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The UFO DAQ-Framework for High-performance Data Acquisition in Synchrotron Applications

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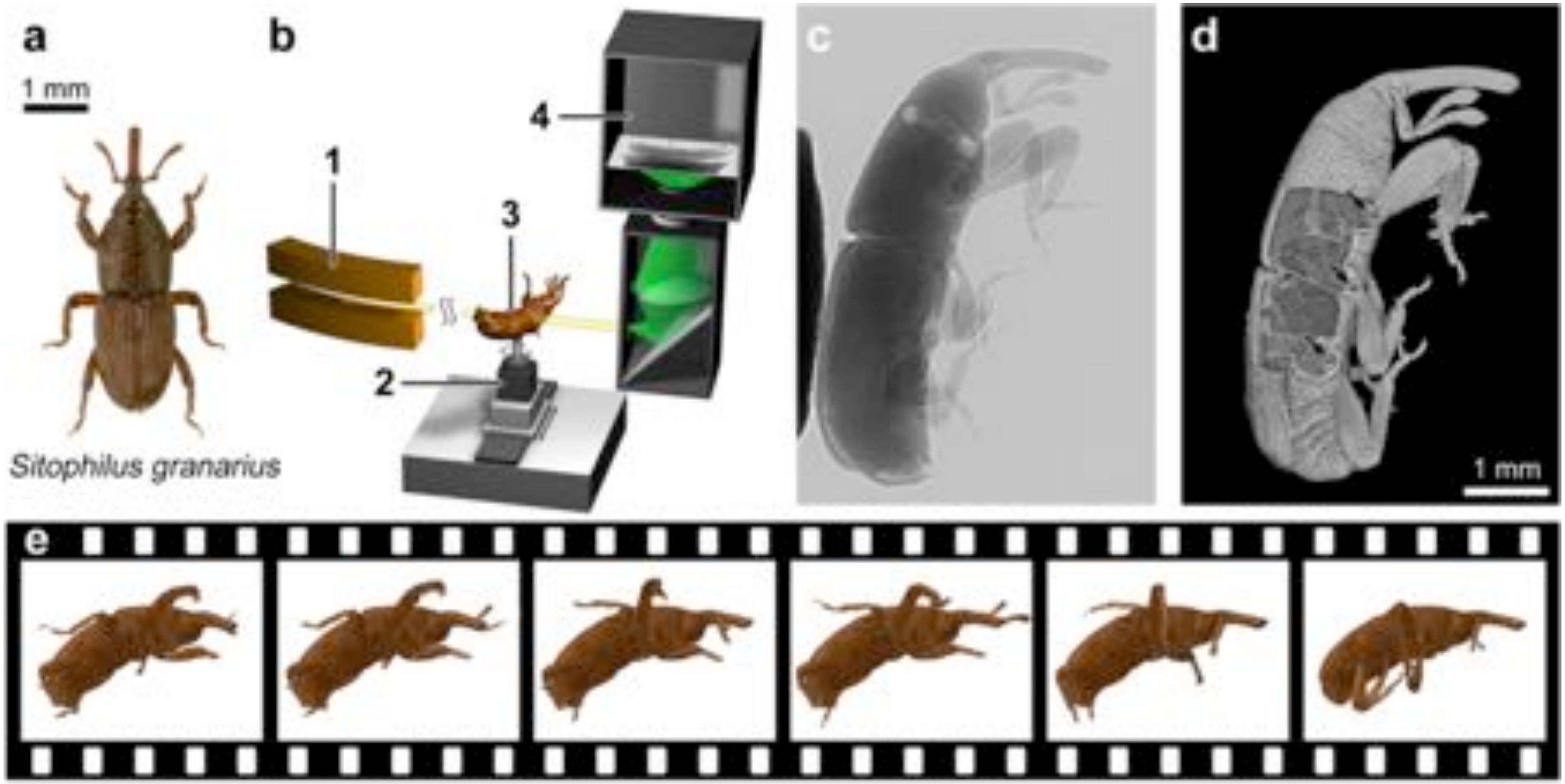
Institute for Data Processing and Electronics - IPE

Goals

- Micro X-ray imaging offers a broad field of applications:
  - Medical science
  - Non-destructive testing
  - Material and life science research etc…

- Are time-resolved measurements possible?

Application: 4D X-ray Cine-Tomography



dos Santos Rolo T et al. PNAS 2014;111:3921-3926

Goals

- Micro X-ray imaging offers a broad field of usage:
  - Medical science
  - Non-destructive testing
  - Material and life science research etc…
- Are time-resolved measurements possible?
  - 2D: radiography with > 1000 fps
  - 3D: tomography and laminography > 10 fps
    - 2D projections > 5000 fps
- DAQ Requirements:
  - Large (continuous) data rates
  - On-line data analysis + monitoring
  - Trigger + automatic control

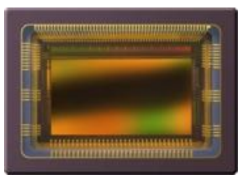
Motivation: Smart scientific cameras

- **Detectors for high speed imaging**
  - What is commercially available?

Data rates limit camera performance

Scientific sensor developments?

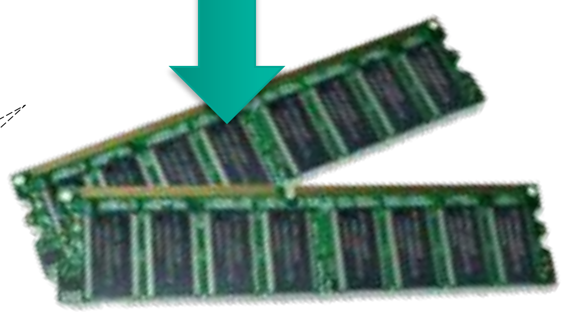
CMOS sensor



pco.dimax 4MP@1300fps
(7500MB/s)

Readout
Camera Link (250 / 850 MB/s)
USB3 (new: 500 MB/s)
GigE Vision (125 MB/s)

Internal Memory
e.g.: 36GB → 5s



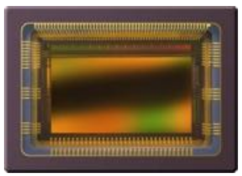
No online data analysis

Custom embedded logic is missing

Motivation: Smart scientific cameras

- **Goal: Modular DAQ Framework**

1. Modular sensor interface



e.g. for Helmholtz Detector and Systems Platform (DTS)

2. Embedded logic & Control
e.g. Smart Phase Contrast (w HZG)

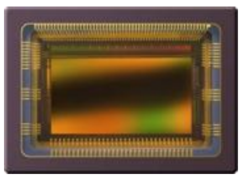
3. Full streaming readout
e.g. using PCIe, IB

4. Real-time data processing
e.g. with GPUs

Motivation: Smart scientific cameras

- **Components:**

1. Modular sensor interface

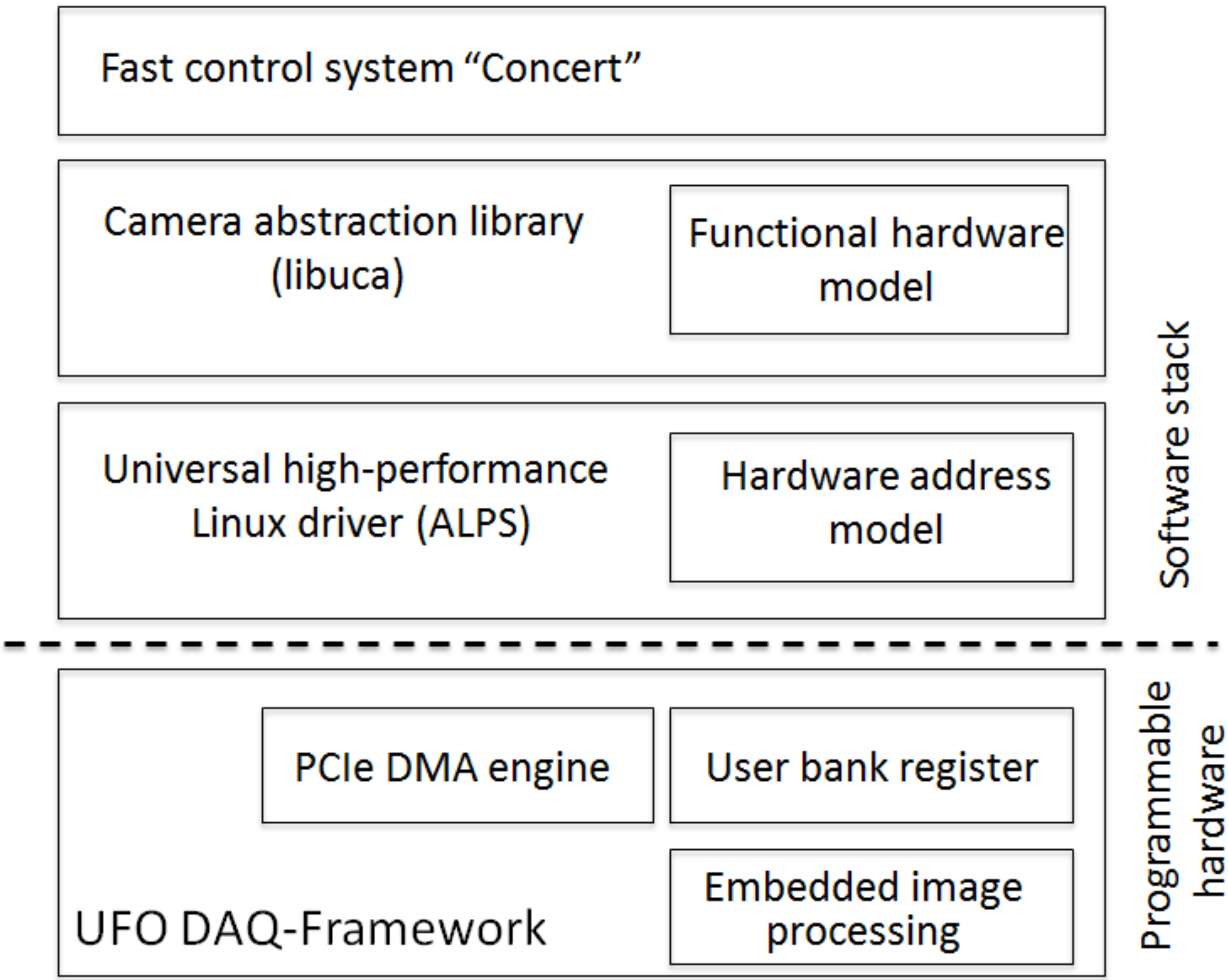


2. Embedded data processing
- Fast control system

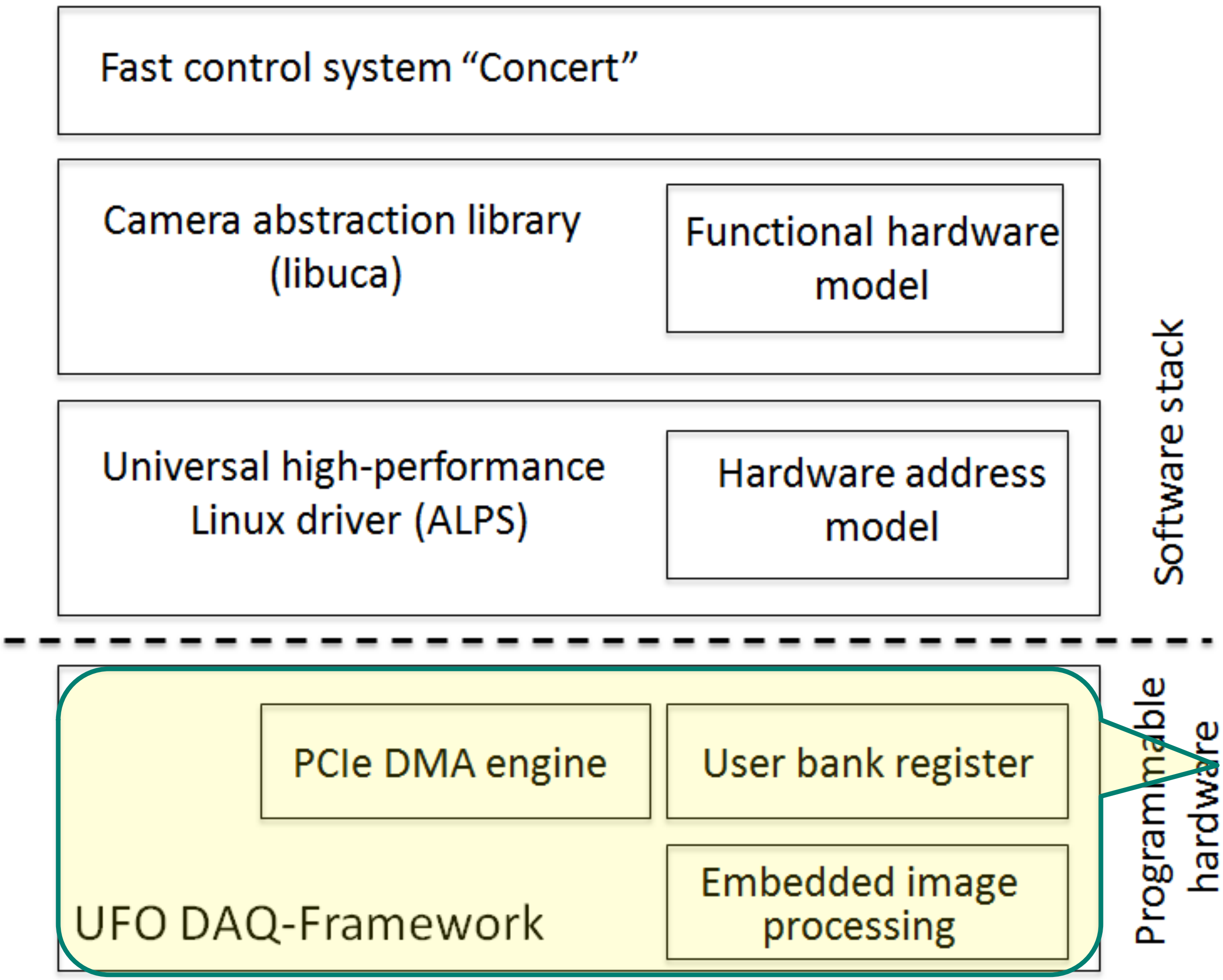
3. Readout
- DMA engine
- Linux drivers

4. GPU Computing
- Camera abstraction
- Programming environment
- Optimized algorithms

DAQ framework

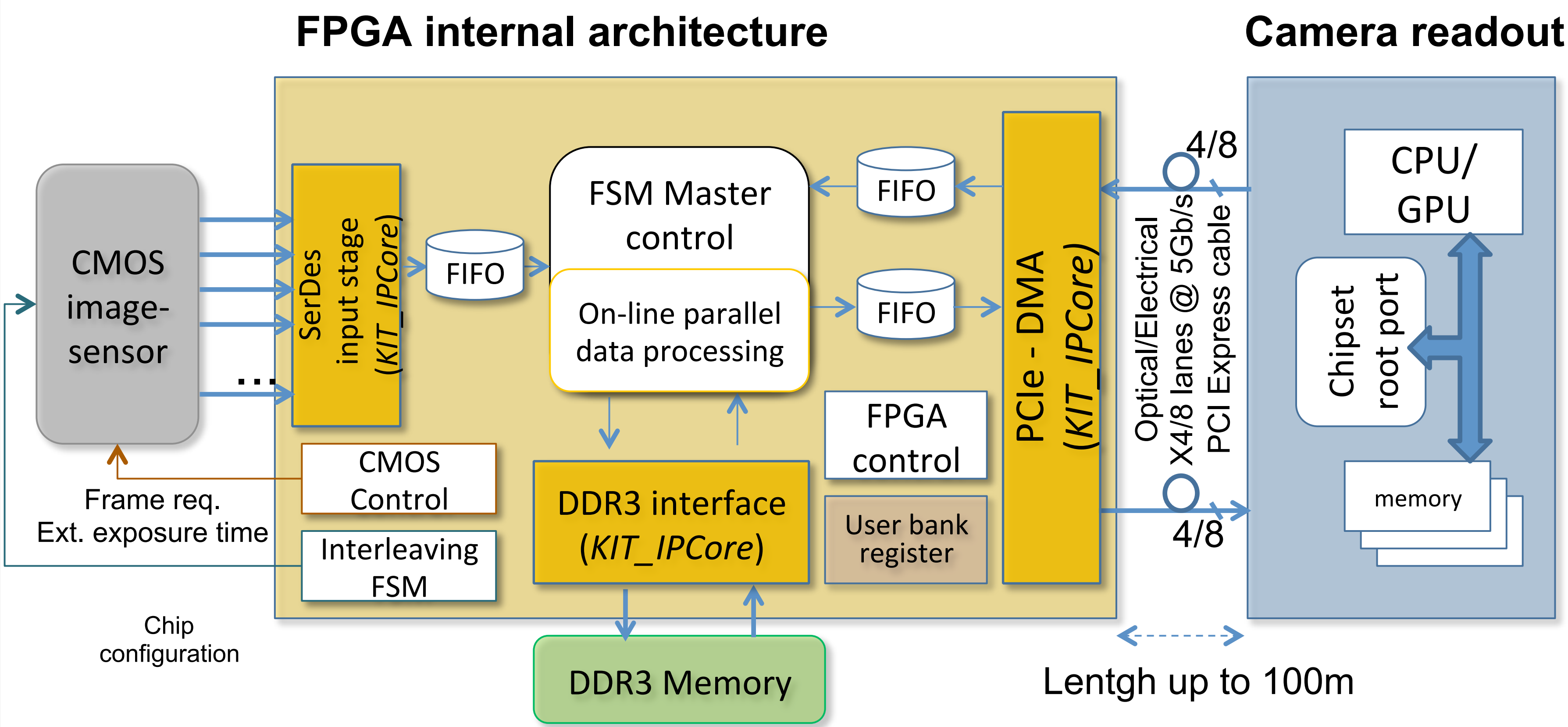


DAQ framework



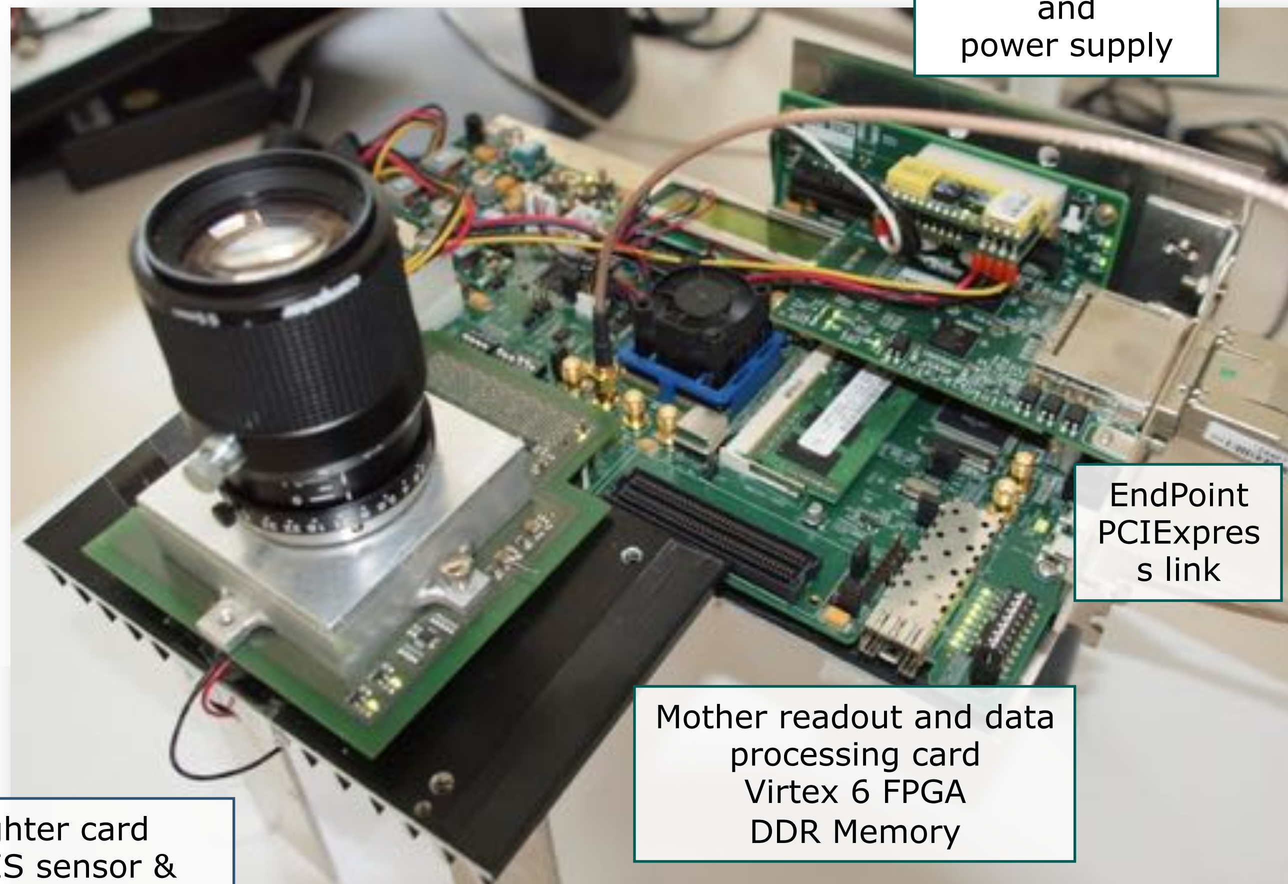
- Smart camera platform
- Image based trigger
- PCIe DMA engine for fast data streaming

Smart camera platform – architecture

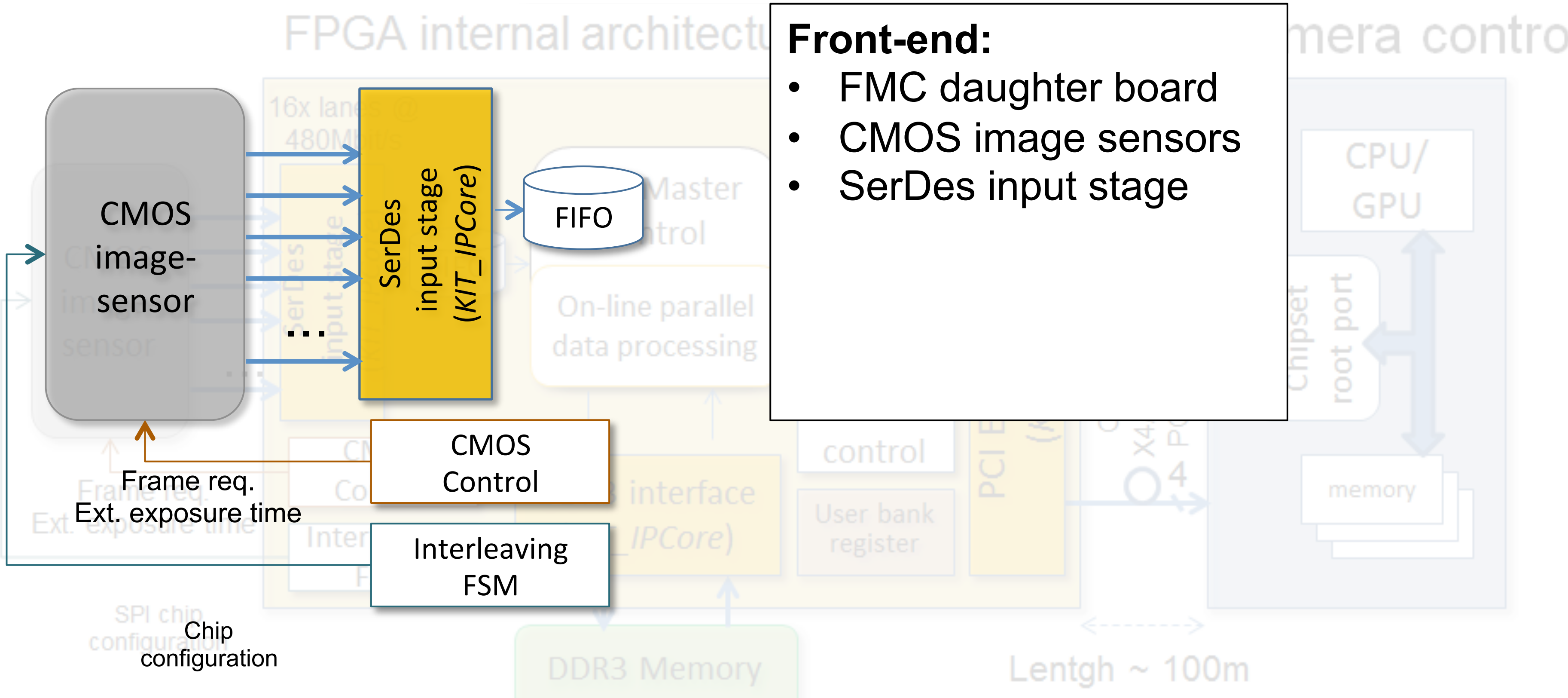


First high smart camera with CMOS sensor

- Low noise daughter PCB design
- Cooling system (silicon sensor) controlled by FPGA.
- Remote camera control (i.e. external exp. time, frame req, enable readout, busy, etc.)



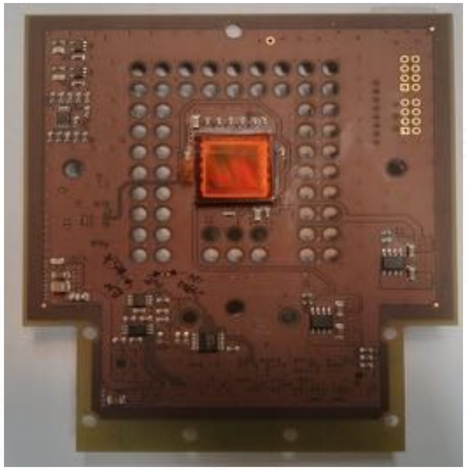
Smart camera platform – front-end



Front-end:

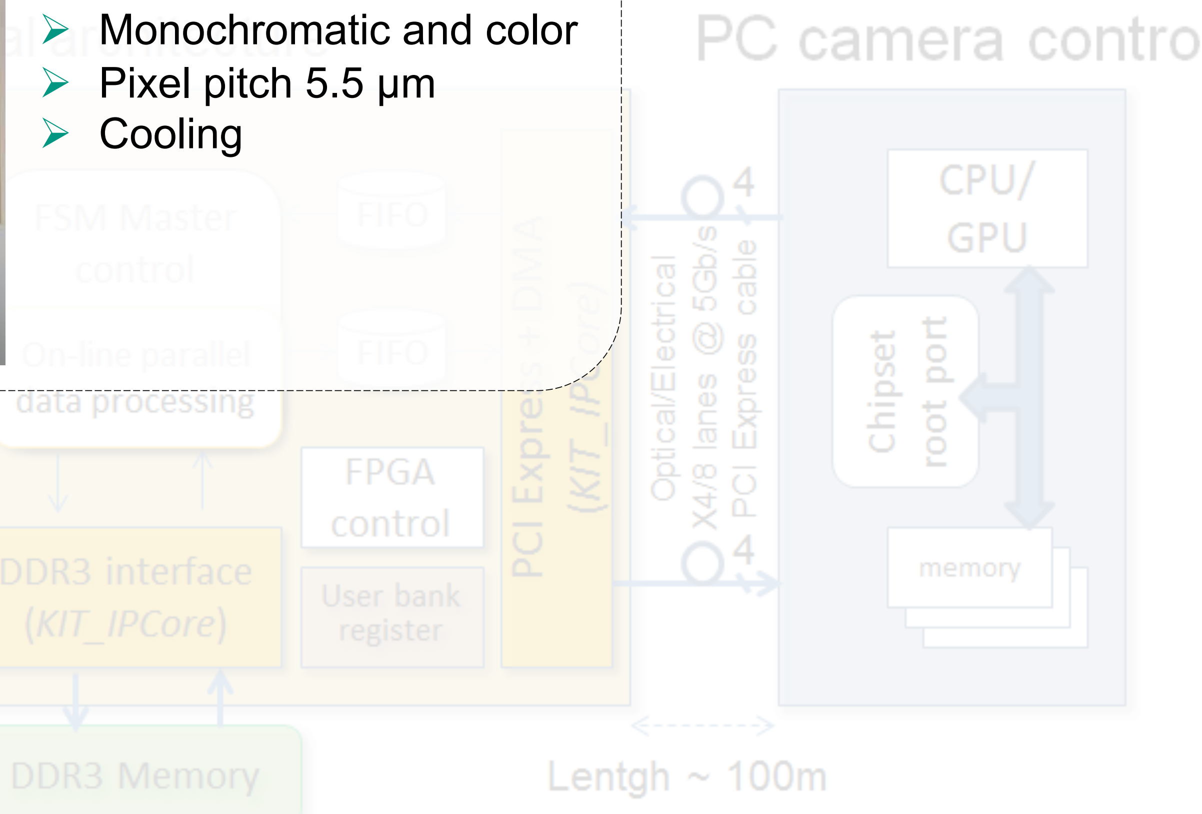
- FMC daughter board
- CMOS image sensors
- SerDes input stage

Smart camera platform – sensors

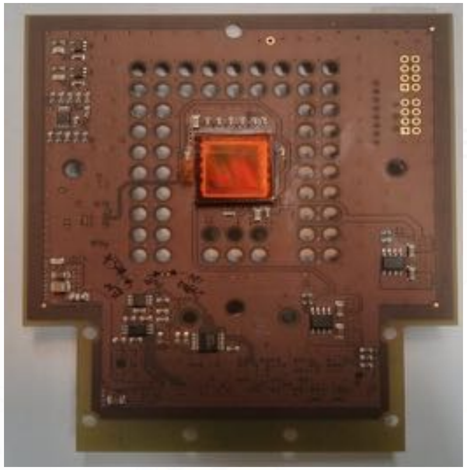


CMOS sensors:

- 4 MPixels and 2.2 MPixels
- Monochromatic and color
- Pixel pitch 5.5 µm
- Cooling



Smart camera platform – sensors



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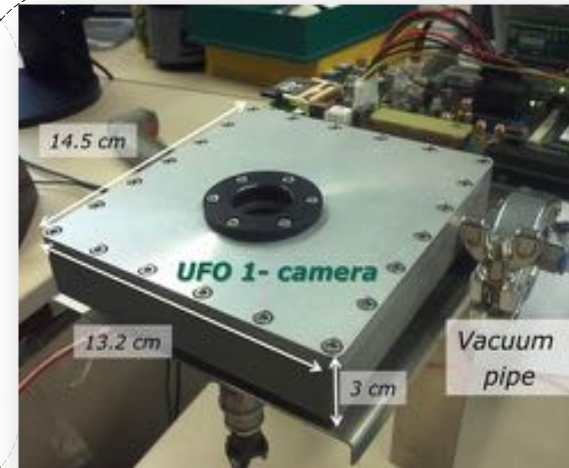
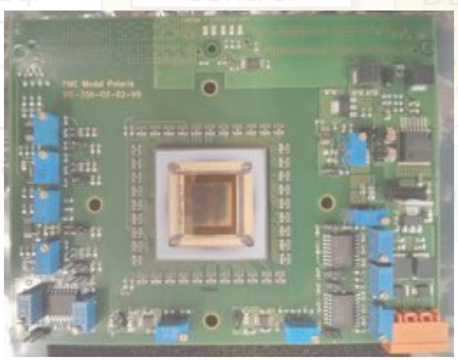


- Vacuum environment
- Peltier cell: -5 °C with 30 % of the power



In progress:
High frame rate CMOS sensor

➡ 5k fps @ 1MP

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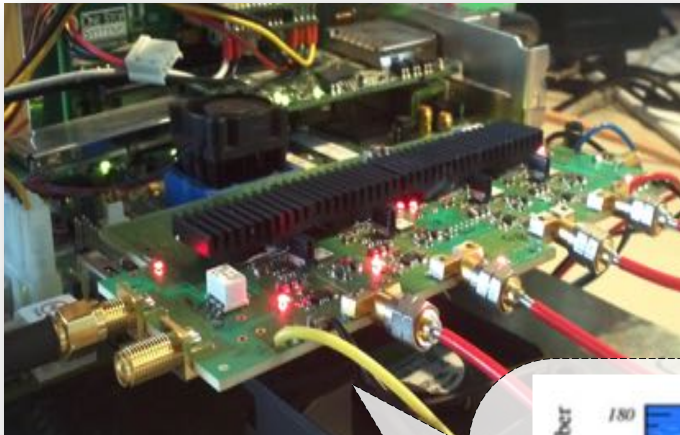
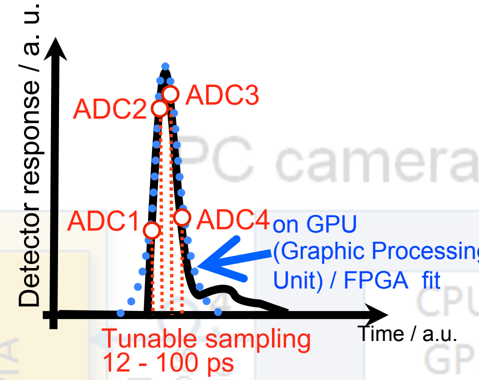
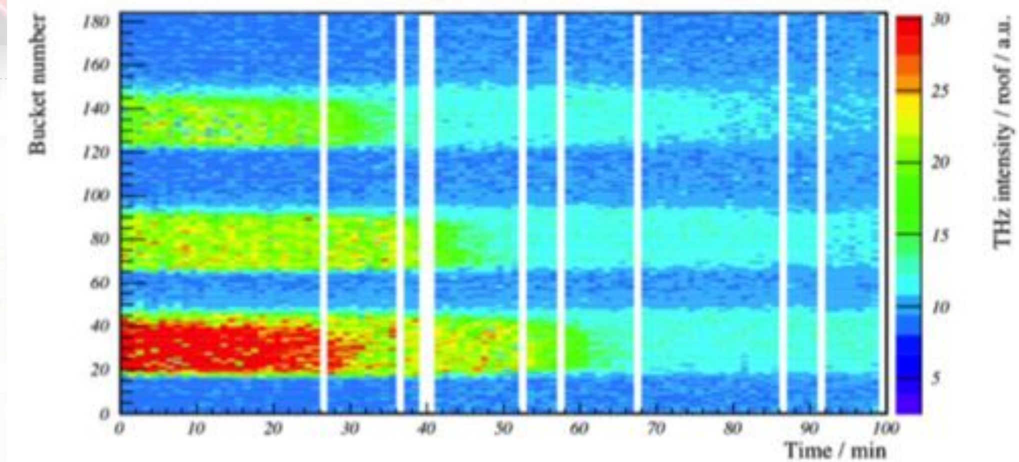
A smart non-camera application





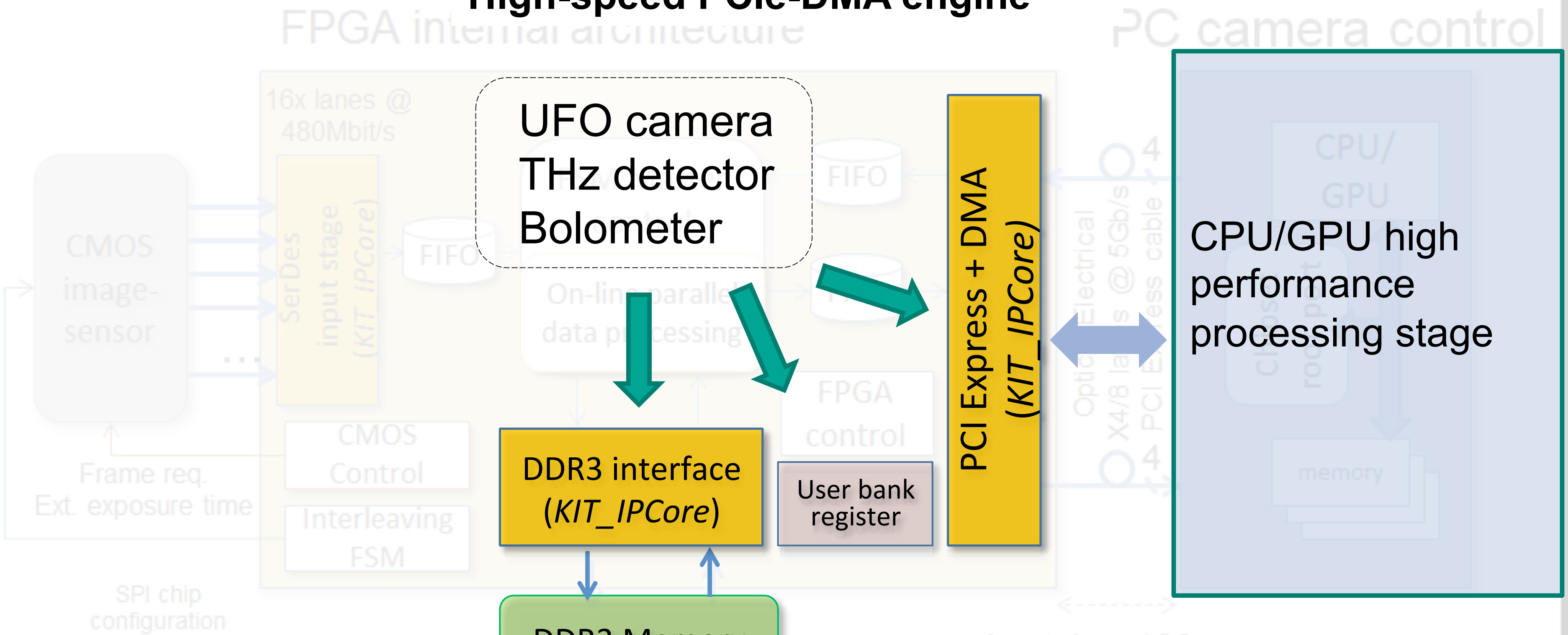


Ultrafast digitizer for beam monitoring:

- Programmable picosecond sampling
- Data rate 4x500MS/s → 3 GB/s
- Pulse reconstruction

Smart camera platform – streaming readout

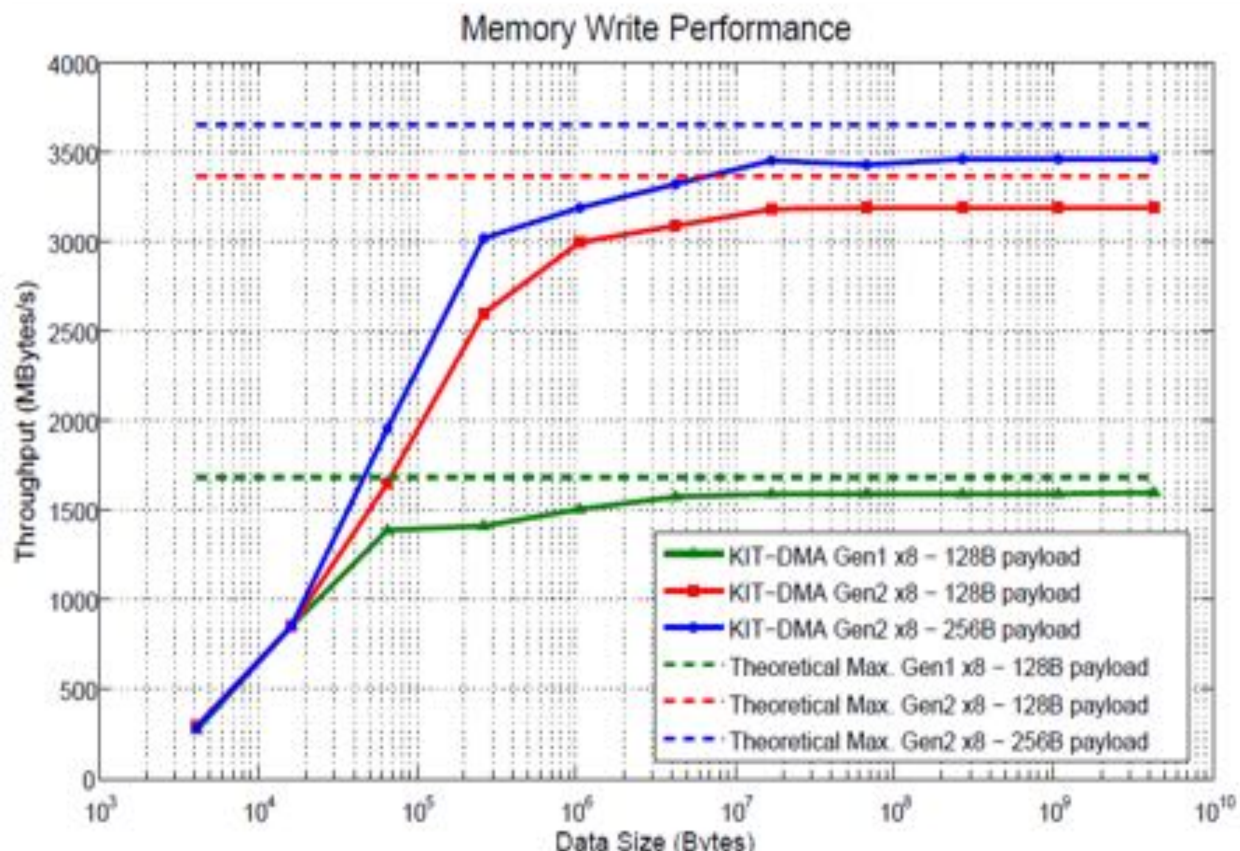
High-speed PCIe-DMA engine



Gen2 x8 – 3.4 GB streaming

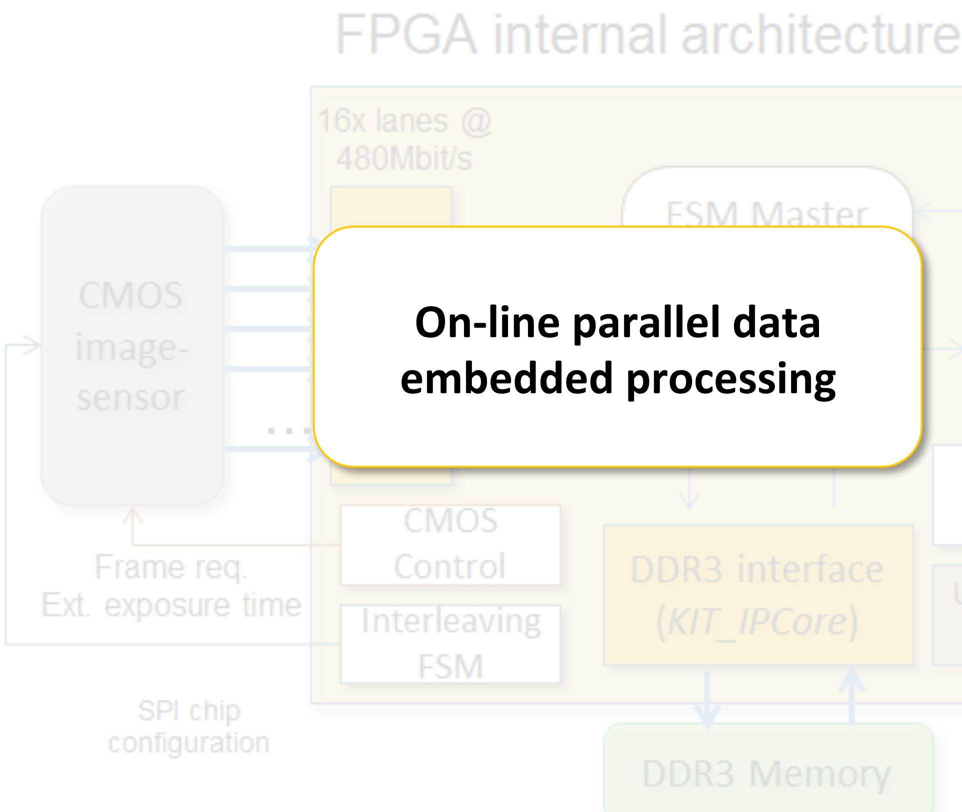
Smart camera platform – streaming readout

High-speed PCIe-DMA engine



CPU/GPU high performance processing stage

Smart camera platform – embedded processing



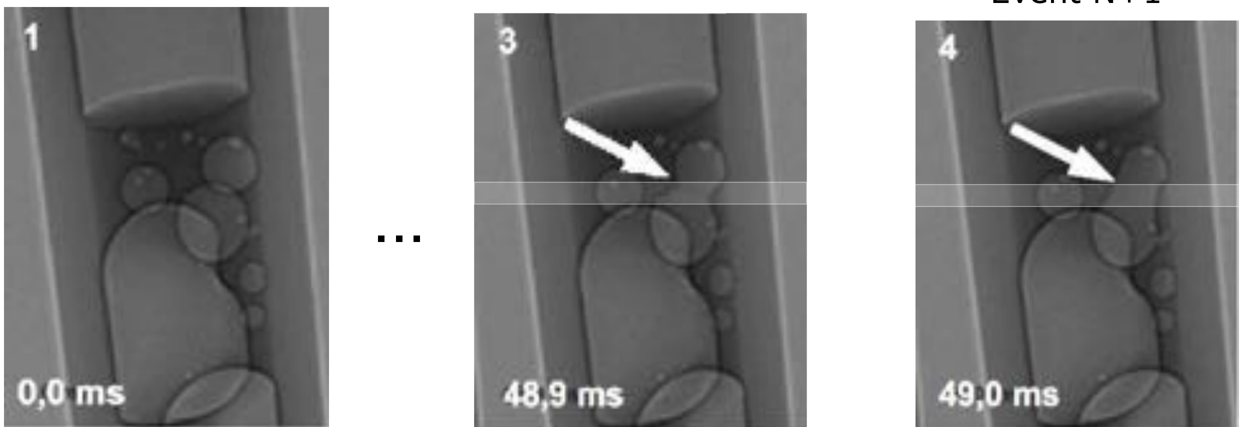
Possible applications:

- (Simple) image processing
- Camera internal control:
  - Trigger
  - Selective readout
  - Exposure/gain control
- Control of sample environment
  - Automation of complex procedures
  - Feedback control

Example: Image based self-trigger

Application: Bubbles merging in gelatinous agar

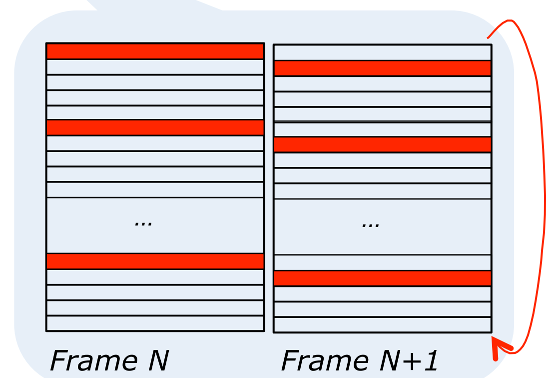
Reference frame … Event N … Event N+1



Most of the time
no changes

Rare fast event
@ 10 KHz

Only 2% of rows
have changed



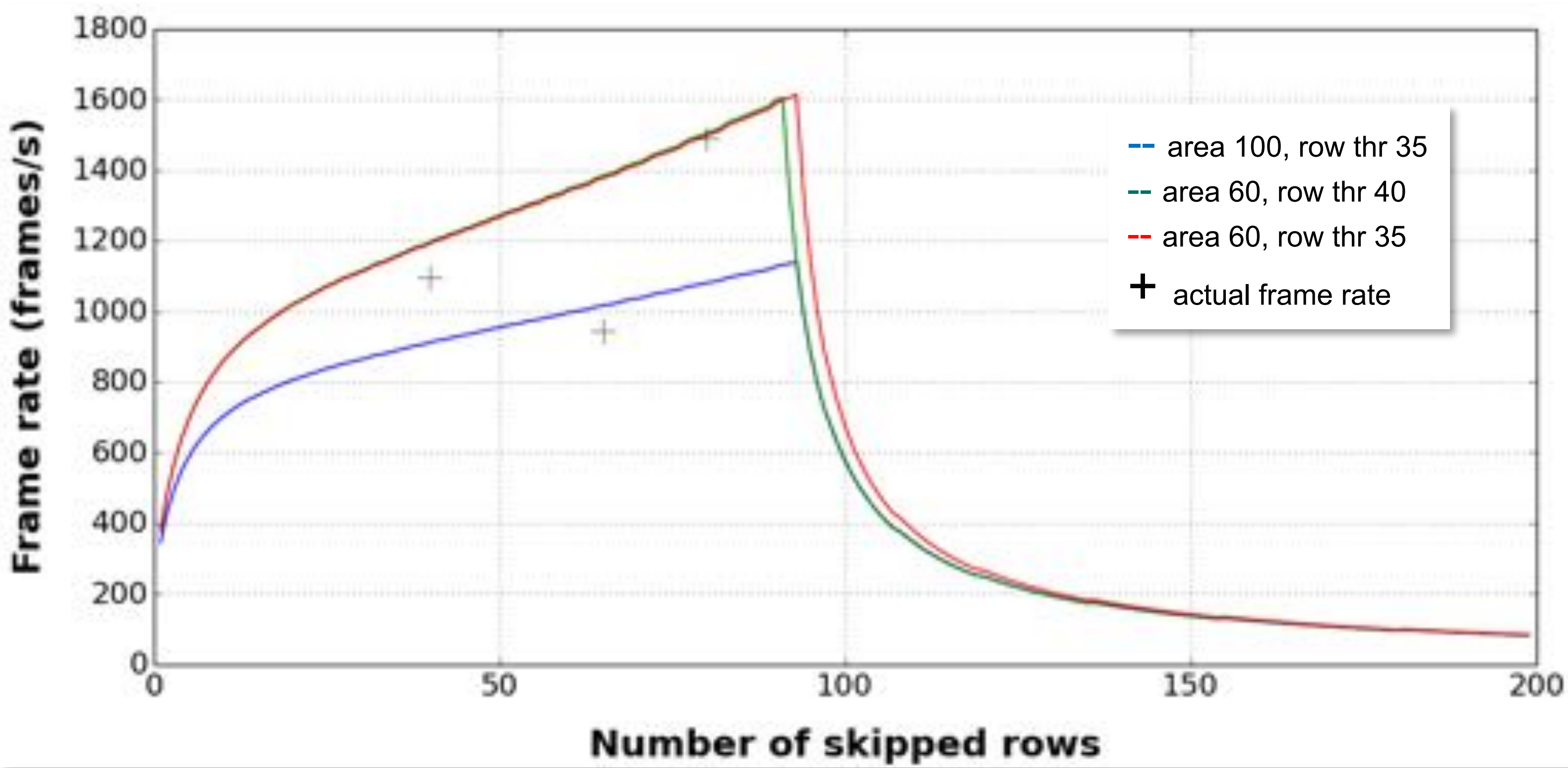
Only small and a-priori unknown changes

→ Need for adaptive frame rate

Solution:

Interleaving readout
and event-trigger

Fast reject efficiency



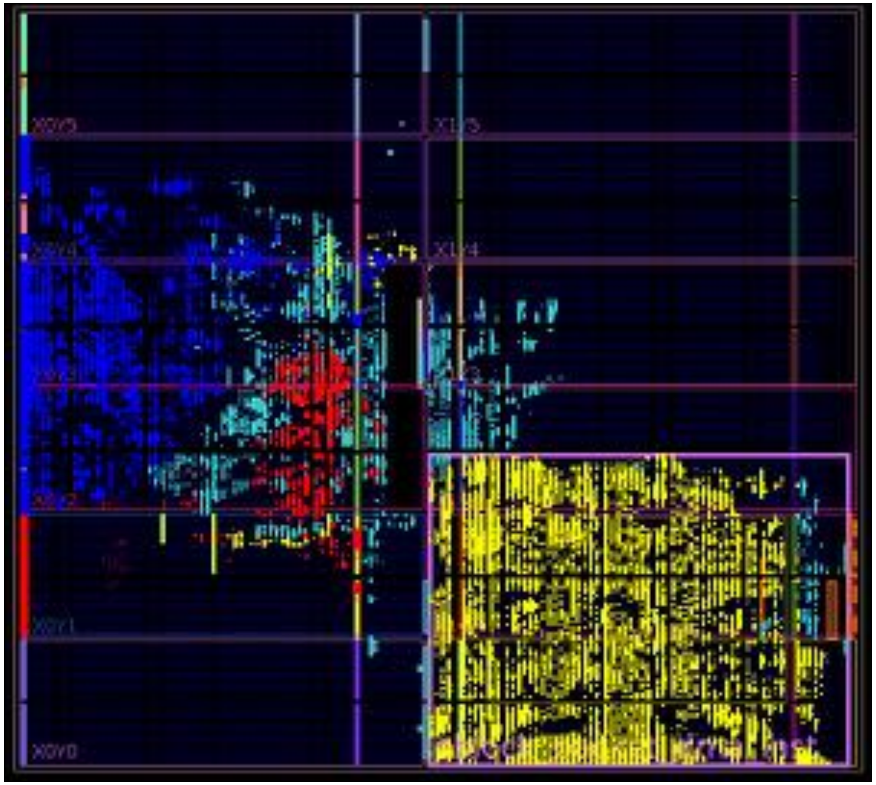
- Frame rate depends on the used parameters and the event size
  - Effective frame rate can be more than five times higher than nominal
- Concert can automatically set initial parameter values with the desired maximum speed, object size detection, and minimum noise influence

Programmable hardware

- The DAQ framework is fully programmable
  - Based on FPGAs
  - Three IP cores
  - Custom “smart” logic

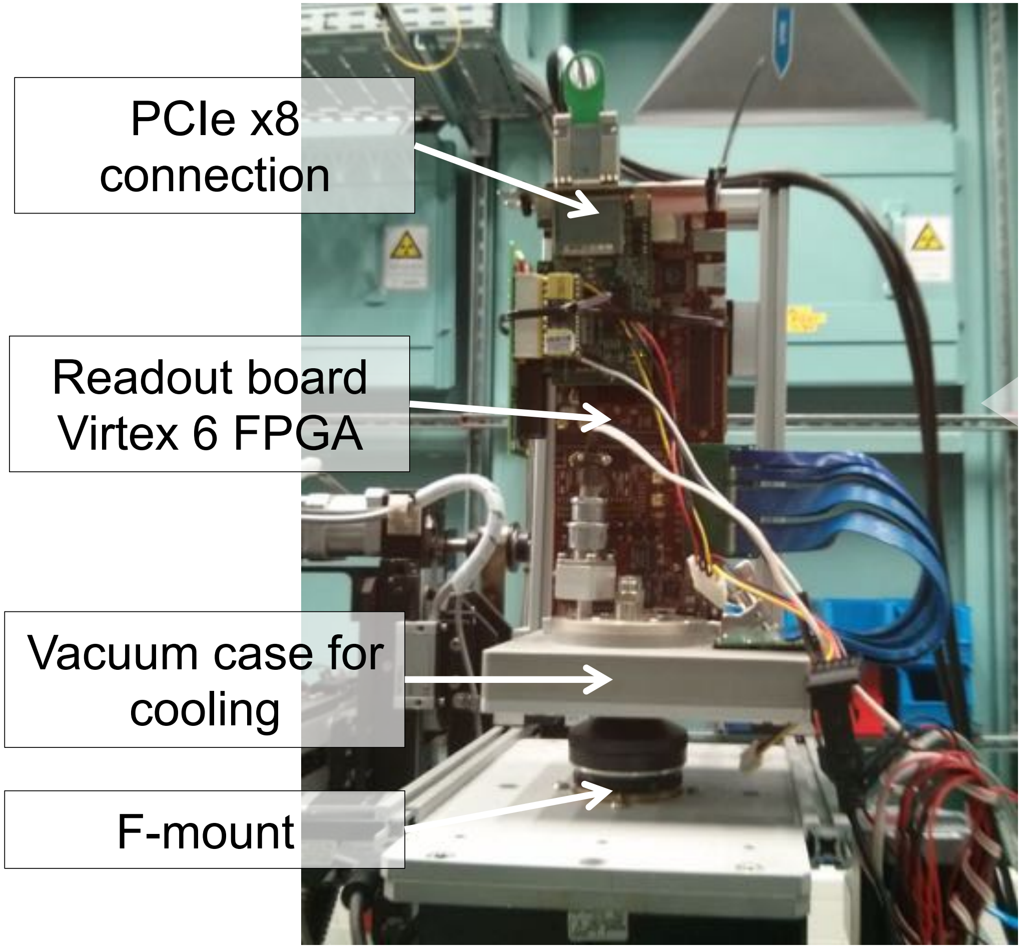
UFO camera FPGA utilization:

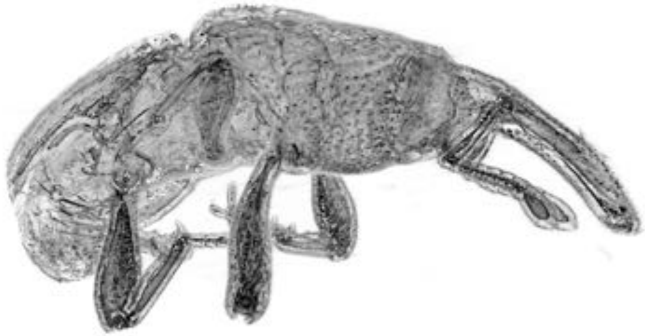
- Yellow: PCIe DMA
- Dark Blue: DDR3 interface IP
- Red: Input stage
- Bright blue: Control and processing logic



Xilinx XC6VLX365TFF1759-2

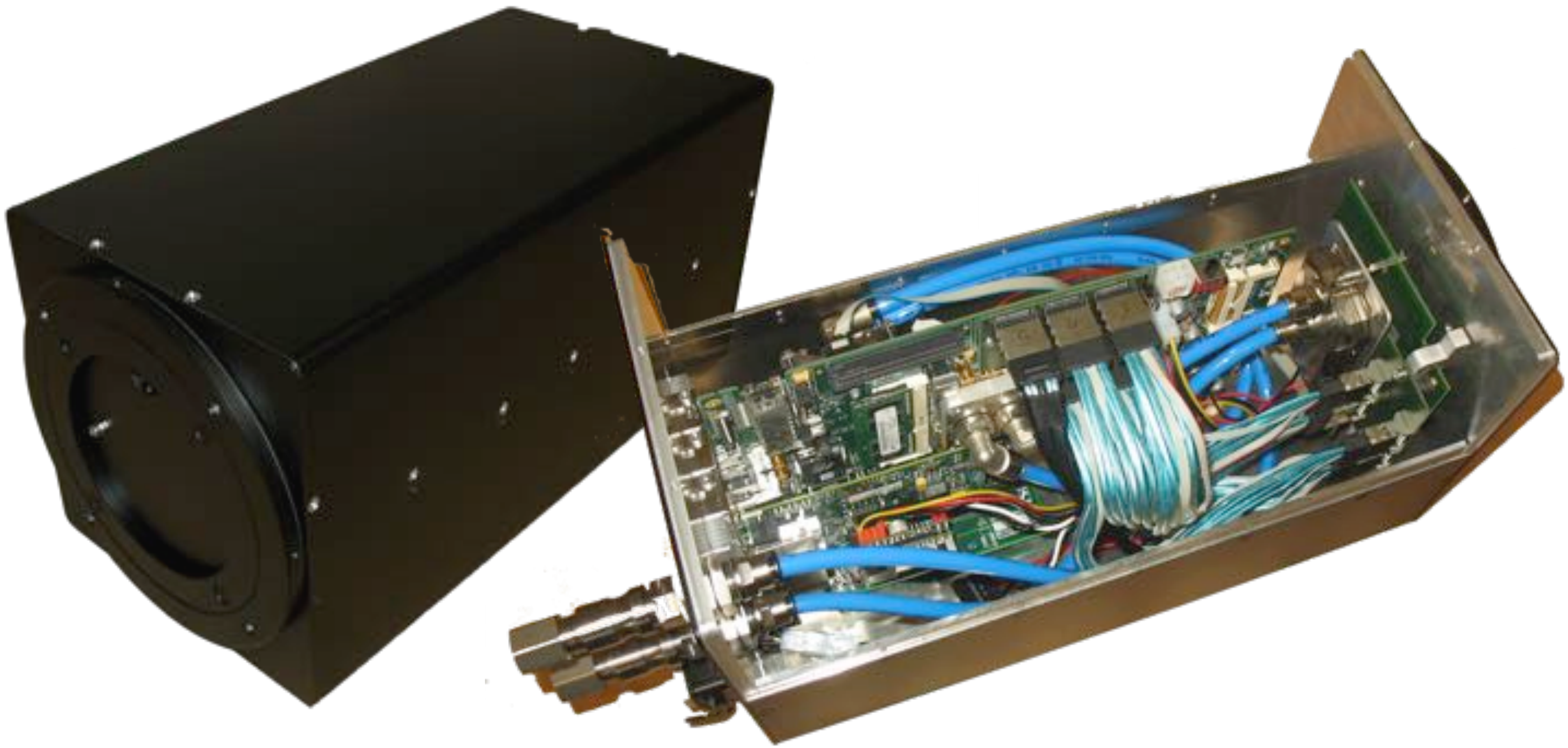
UFO camera at the IMAGE beamline



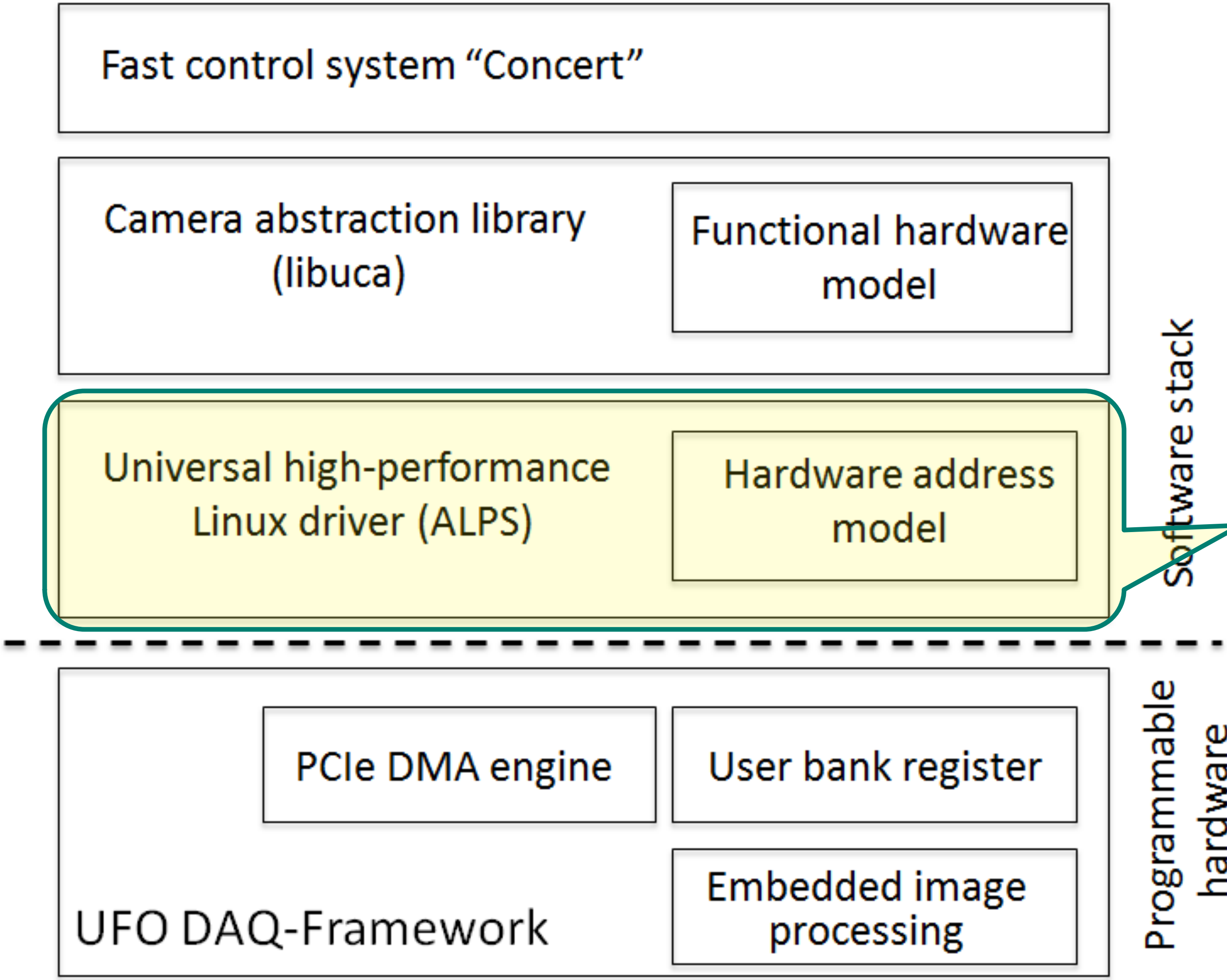


Smart phase contrast camera

- Goals:
  - Automatic grating control
  - Reconstruction (with GPU)



DAQ framework



- Optimized for high throughput
- Configurable register model
- Comfortable usage

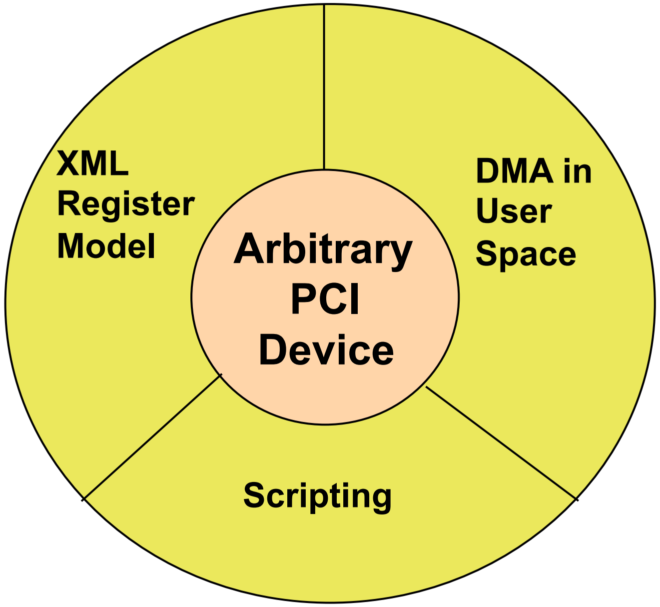
ALPS

Advanced Linux PCI Services

A reusable components for custom PCI electronics

Motivation

- Synchronization Software and Hardware development
- Easy hardware debugging
- Keeping drivers up to date with latest Linux kernels
- Multiple common components



Components

- PCI driver
- Register Model
- DMA Engine
- Custom Event Plugins
- Web API (planned)

PCI + PCIe interface in user-space

Scripting
Bash, Perl, Python

LabVIEW
Control System Integration

pcitool
Command-line tool

GUI
User Interface in Python/GTK

Web Service
Remote Programming Interface

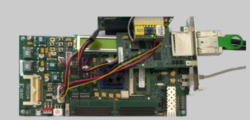
PCILIB
User-space Layer

VFIO + UIO

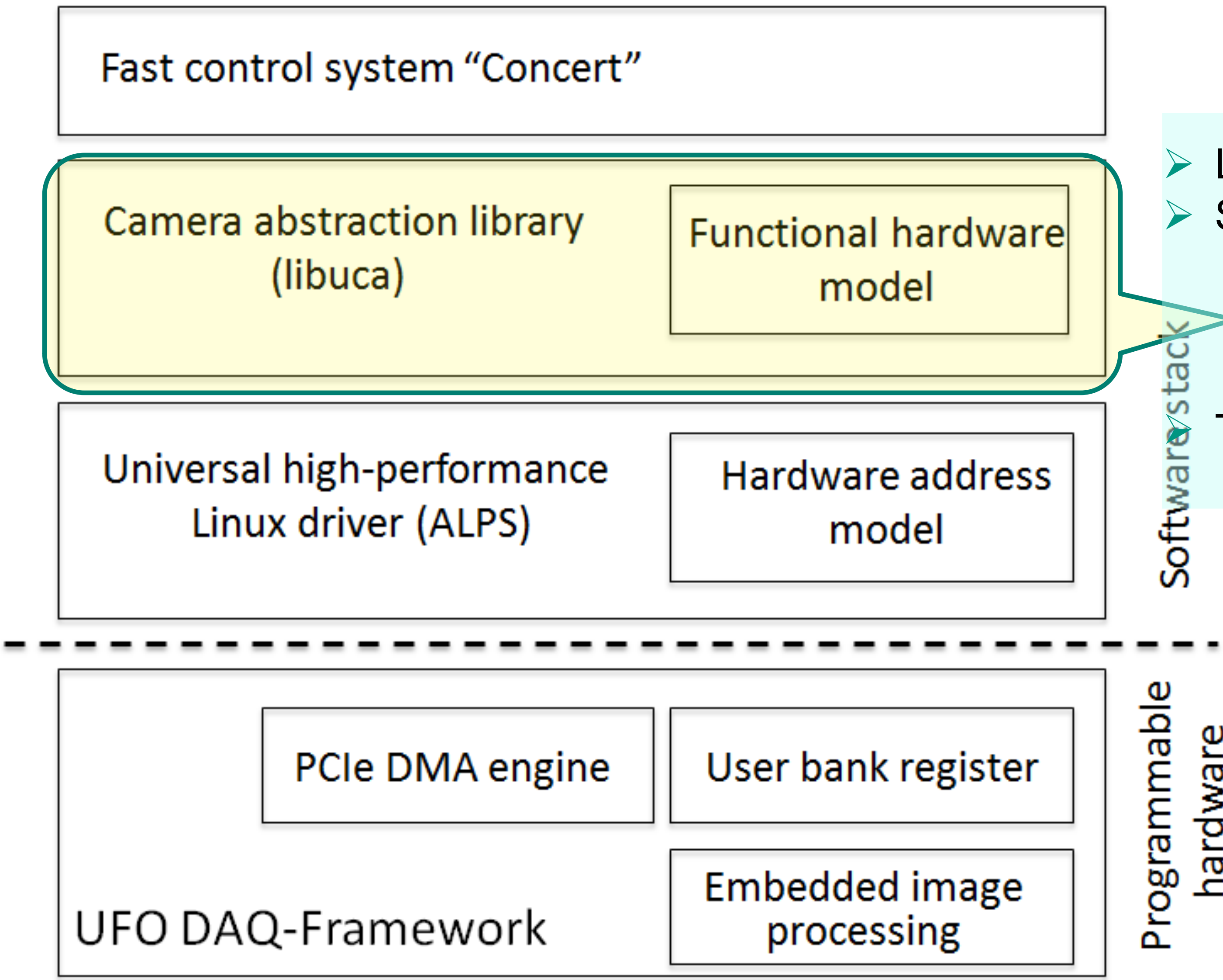
- PCI Bar mapping
- DMA Memory Management
- IRQ Handling
- Interlocking

PCI / PCI Express Board

(Variety of FPGA Boards: IPE Camera, etc)

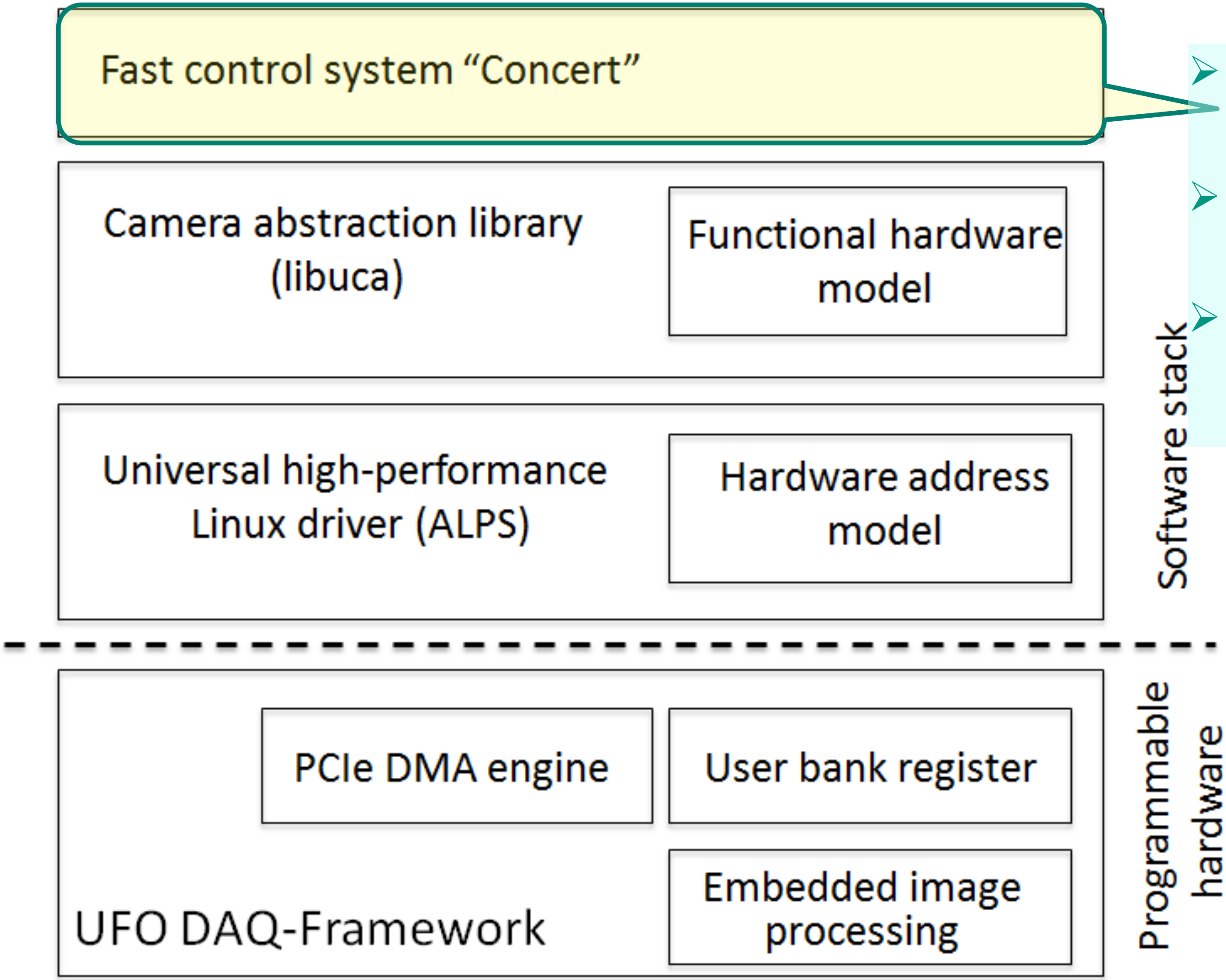


DAQ framework



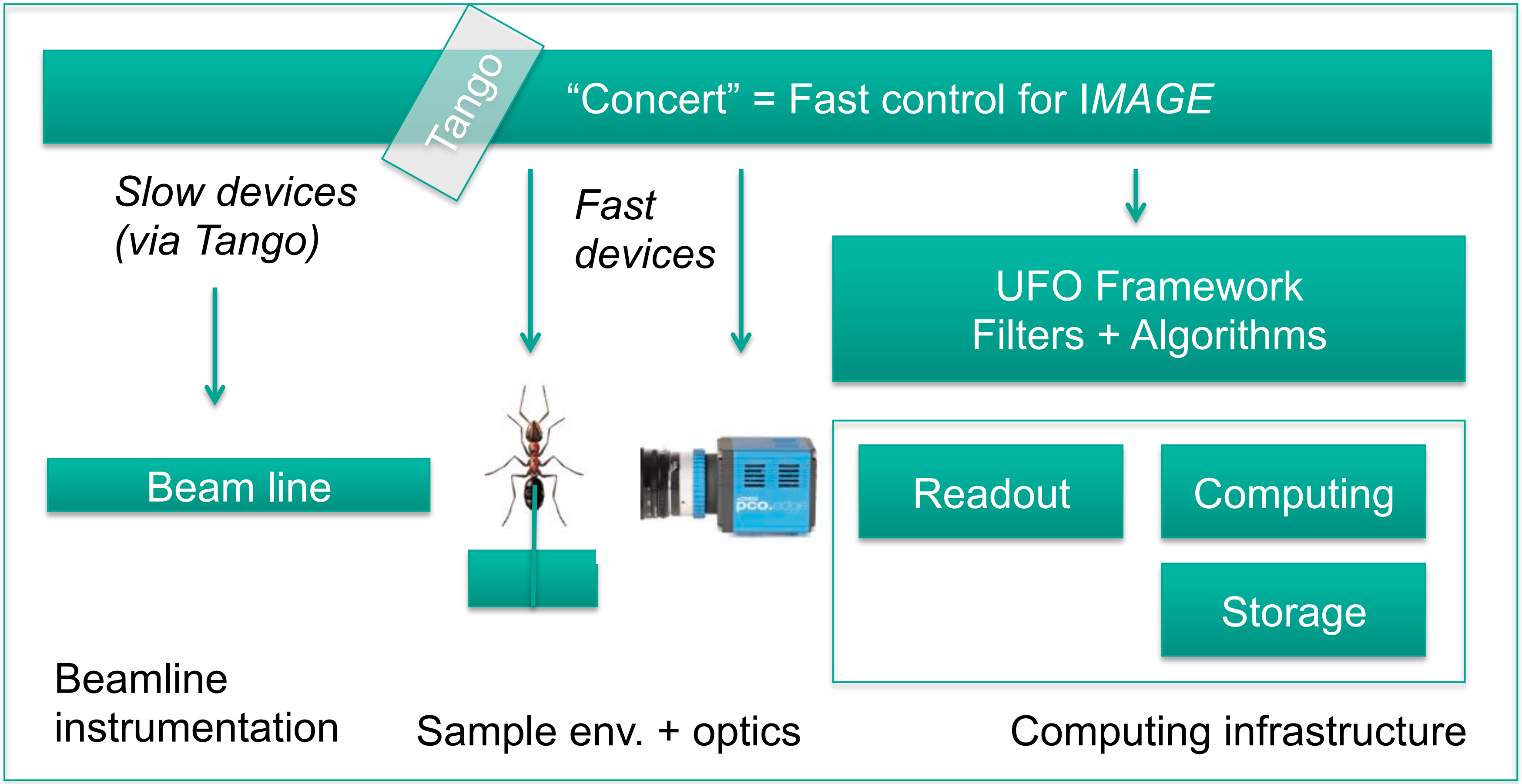
- Linux (64bit)
- Supported cameras:
  - pco
  - photon focus
  - UFO camera
- Tango driver

DAQ framework



- Seamless device integration
- High performance computing
- Image-based feedback control

“*Concert*” = Fast control system for IMAGE



Concert details

- Python based
- Underlying hardware-specific details are abstracted:
  - e.g. *Camera* class provides *grab* method to acquire a frame:

```
frame = cam.grab()
```

  - e.g. setting the exposure time:

```
cam.exposure_time= 2*q.milliseconds   # Req. units
```

- Asynchronous device access:
  - Parameters access and device methods wrapped in *future* objects
  - Methods to query state, final result, callback

```
# Synchronous access
motor.position = 1 * q.mm

# Asynchronous access returns a future
future = motor.set_position(1 * q.mm)
future.wait()
```

```
class Motor(Device):
    @async
    def move(self, delta):
        self.position += delta

motor.move(-2 * q.mm).wait()
```

Filtered back projection performance

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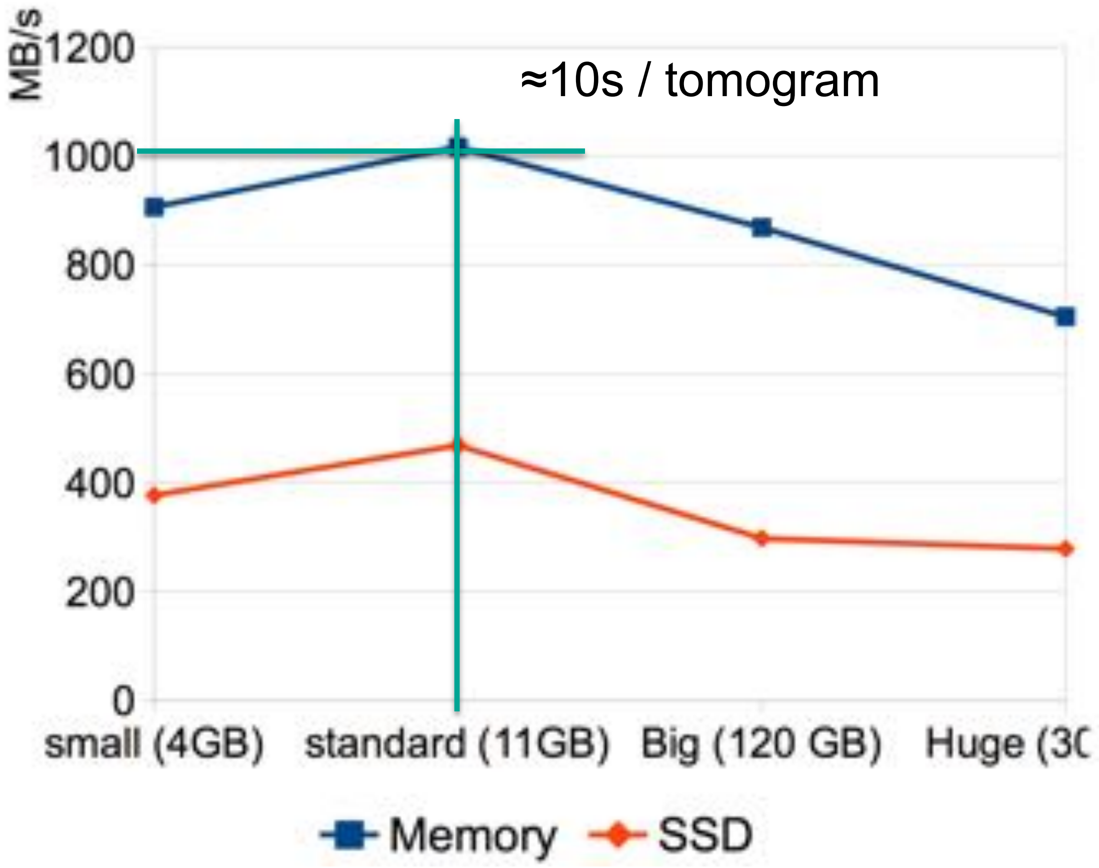
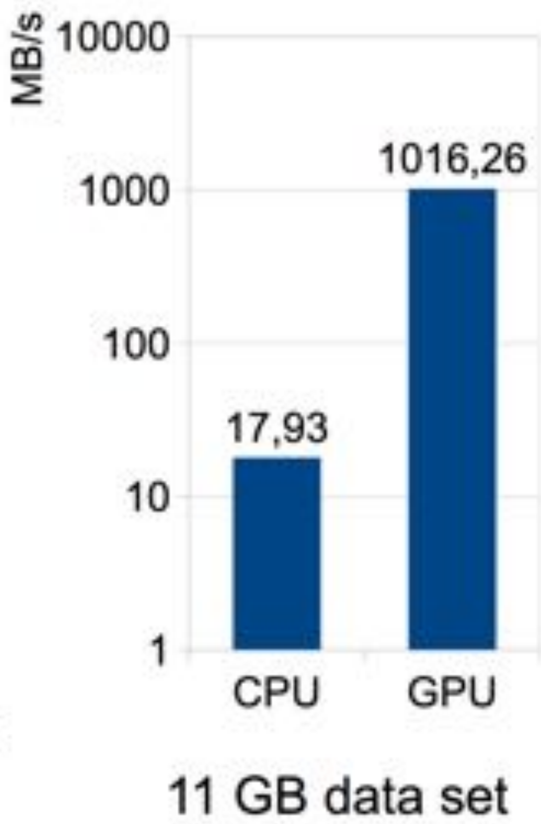




GPU: 4 x GTX590 , 8 cores
CPU: 2 x Xeon X5650, 12 cores
(both from 2011)

FPD Computing throughput
== Readout rate ✔

UFO parallel computing framework

How to support code development for GPUs?

Requirements:

- Processes data streams (usually 1 to 4 dimensional floating point data)
- Detect and use all hardware resources

Developer:

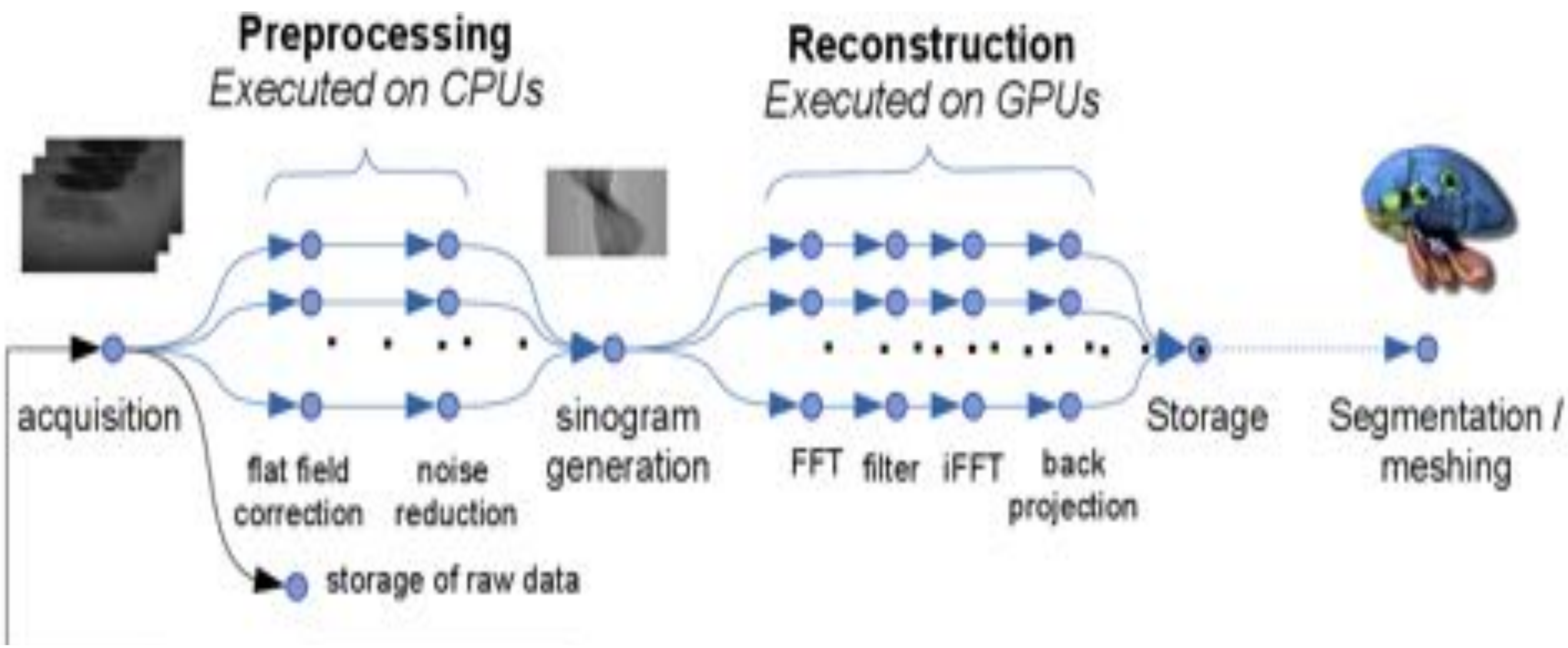
- Hides parallelization and concurrency details
- Management of memory transfers
- Multiple implementations (e.g. for CPU + GPU)
- Automatic scheduling

User:

- Simple end-user interface
  - GUI + Scripting
- Modular algorithm design

Realization

- Implemented in OpenCL
- Define algorithms as self-contained tasks
- Specify data flow as edges in a graph

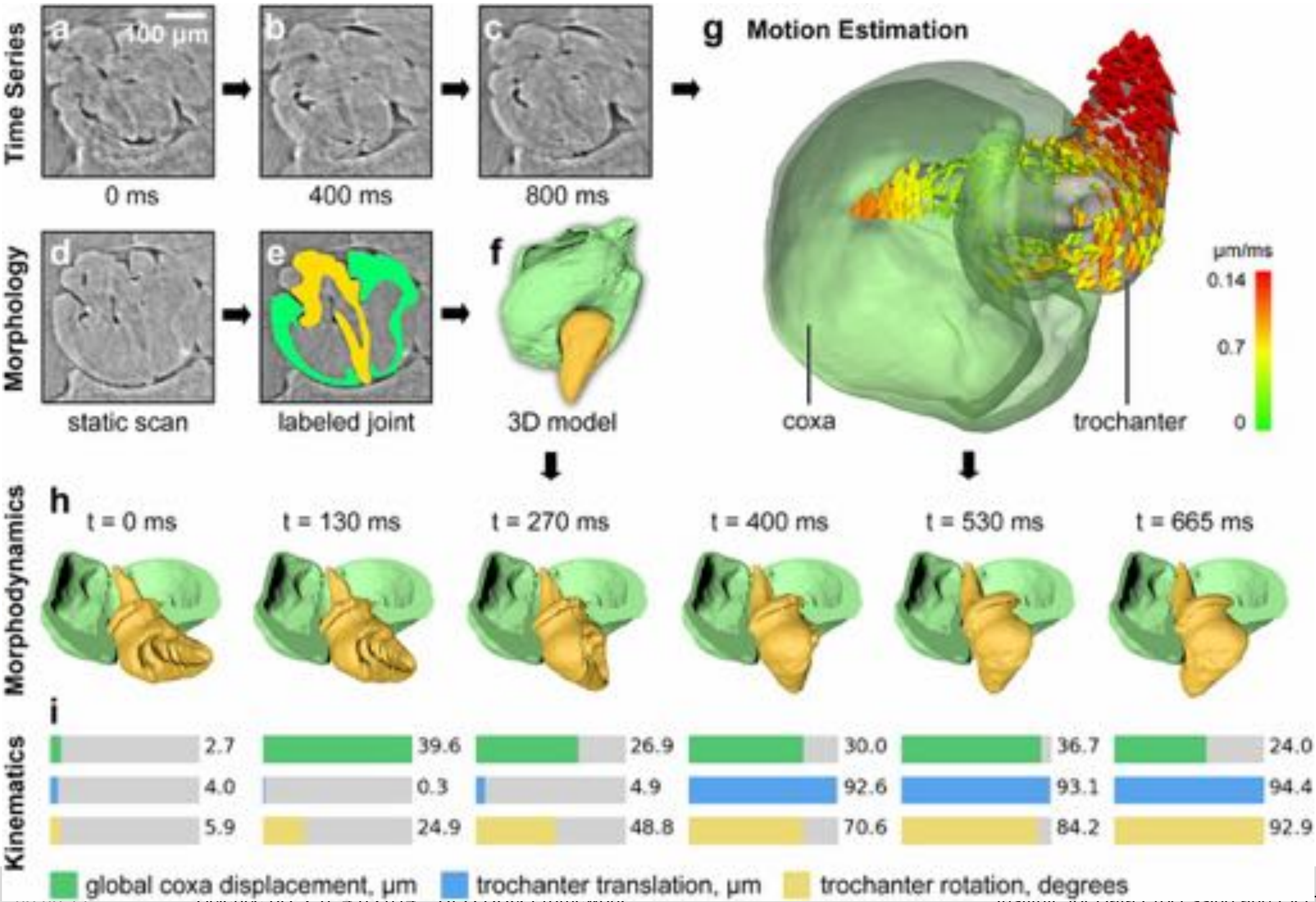


→ Matthias Vogelgesang gives an introduction tomorrow

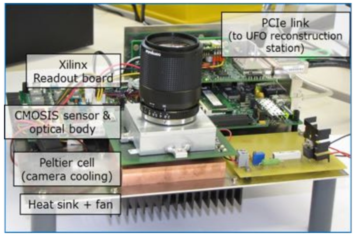
Summary

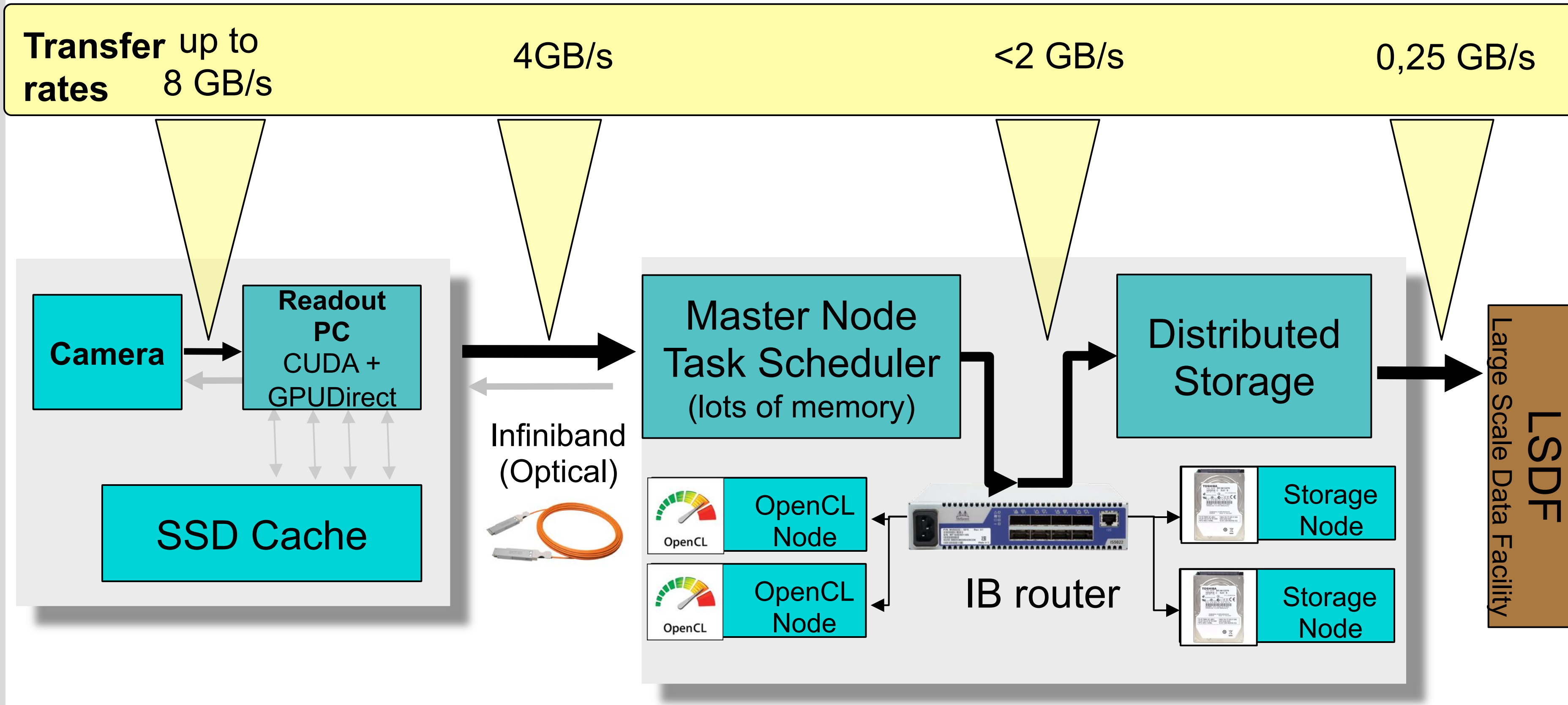
- The UFO DAQ framework is modular
  - Front-end / embedded processing / fast readout / GPU computing
  - Various sensors exist
  - Applications:
    - high-throughput camera,
    - intelligent trigger,
    - phase contrast
  - Non camera use: beam monitoring with ps resolution
- UFO parallel computing framework supports
  - Development and management of optimized code
  - Supported architectures GPU, CPU, Xeon Phi, <*every OpenCl device*>
  - FBP is now faster than DAQ
    - throughput ~1 GB/s

Morphological dynamics and kinematics analysis of a moving screw joint



What’s next? Scaling up to clusters





http://ufo.kit.edu

https://github.com/ufo-kit/concert

Thank you!