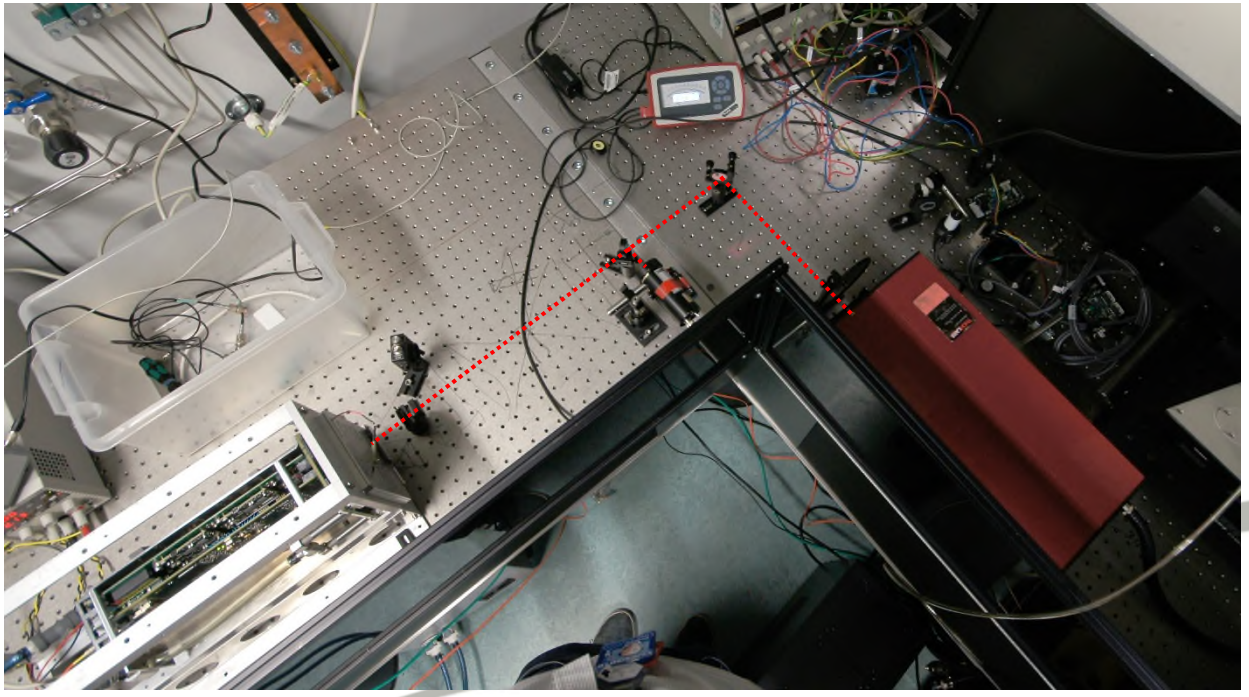
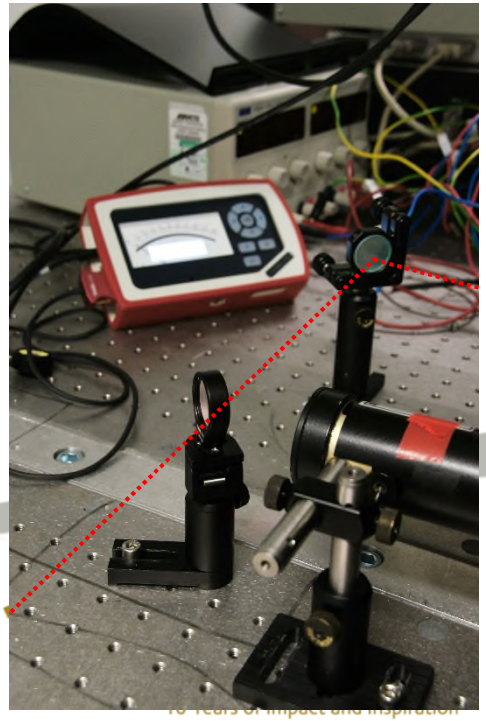
Beamtime at RAL - CLF

Central Laser Facility

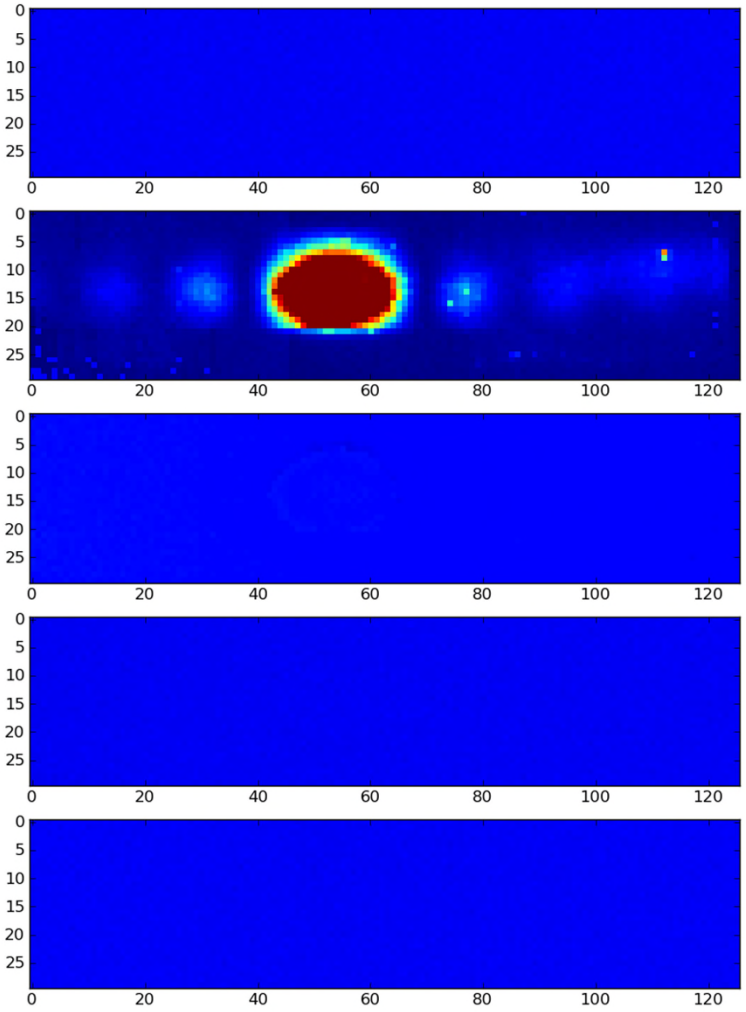
- Class 4 laser
- ND filter attenuation
- Intensity monitors
- Single shots synchronised to LPD



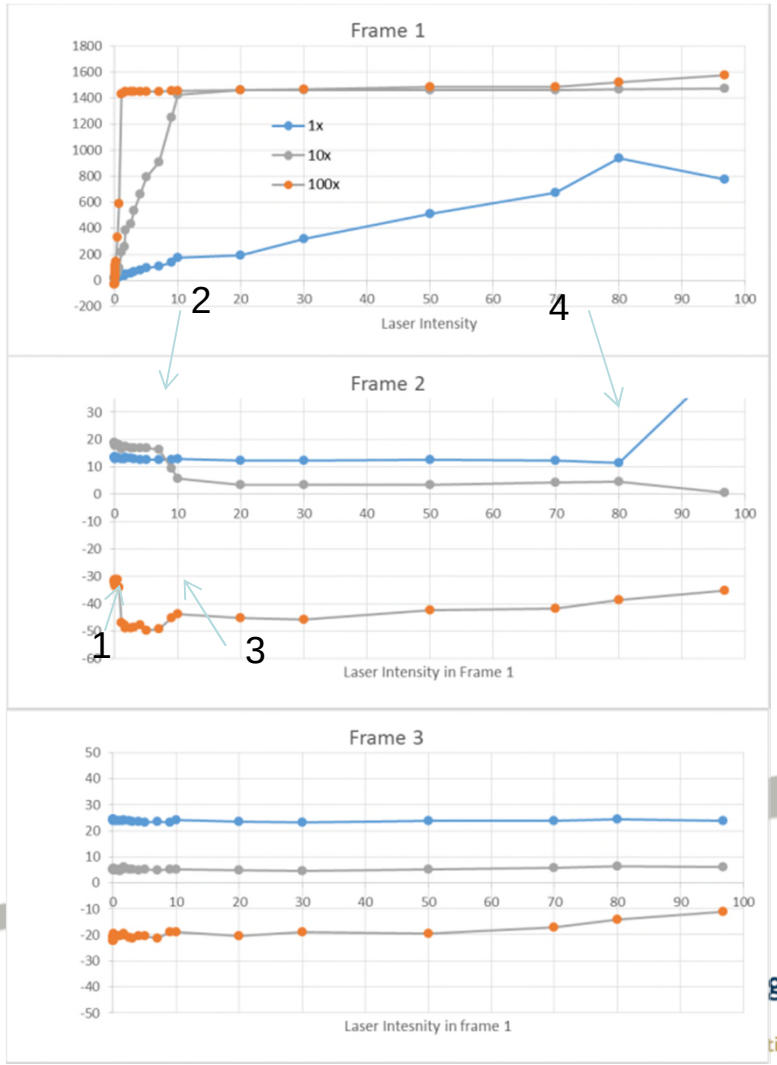


Beamtime at RAL - CLF

5pF x100 – Average of 10 Trains with dark subtraction

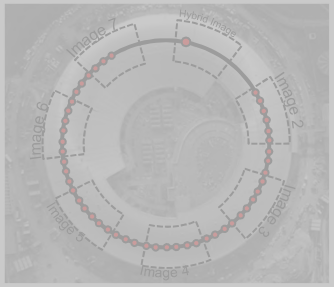


Single Slit Diffraction – 4.5MHz Train



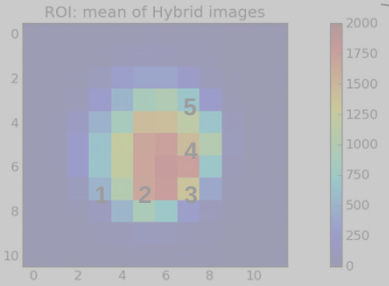
Xray Set Transmission Images

Hybrid mode at SR sources and FELs



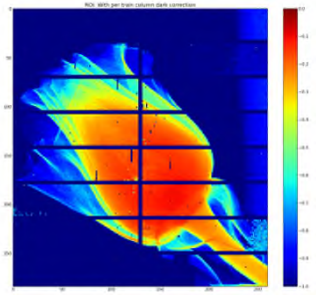
1. Obtain high quality calibration sets from synchrotron source for small scale systems

Optical/IR Lasers



2. Compare calibration results with lab based sources to validate use with LPD

X-ray set lab sources



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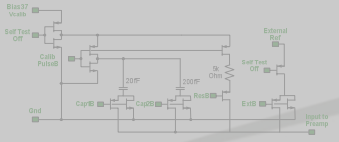
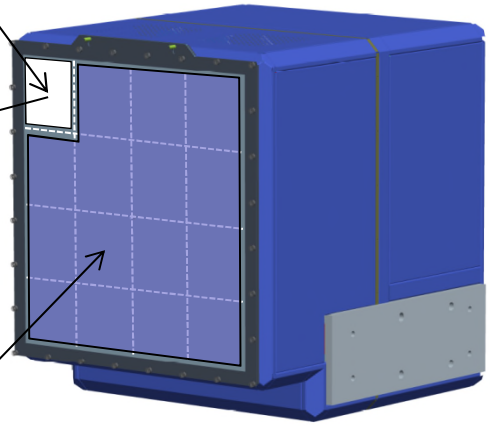
On-Chip Test Pulses





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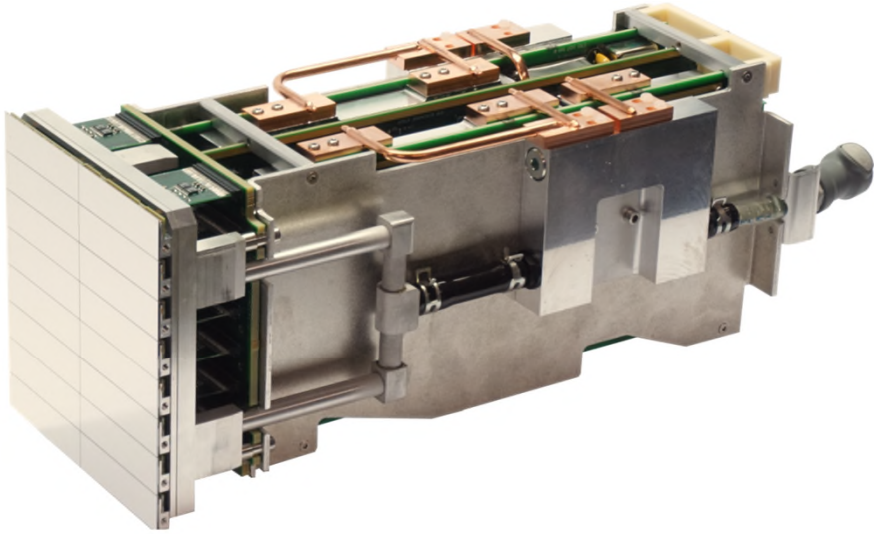
Transmission Imaging

X-ray Set – Each LPD super-module to be tested on RAL x-ray set to provide flat field information and bad pixel maps.



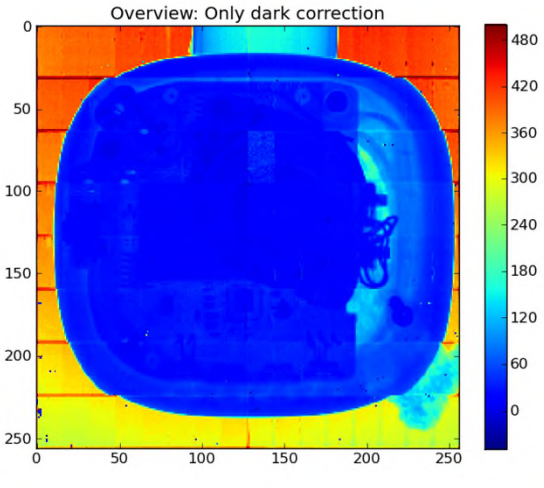
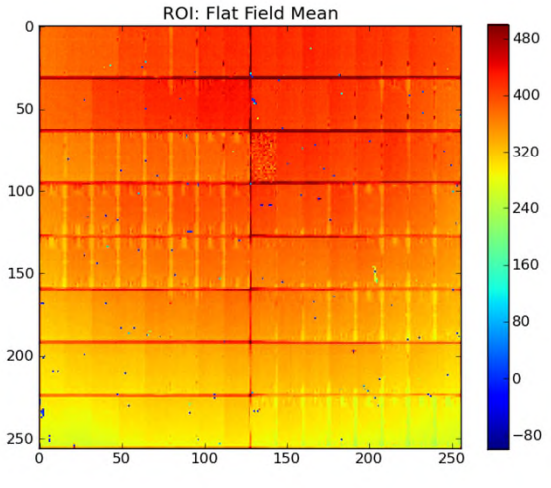
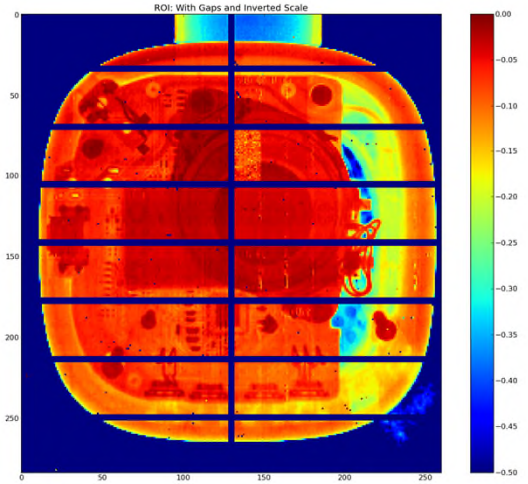


Image Data With Dark Correction



Flat Field Data

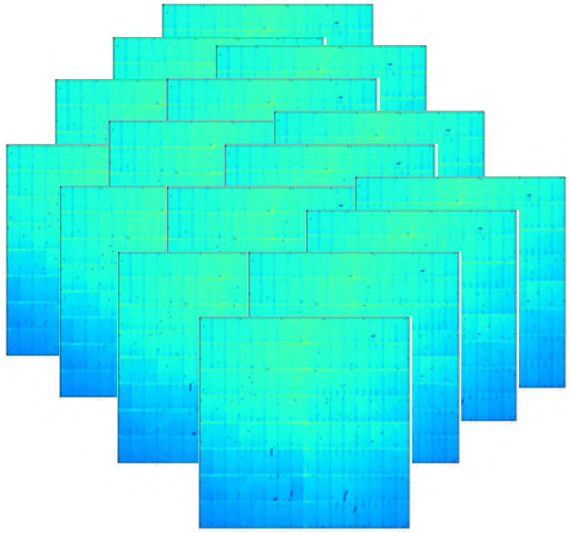


Corrected Data

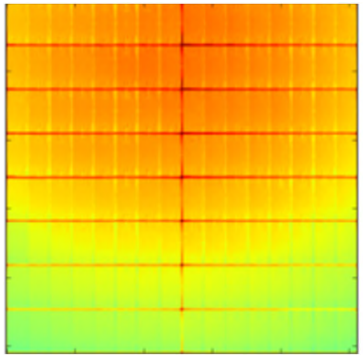
All SM Screened to ‘Map’ pixels

- Identification by two methods
  - Out of range signal – Unconnected or shorted pixels.
  - Out of range noise – Noisy pixels, coupling to shorted pixels, bad power supply units

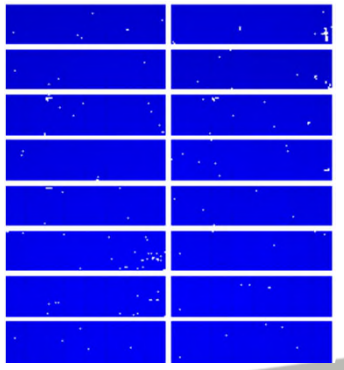
1. Take all 16 flat fields or noise maps



2. Create the ‘ideal’ super-module map from the median



3. Threshold individual data against ideal to produce bad pixel map



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LPD Shipping

Jan 2017 – LPD Complete at RAL

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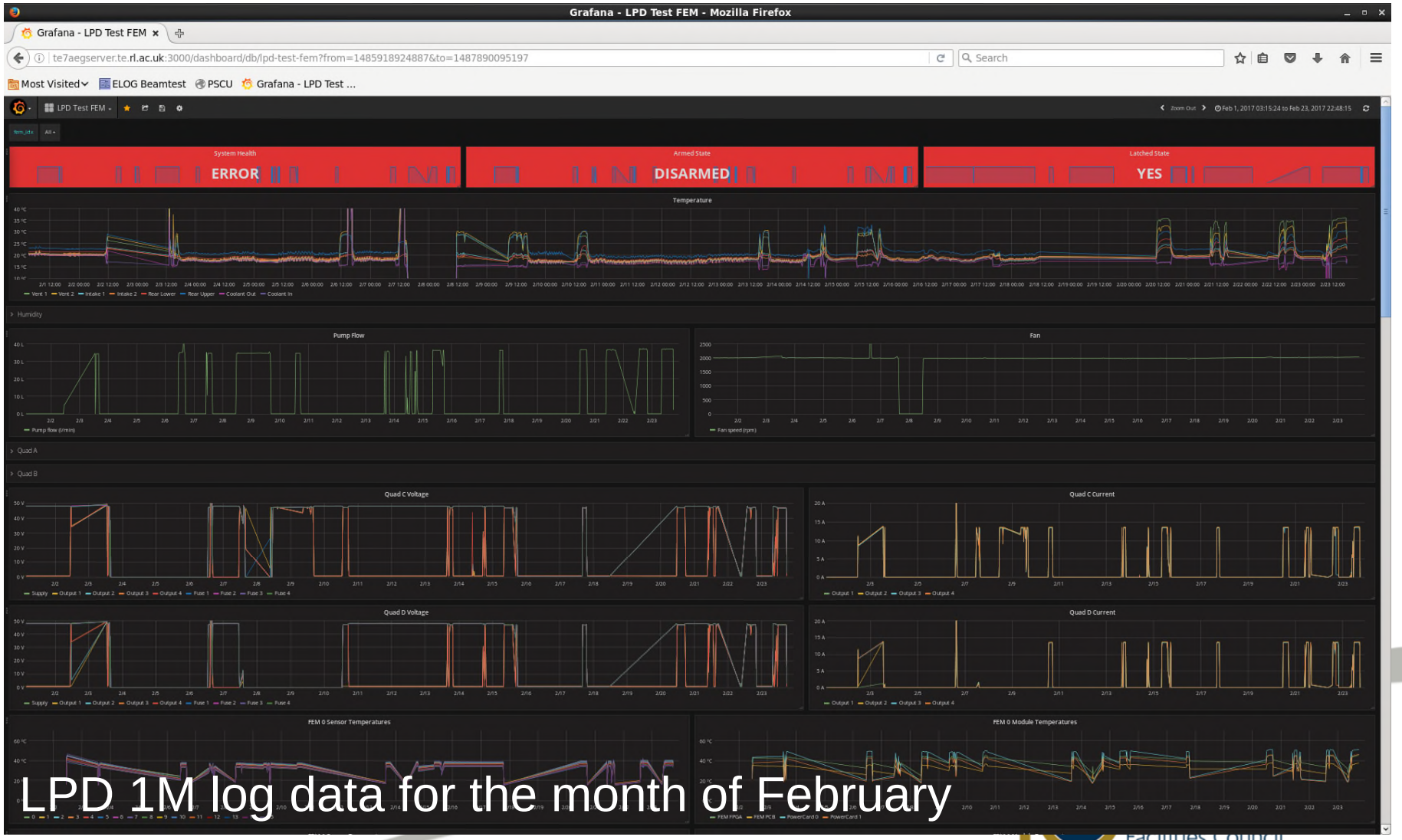
LPD ‘Soak Testing’ prior to shipment



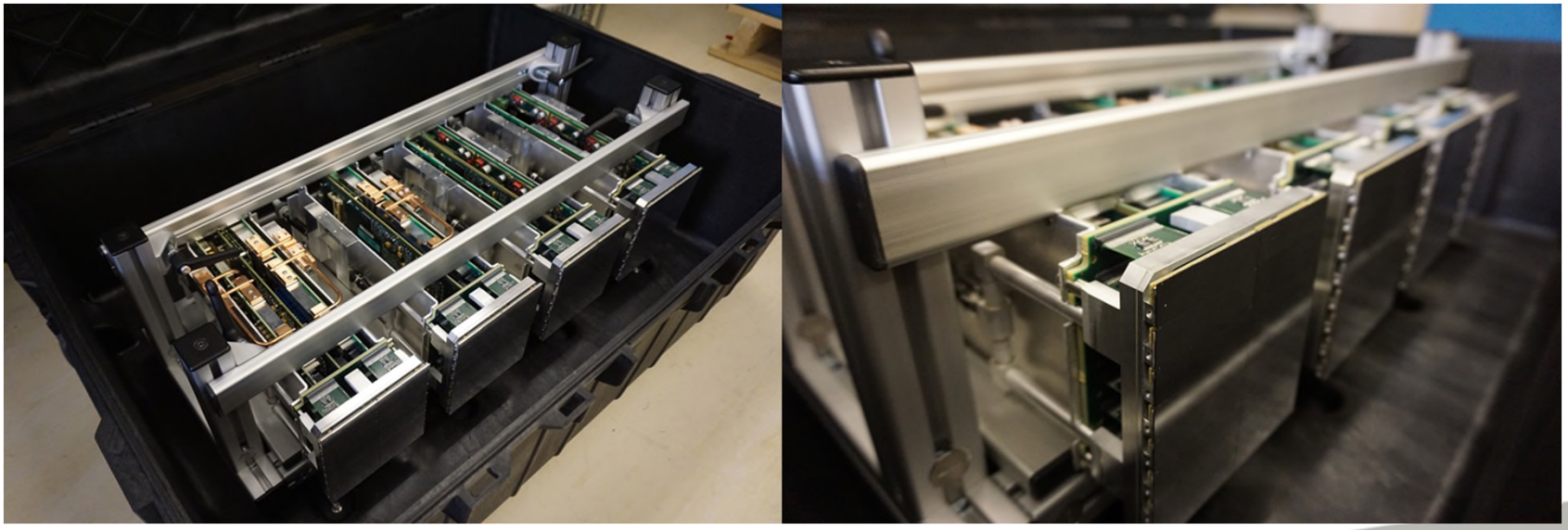
LPD 1M log data for the month of February

Disassembling the System

- Video Clip link

LPD Packing up

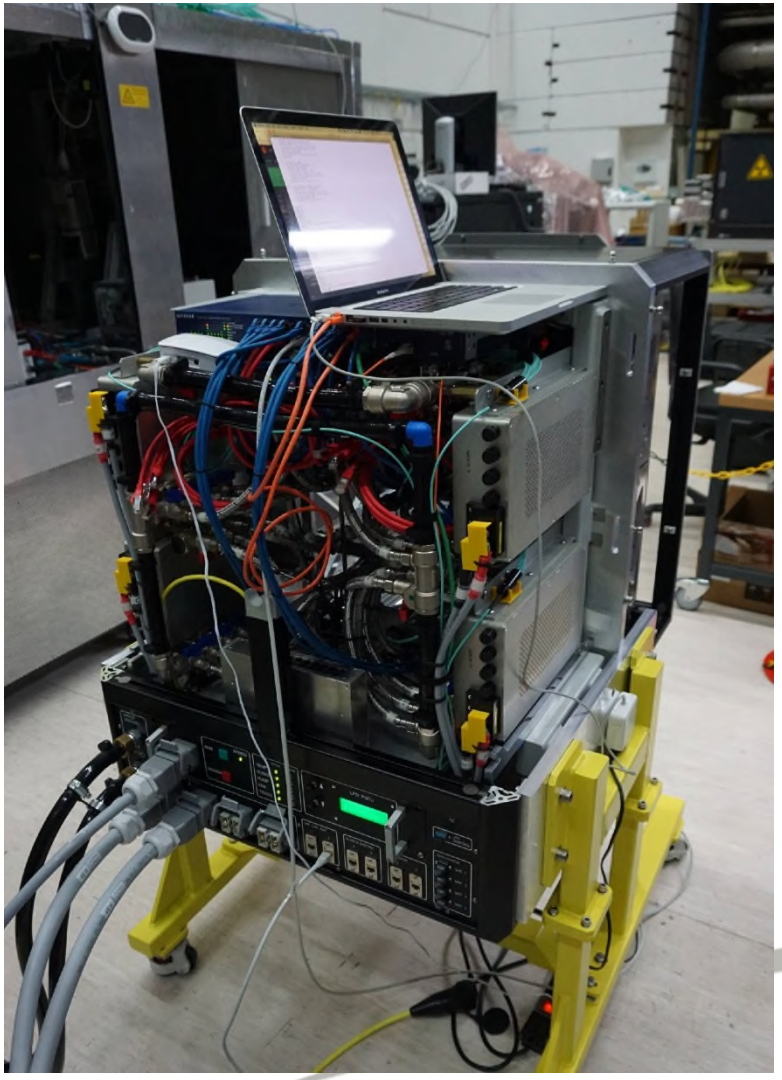
- LPD Super-modules shipped in flight cases. 4 groups of 4.
- 4 Shipping crates built for 1M housing, Power Supply, Chiller and Accessories (Cables etc.)
- RAL Transport drove the equipment to Hamburg.

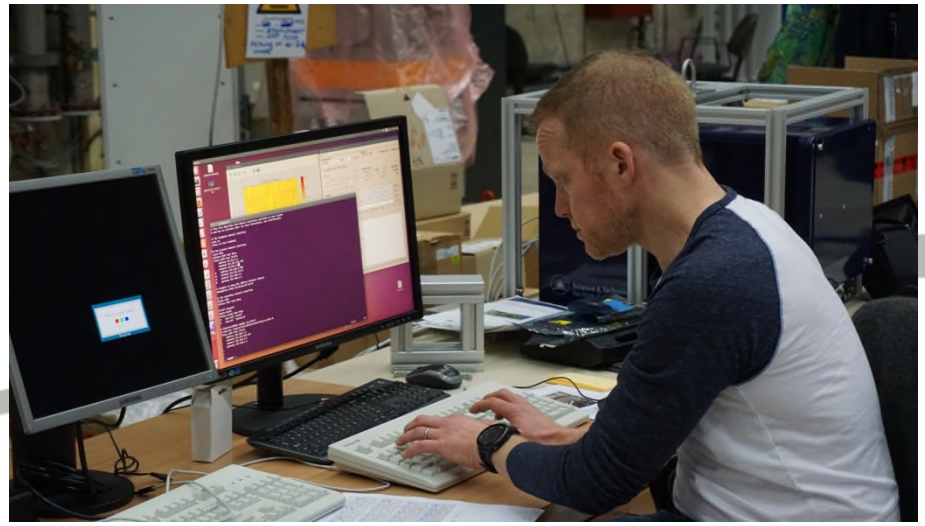


Super-module flight cases

LPD at Hera South

LPD Shipped to Hera South – Feb 27th
Operational at Hera South - March 8th

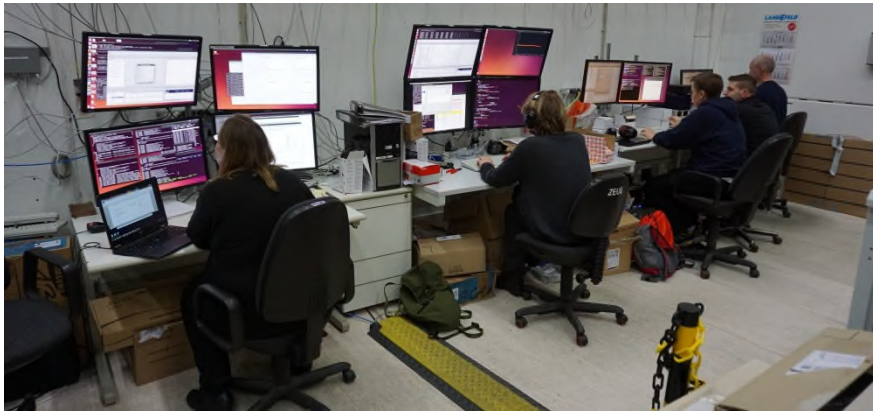




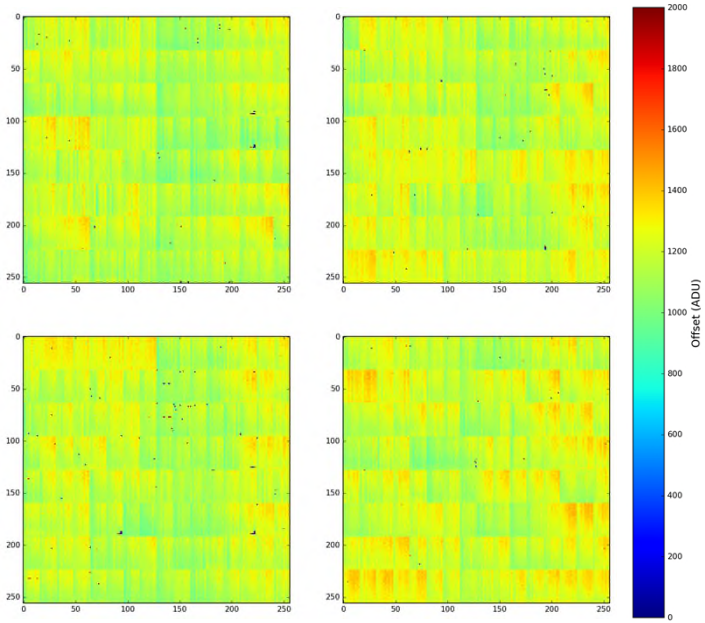
Arrives 2nd March 2017

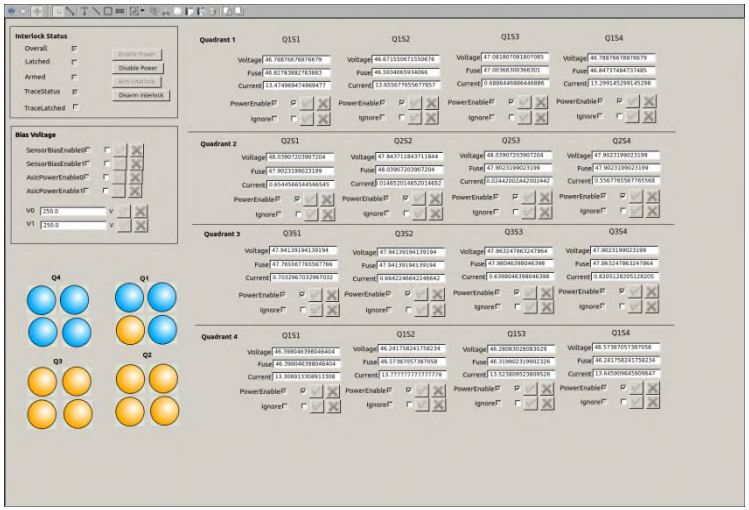
LPD Commissioning

Hera South End-to-end Test



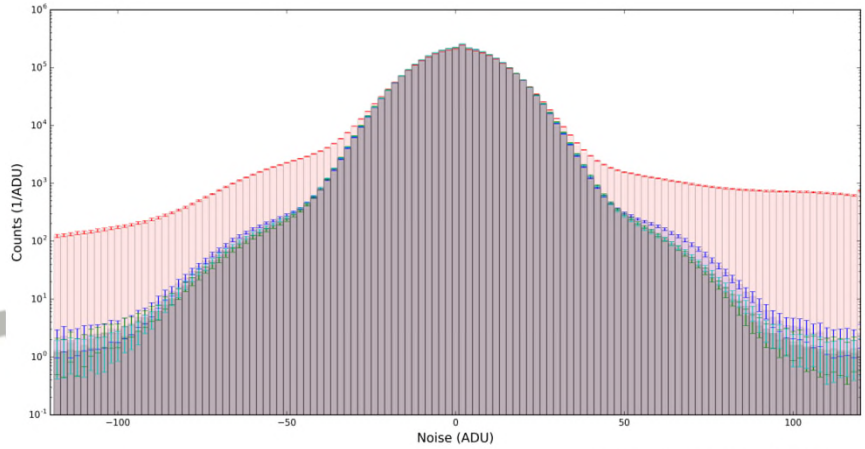
Offset Maps for Q4



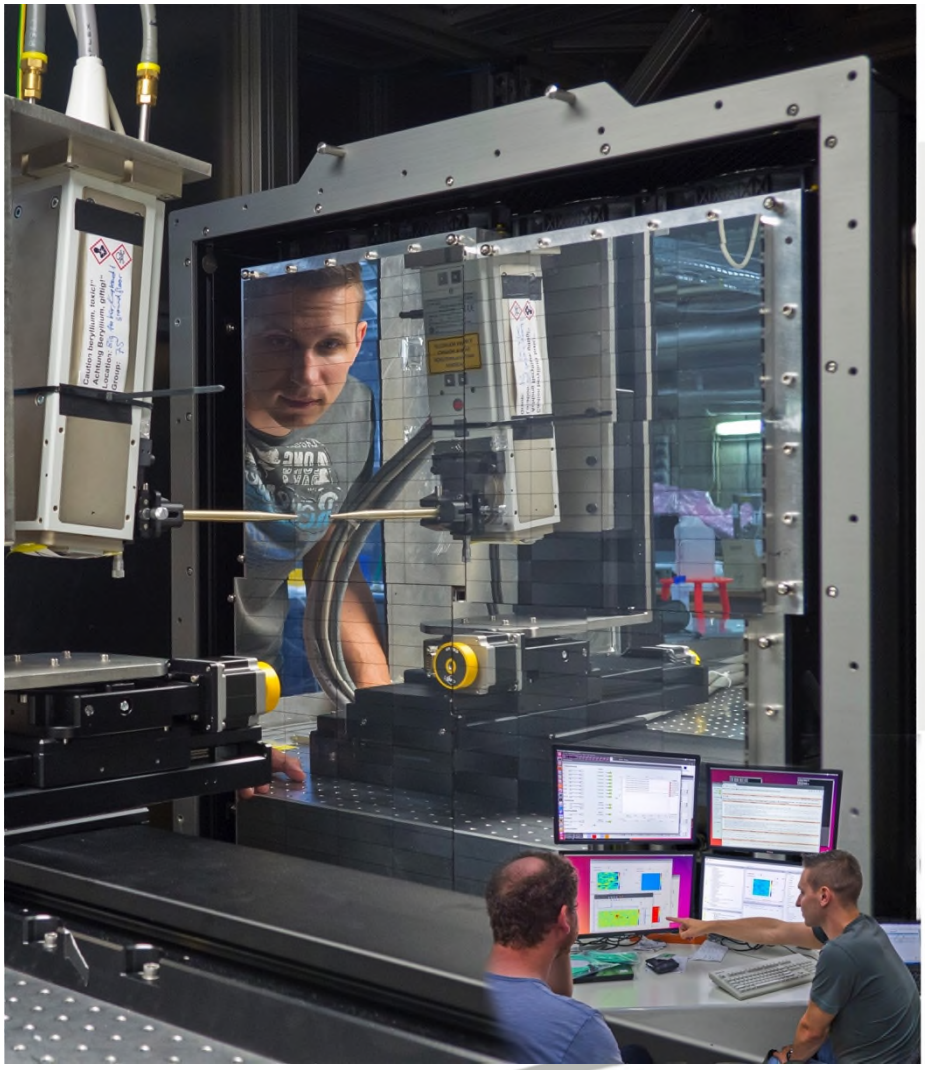


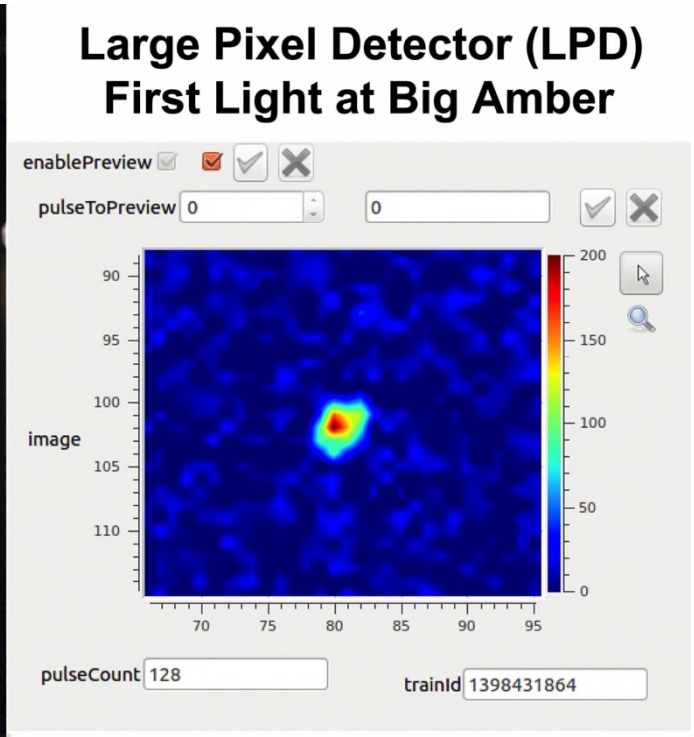
GUI bringing together multiple
LPD Karabo Devices

Noise histogram for Q4 (log scale in y)



LPD First X-ray Light





4.5MHz with C&C providing trigger, clock, and 504 noVeto pulses
X-ray tube with Mo target and focussing optics at 30kV and 40 mA
500 trains with 128 memory cells after online offset correction

Arrival at XHQ

Science & Technology Facilities Council
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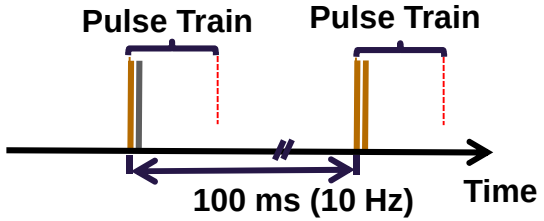
Wedding – Support Meets LPD Detector

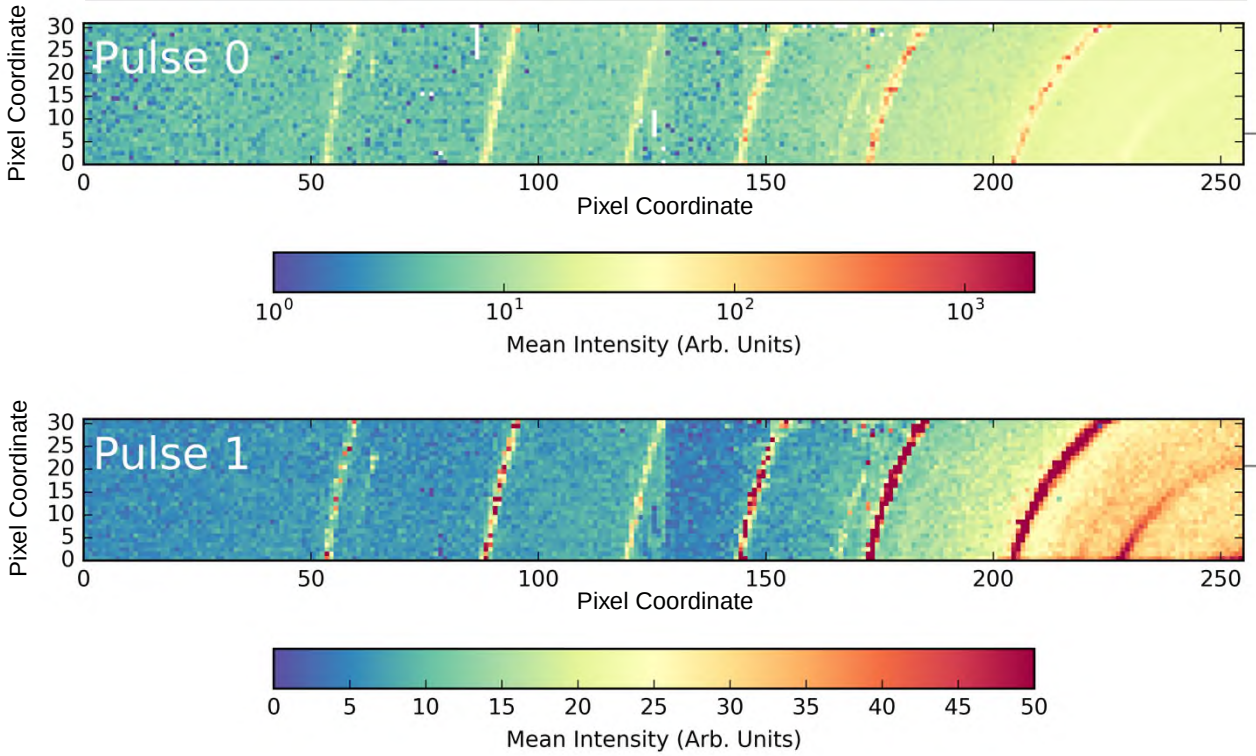
First Xrays at FXE

First Single Pulse Images @ FXE
LPD Two Tile

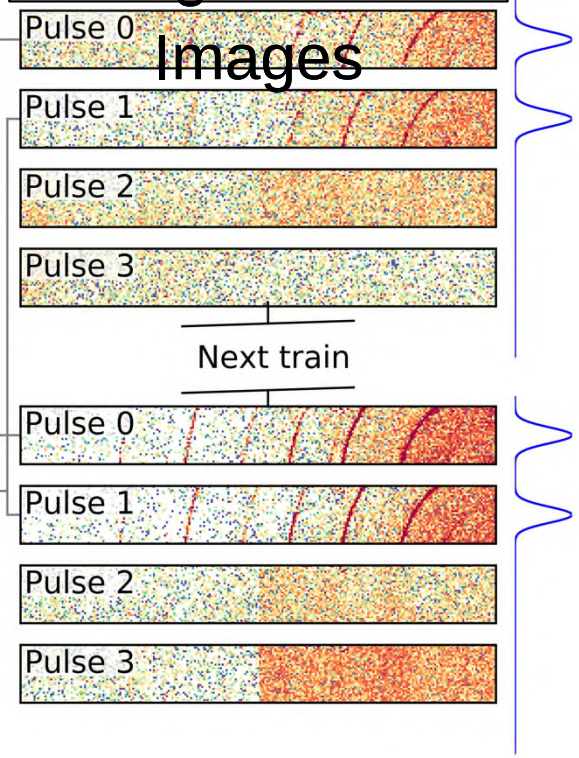
Target LaB_6 Powder
Photon Energy 8.3 keV
Approx. 400 µJ/Pulse



Averaged Offset Corrected Images (200 Pulses)

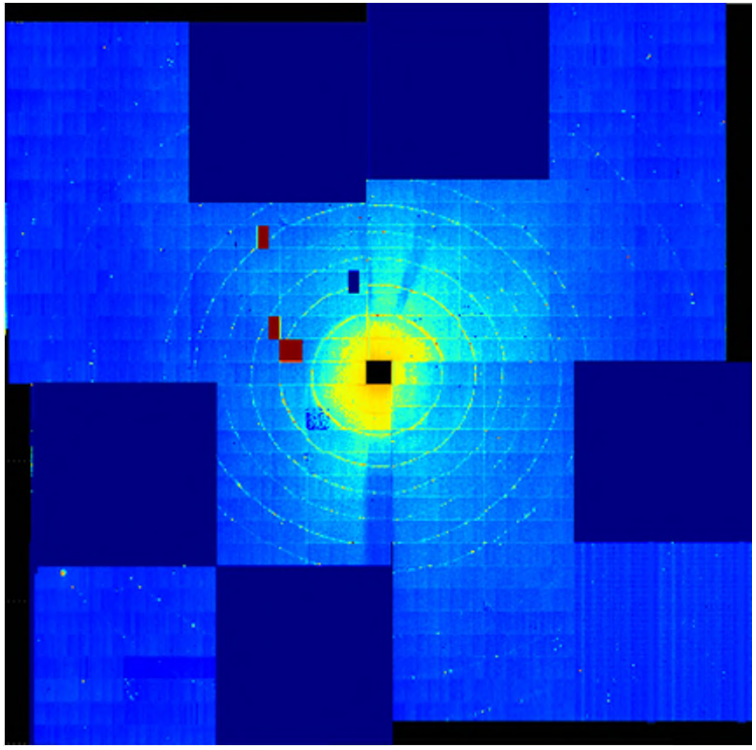


Single Pulse Images



FXE June, 29th – 30th 2017

Commissioning at FXE



- First Powder diffraction with main detector
- Not all SM wired in to DAQ yet
- Some clock timing issues

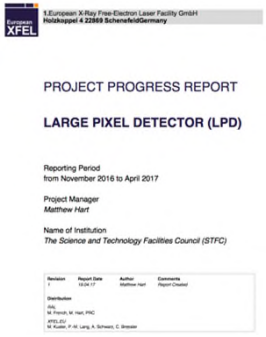
Conclusions and Lessons Learned

10 Years, 4 Months and a Few Days…

(April, 24th 2007 till Sept 7th, 2017)

- Budget (European XFEL)
  - Phase I
  - Phase II
  - LPD Prototype system
  - Spares and Support etc

- Project Changes
  - 3 Project Change Requests
    - ► Detector Cooling System
    - ► Housing size
    - ► Power connectors
  - ASIC Resubmission



- 21 Reports to the European XFEL Detector Advisory Committee
- Various manuals, drawings intermediate reports

- 21 Meetings of the Detector Advisory Committee
- 12 Calibration Working Group Meetings
- 11 Integration meetings
- 2 Project readiness review meetings
- 1 Go/No-Go Review

- Σ=4394 project related mails
  ➔on average 1.8 mails per working day

- Several hundred cups of tea

- Sleepless nights – none?

XFEL Lessons Learned

- Modular design and early availability of test systems played off in many respects
  - Performance testing and optimization
  - Early DAQ and software integration
  - Verification of integration and calibration conceptsLPD 1 Mpixel detector is installed at FXE and will be commissioned during the next weeks
- End-2-end test could not be completely finished; commissioning and calibration tasks will be finished at beamline
- Testing and commissioning at photon beam lines and with laboratory sources is essential incl. data analysis
- Project scheduling is typically more on the optimistic than realistic side
- Clear definition of scientific requirements and use cases avoids design iterations, extra cost and delays
- Avoid “last minute” changes to designs or requirements

RAL Lessons Learned

- Testing of the system took much longer than expected
- Many technical challenges
  - The flat geometry
  - Radiation shielding
  - Heatsink technology
  - Power supply noise
  - Sensor bias link
  - Interconnect technology
  - Multiple jigs and packaging
  - Numerous firmware revisions
  - Software development
  - Data handling and visualisation
- But its still been fun!

Tiles with low resistance sensor bias

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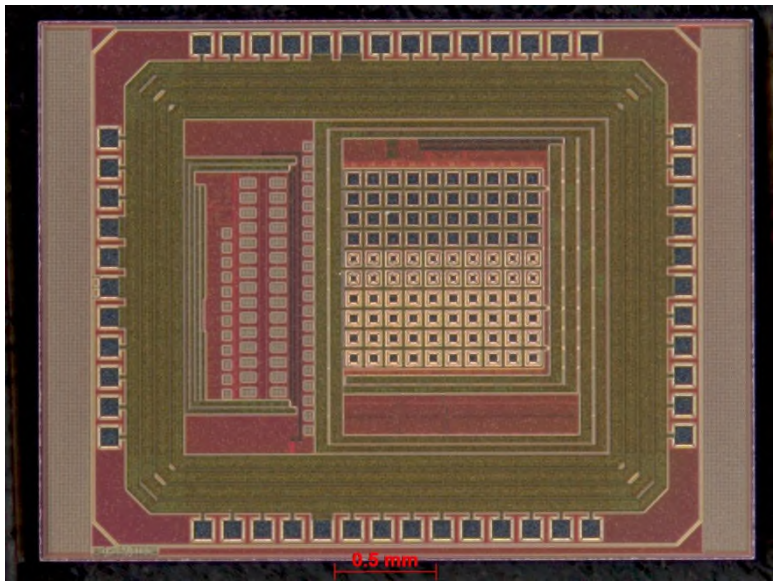
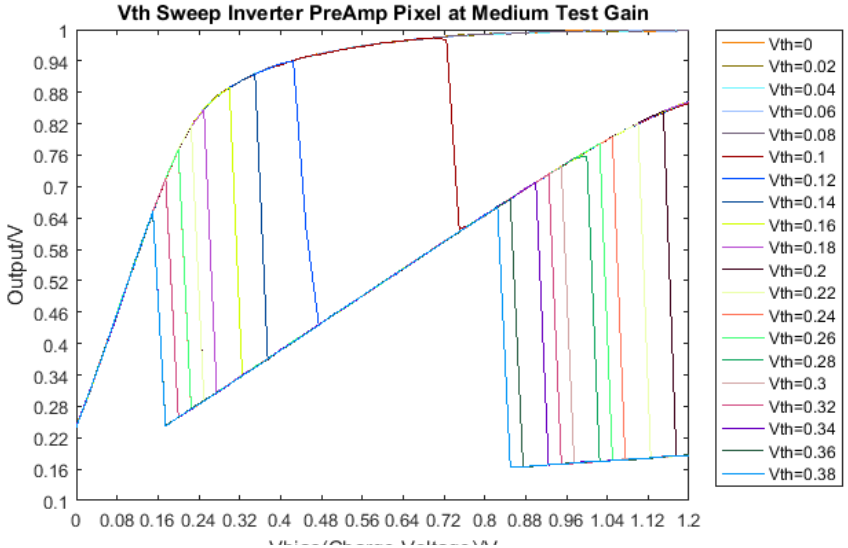
The Future?

Prototyped various pixels for LPD upgrades

- Built on IBM130nm
- 10 x10 array with various amplifier designs
- Could be imbedded to replace 50pF mode in the current ASIC
- Other significant improvements possible following the learning from all the LPD testing





Planning for future Data Rates

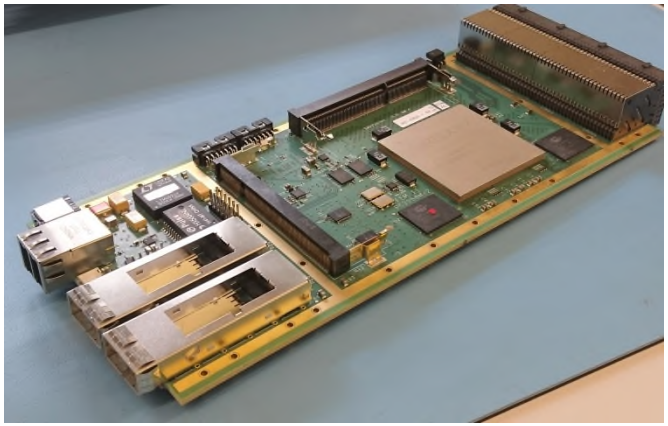
Today we are building CMOS sensors with:

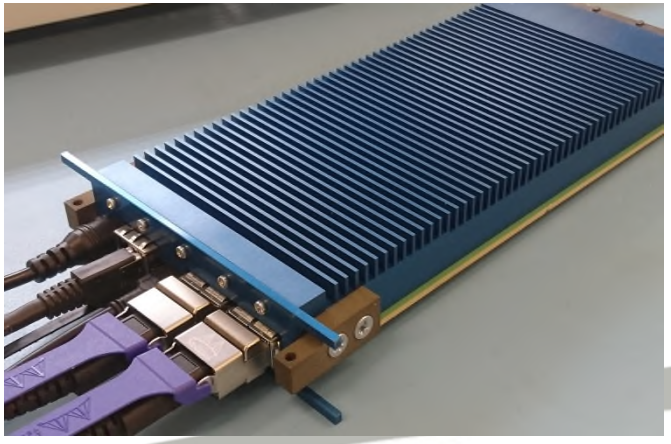
16 Million (4096x4096) pixels with a frame rate of 1,000 fps

So - 16Gpix/s

Digital output @10+1 bits => 176Gbit/s

256 LVDS Double Data Rate lines at 720Mb/s





- FEM II DAQ Board – for next generation detectors
- Has dual 40Gb data output – 10GB/s capacity for each board.
- Increase of 4x on the current LPD DAQ board, of which there were 16 inside the LPD system.

Closing Thoughts

- With LPD we have a flexible system
- Super-Modules could be upgraded with smaller pixels
- The ASIC was delivered in 2012 and significant performance improvements are possible today
- STFC is proud that the system is ready for day 1

- Lets look forward now to the new science that will come from this exciting facility!

Thank you very much!

Acknowledgements

Key People:

LPD Team

- Matt Hart
- …

XFEL Team

- Philipp Lang
- Markus Kuster
- Andreas Koch
- ….

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flythrough link

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