Real-Time
Image Acquisition and Processing for Plasma Diagnostics

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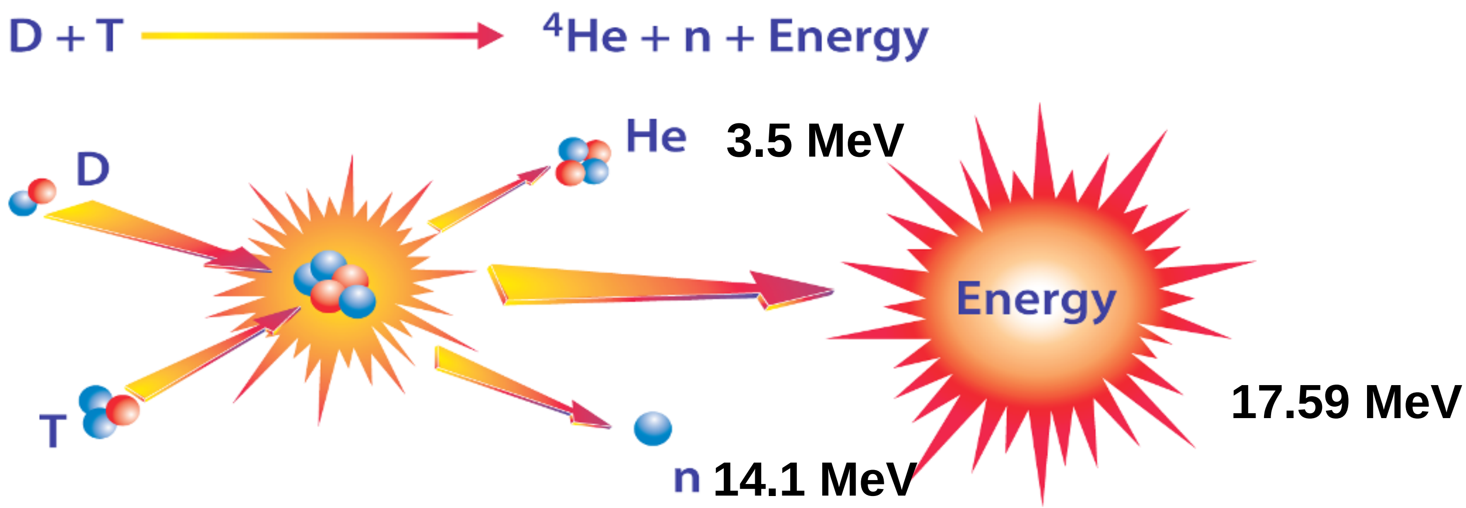
A. Winter and IPP Team

Wendelstein 7-X
IPP Max-Planck-Institut für Plasmaphysik

Fusion - Plasma Conditions



Sustained fusion reactions require **enough particles (density)** that are **energetic enough (temperature)** and collide **often enough (confinement time)**.

The fusion **triple product** is the figure of merit:

$$nT\tau_E \gtrsim 5\times 10^{21}\ \mathrm{keV\ s\ m^{-3}}$$ (Lawson criterion)

T = 100 – 200 milion ^{o}K (10 – 20 keV, peak at 70 keV)
n = 2-3 * 10^{20} ions/m^3
T_E = 1-2 s

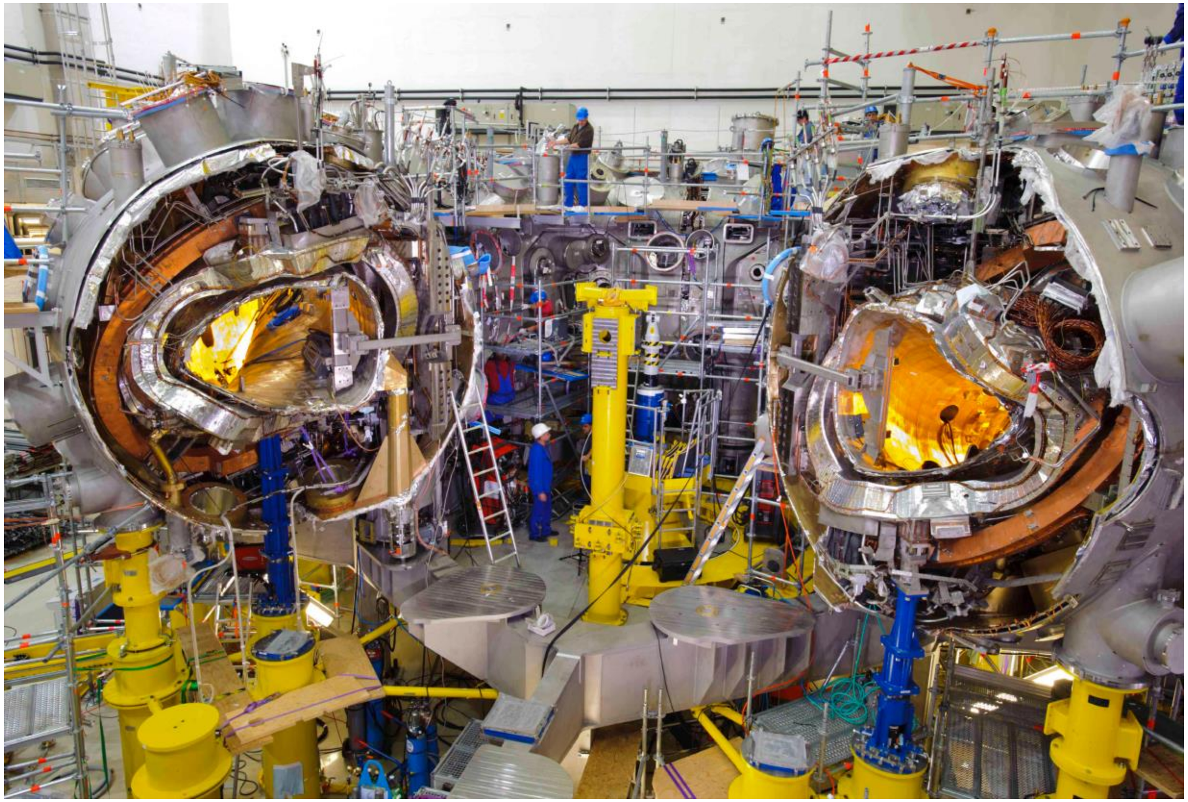
Wendelstein 7-X Stellarator

Mission of Wendelstein 7-X:

- Demonstrate feasible **modular coil design**
- Good equilibrium properties with small error fields
- **Steady-state compatible power and particle exhaust concept**
- Optimized plasma performance

Results:

- **First plasma OP1.1** in Dec'15 (helium, 1 MK for 0.1 s)
- **More in OP1.2** in 2017-2019 (max. 100 MK, max. 100 s)
- **OP 2.X is planned for 2022** (**cooled divertor**, up to 18 GJ, 30 minutes at 10 MW ECRH)



Wendelstein 7-X Stellarator
Greifswald, Germany

➢ **Axel Winter talk Thu 9/12, 14:20**

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Infrared Image Mapped to CAD Models

- **Divertor tiles**:
  Carbon Fibre Composite (CFC) joined to CuCrZr cooling structure
- Max. Operational temperature is limited by a **Cu to 475 °C**
- **Max. surface temperature** is **1200 ° C** for 10 MW/m2
- PFCs (graphite tiles) up to 400 °C
- Wall and pumping gap panels up to 200 °C

A. Puig, IAEA 2021

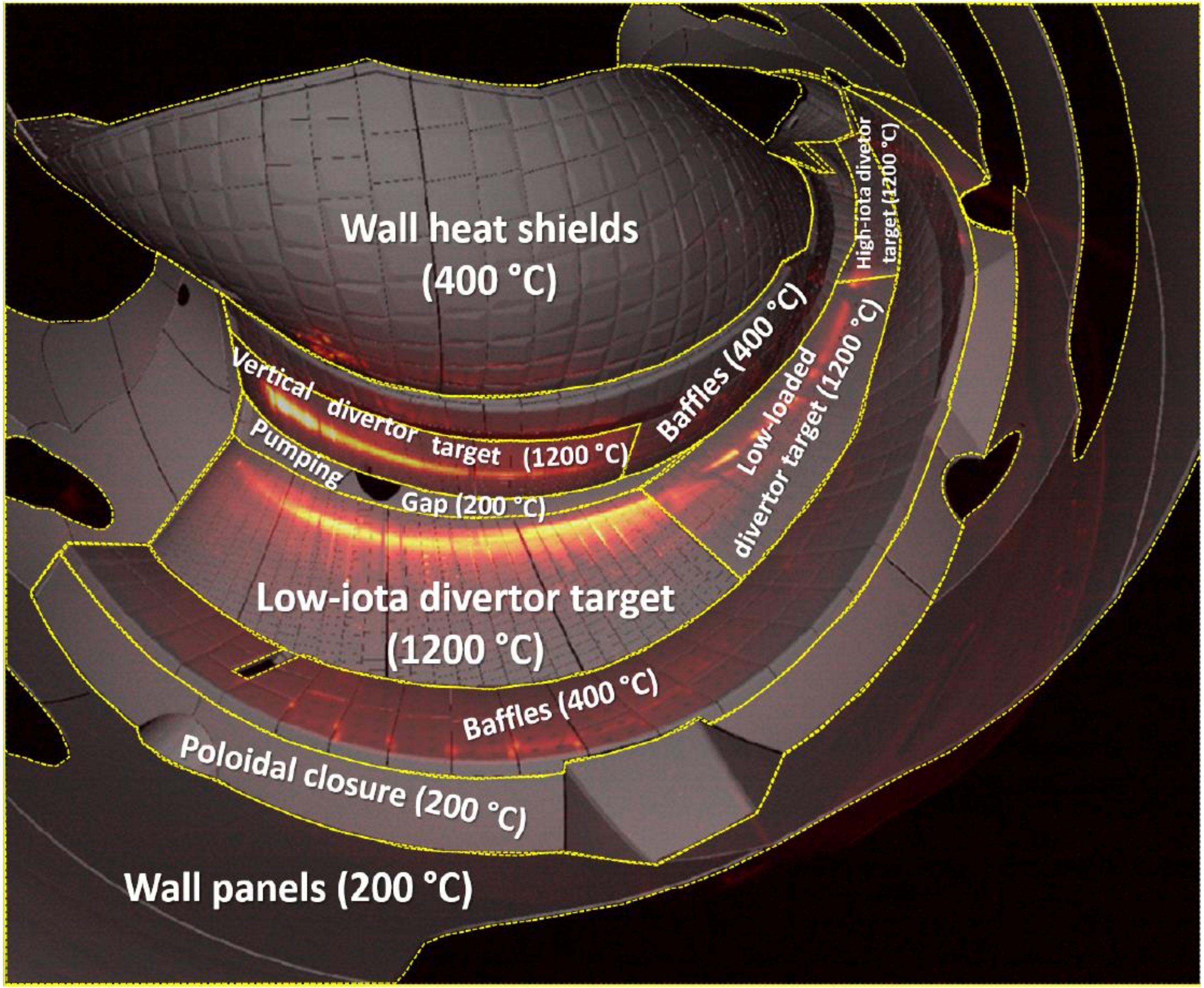

Image Acquisition and Processing

Tasks:

- Propose a **scalable and reliable hardware architecture, long support time**
- Develop **new hardware components** - frame grabber and firmware
- Develop **software framework for IA and IP**
- **RT algorithms** for image processing

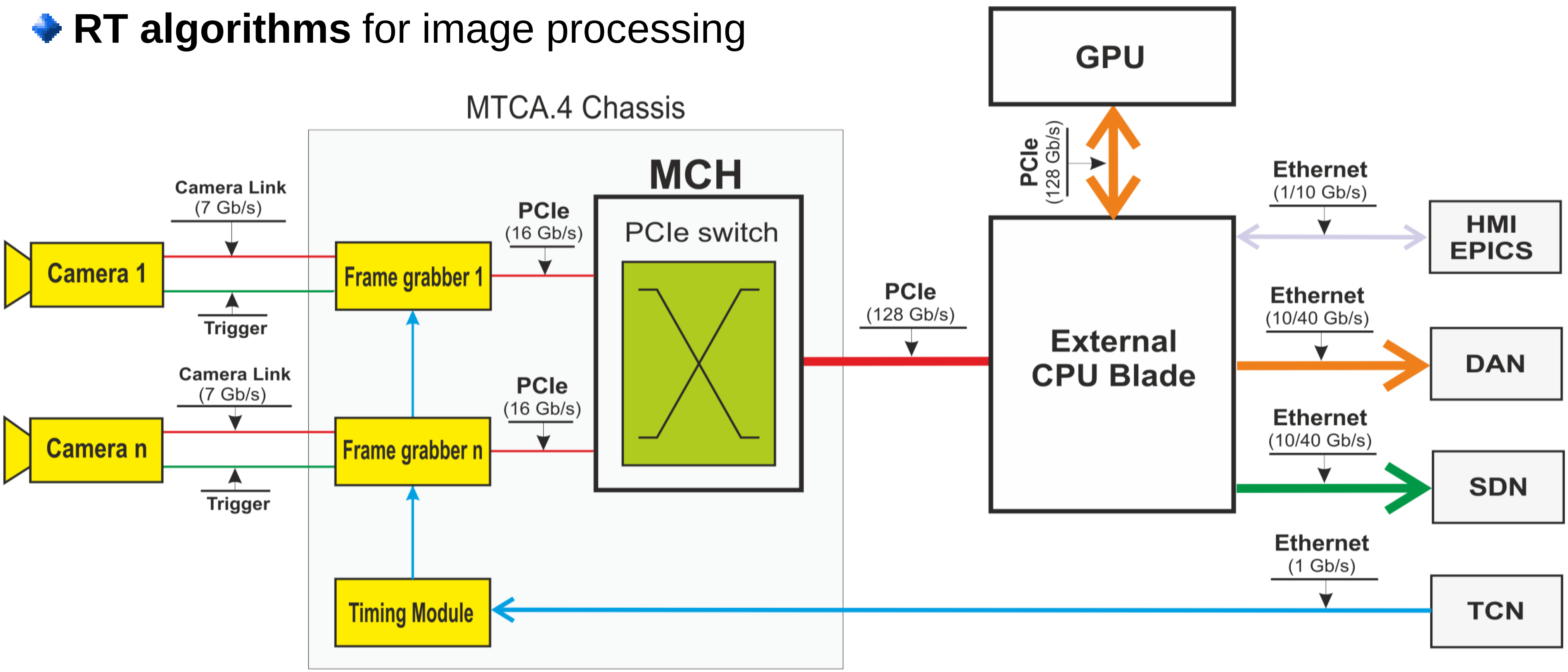

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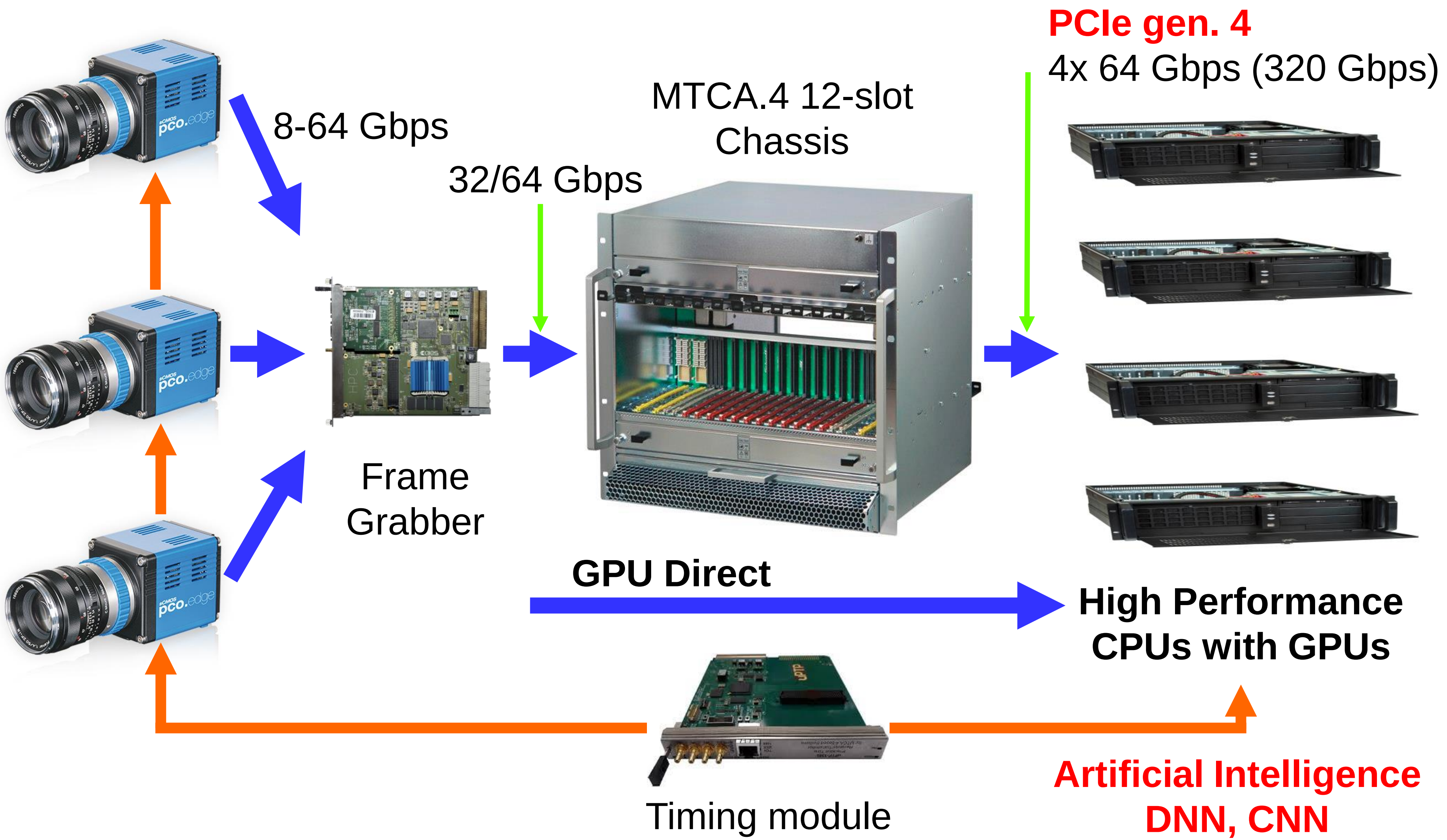
Image Acquisition and Processing with MicroTCA.4



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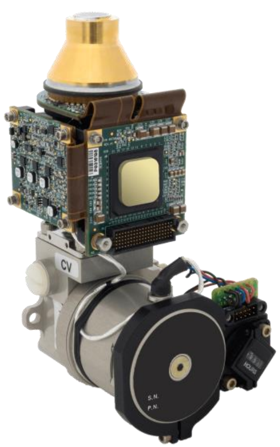
Various Cameras and Interface Standards

- **Camera Link** — 2.04 Gb/s, 5.44 Gb/s, 6.8 Gb/s
- **Camera Link-HS** — 2.4 Gbps / 128 Gbps
- CoaXPress 2.1 — n x 6.25/12.5 Gb/s (n=4 → 25/50 Gb/s)
- 1 GigE Vision — 800 Mb/s
- 10-25 GigE Vision — 10/25 Gbps
- IEEE1394/Fire Wire — 0.4 Gb/s (1394a) or 0.8 Gb/s (1394b)
- HD-SDI — 1.45 Gb/s (max. 2.9 Gbps)

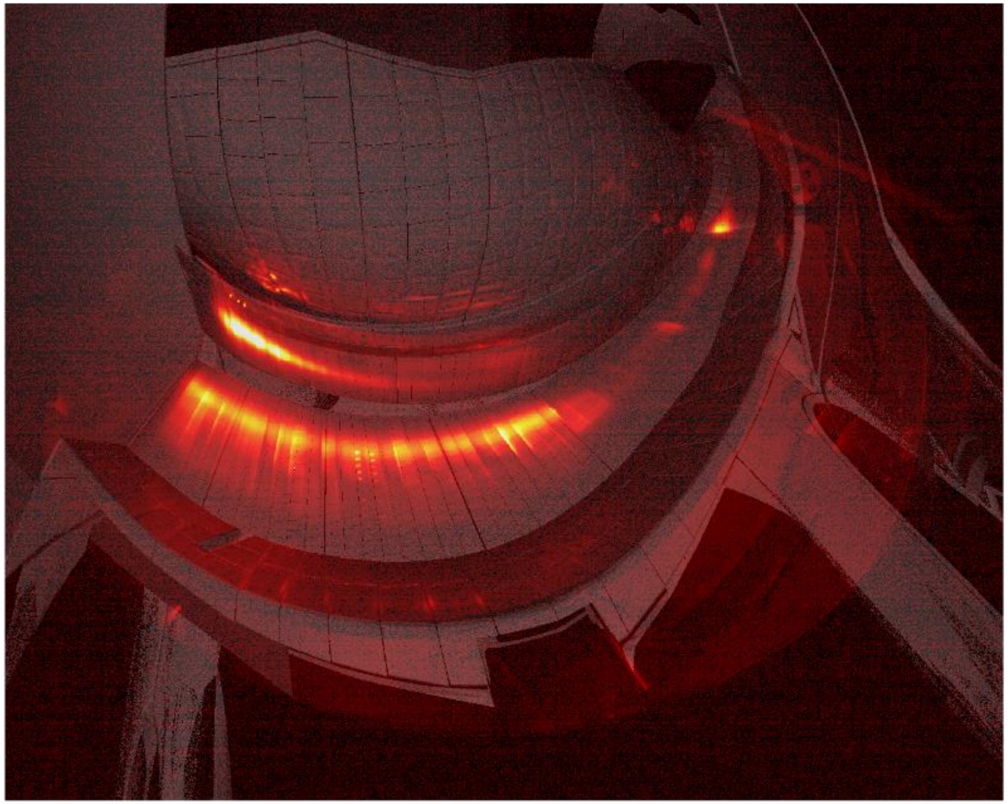
SCD Hercules (CL)

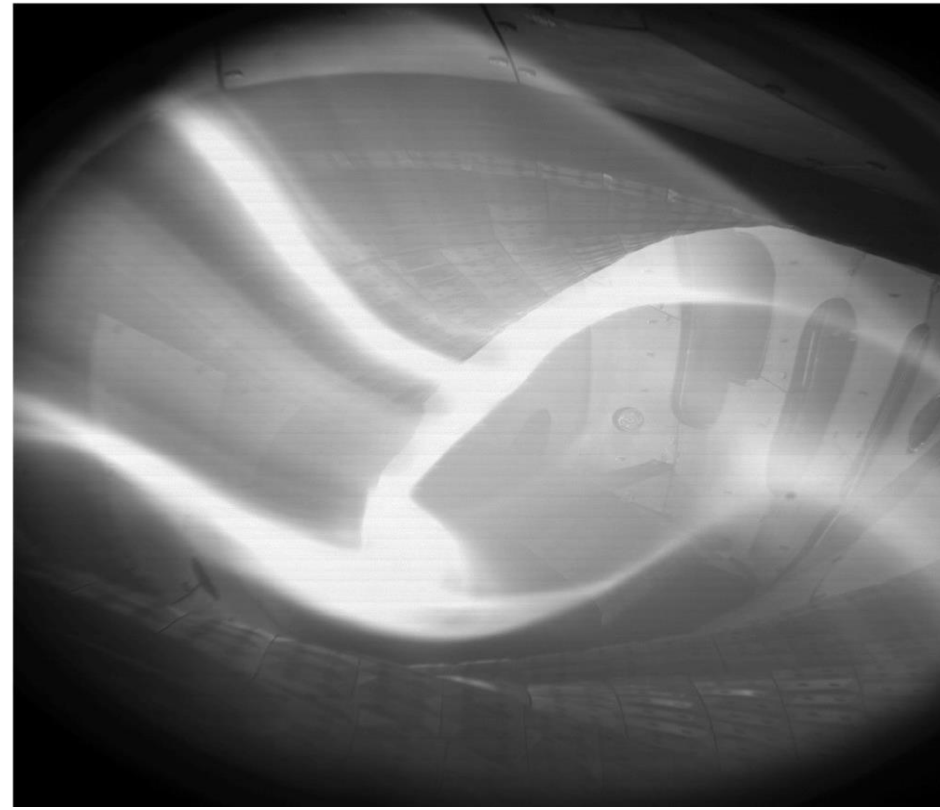


Active Silicon (CXP-12)

Imperx Cheetah (10GigE Vision)

Imaging System for Plasma Facing Components Protection





- **Imaging system** for PFC protection:
  - IR cameras with **frontal view** of divertors
  - Video cameras with **tangential view**
- **OP 1.2**
  - 9 immersion tubes
  - 1 prototype endoscope

- **OP 2.1**
  - **2 endoscopes**
  - 8 immersion tubes
  - 2 simple systems for high iota target
- **OP 2.2**
  - **10 endoscopes**
  - 2 simple systems for high iota target

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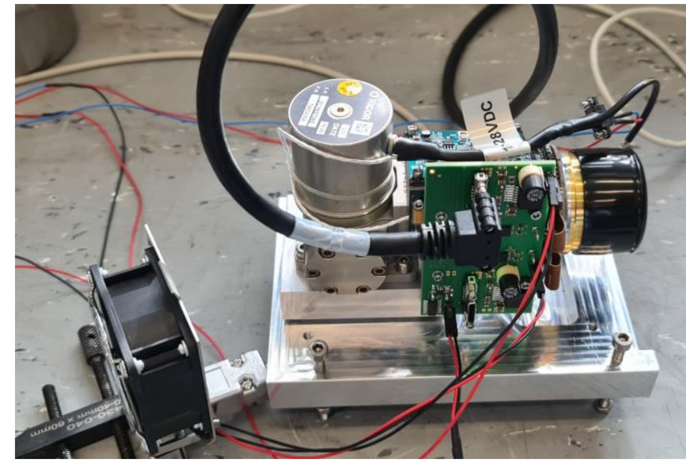
W7-X IR Cameras

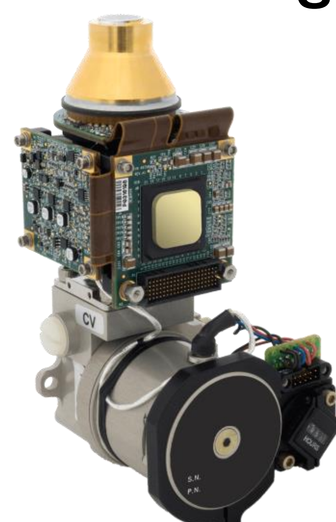
W7-X: OP2.1

IRCAM Caleo 768k L

W7-X: OP2.X



SCD Hercules



- IR Camera:
  - Hercules sensor InSb
  - Spectral range: 2-5.7 µm (MWIR)
  - Sensor size: 1280x1024
  - Pixel size: 15 x 15 µm
  - Bit depth: 14 bit
  - Frame rate: 100 Hz

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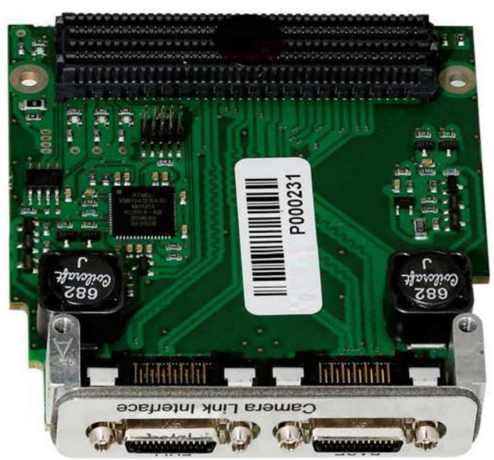
W7-X VIS Cameras

W7-X: OP2.1

Raptor Cygnet 2.1MP



W7-X: OP2.X

PCO Edge 5.5

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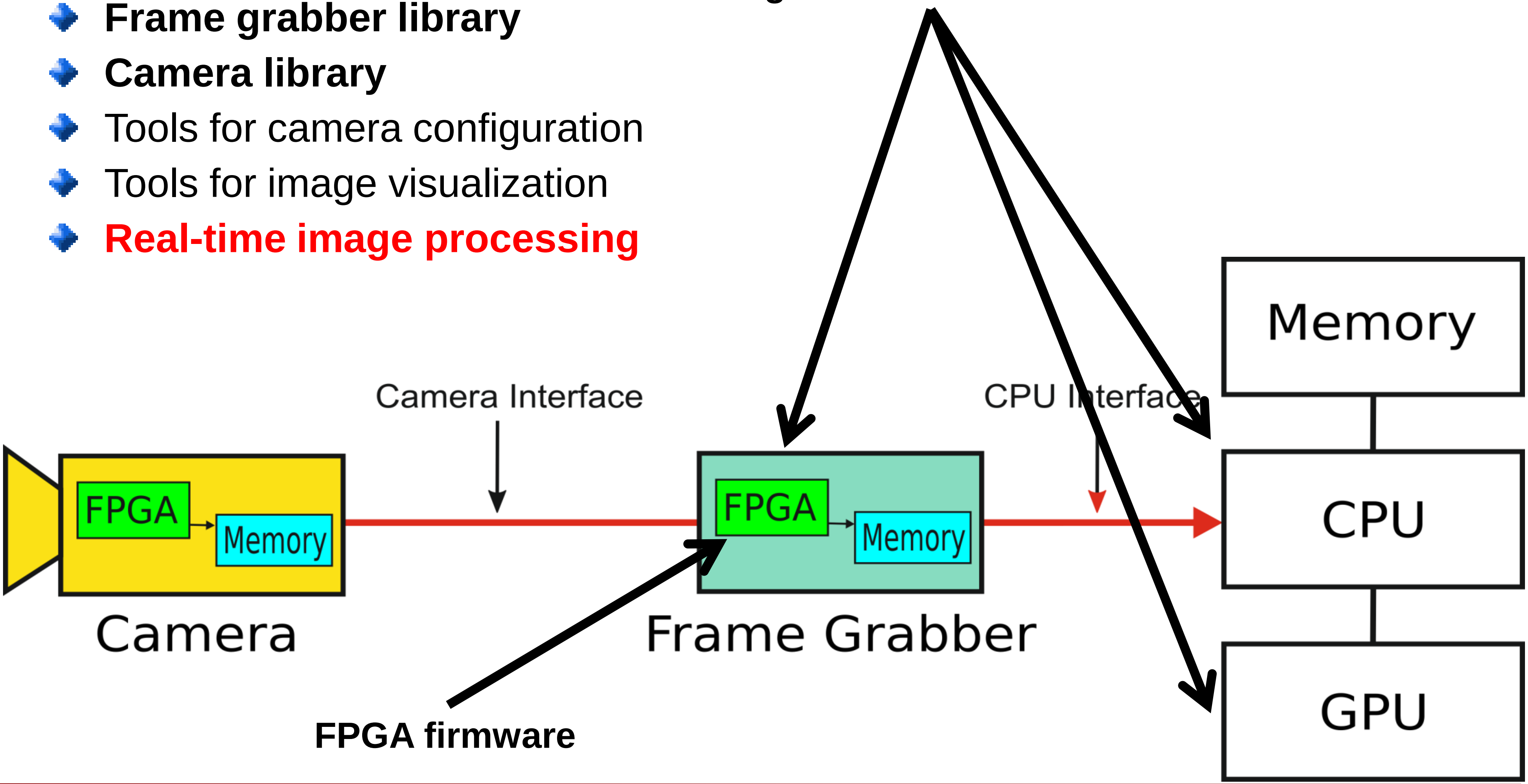
Universal Frame Grabber Module - Software

- **FPGA firmware**
- Linux driver
- **Frame grabber library**
- **Camera library**
- Tools for camera configuration
- Tools for image visualization
- **Real-time image processing**

Hardware we have now
Software is actually the main part of work
Working on an universal GenICam framework



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Cameras Assembled in Endoscope

PCO Edge 5.5, CLHS

SCD Hercules, CL

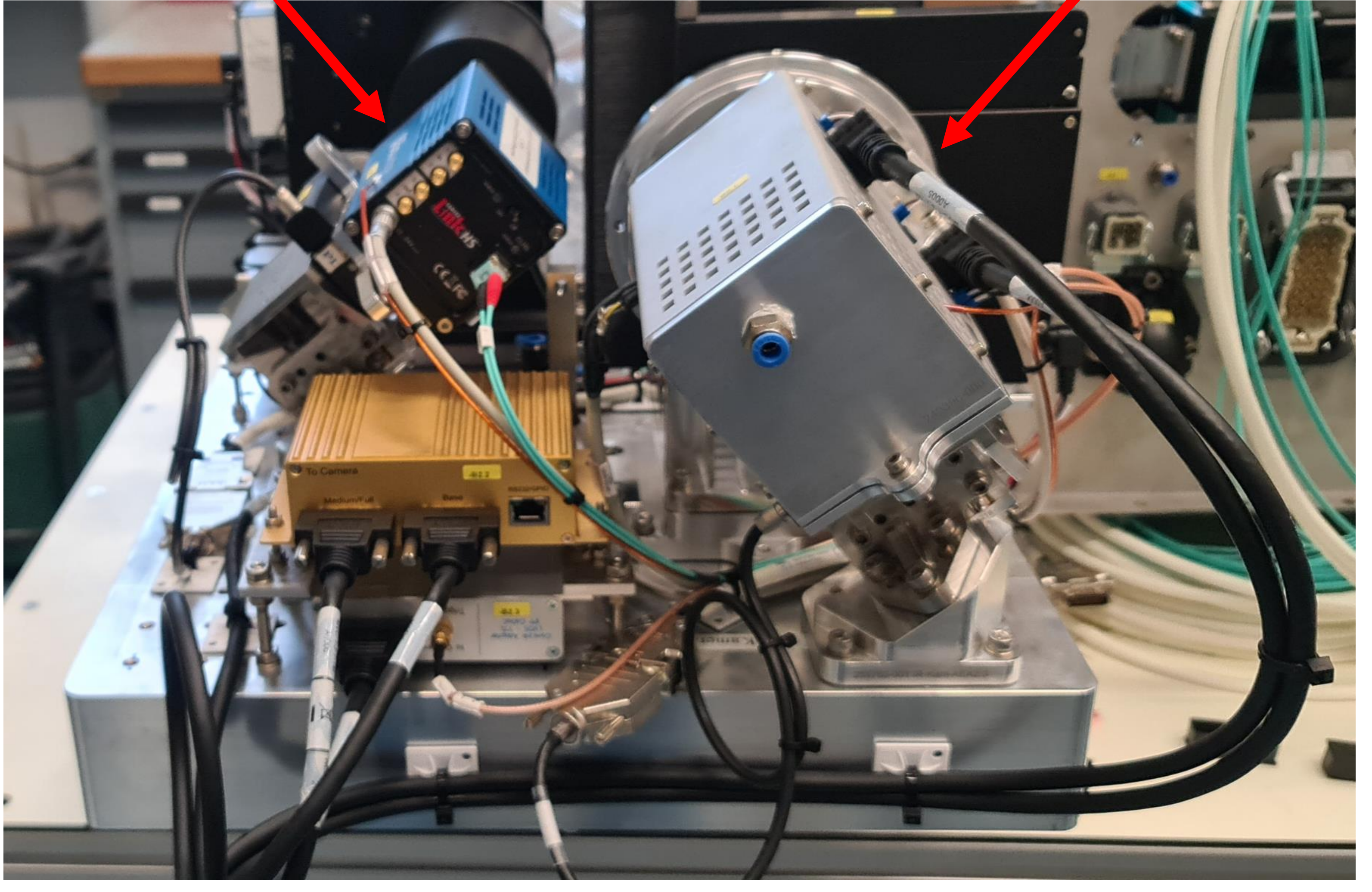

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Image Processing

- High-speed digitisers or high-resolution/frame-rate cameras requires **significant processing power**
  - **Programmable devices** (**FPGA**) are used for signal conditioning and low latency real-time processing (NUC, bad-pixel correction, background subtraction, etc.)
  - **CPU or Graphics Processing Unit** (**GPU**) are suitable for more complex algorithm, especially image processing
  - **Convolutional Neural Network** for image analysis and recognition
- Data copying is always expensive (both processing power and memory)
  - Avoid data copying
  - Use Direct-Memory-Access when possible
  - Ideal situation is direct transfer to data processing unit

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Image Acquisition Architecture with DMA – First Step

- A **single station always process** data from a **single camera**
- During algorithms development we need at least two parallel acquisition path
  - Data archiving and visualisation
    - Machine protection (realisable deterministic algorithms)
  - New algorithms testing (deterministic and AI-based)
- **Multiple DMA transfers:**
  - **Frame grabber to CPU and GPU (Tesla T4)**
  - **CPU to GPU, GPU to CPU,…**

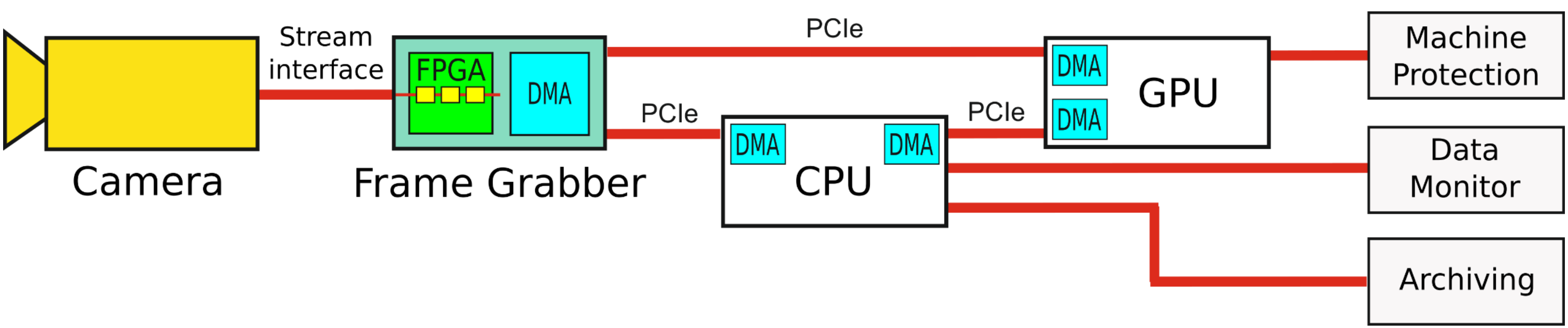

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Image Acquisition Architecture with DMA – Second Step

- Single MTCA.4 system process images from 4 IR cameras
- Four fast stations (CPU and GPU) involved in image processing

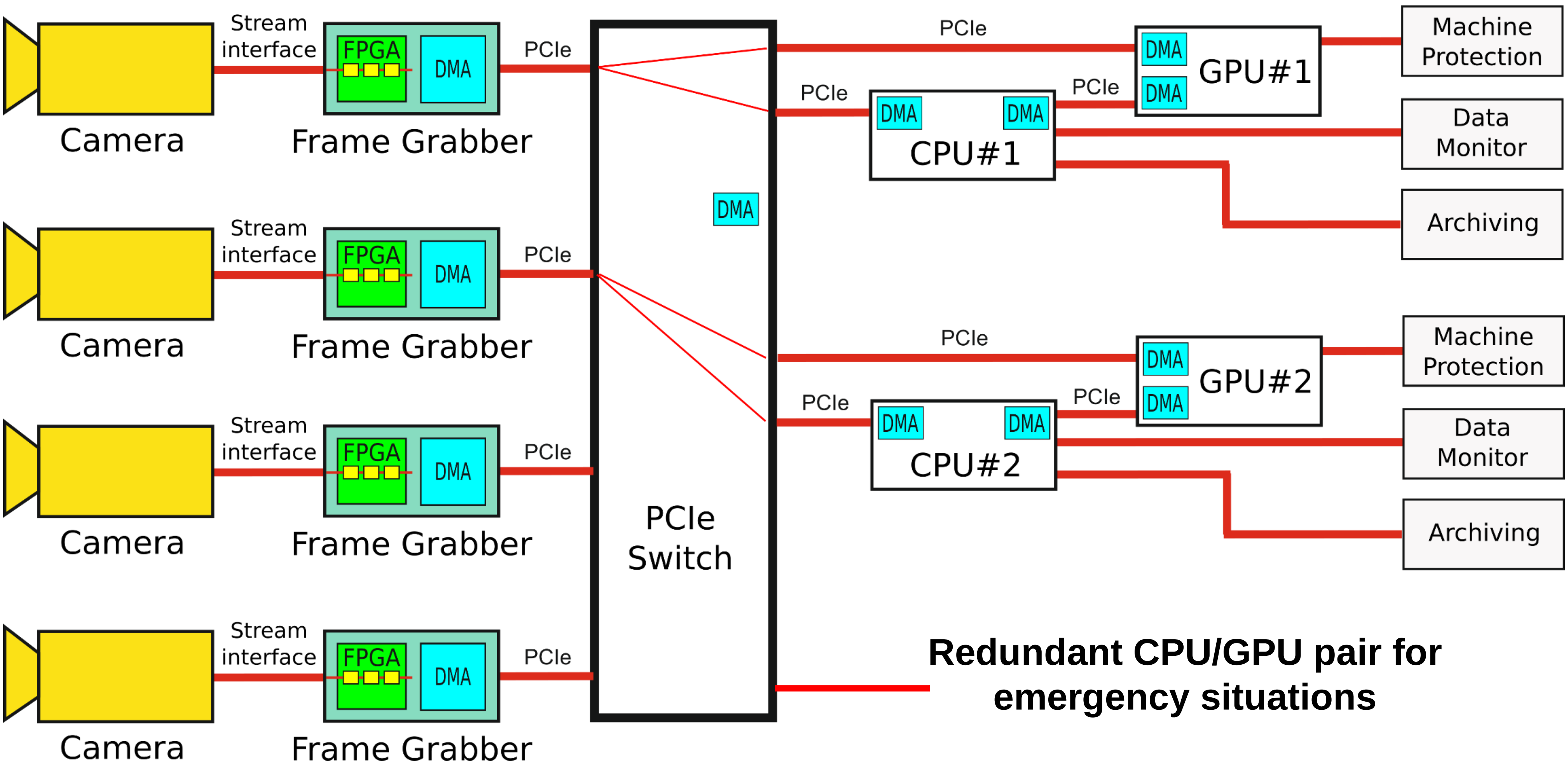

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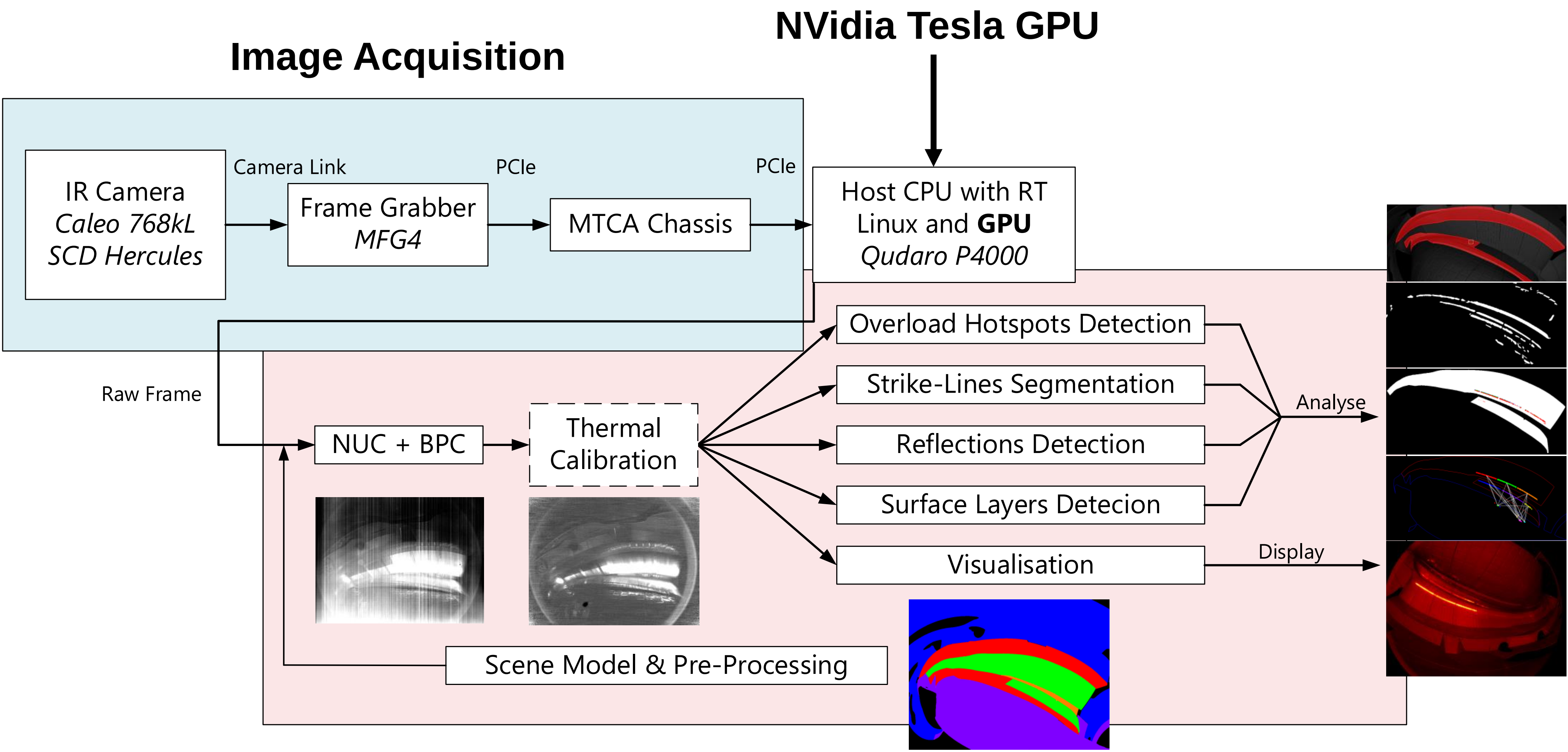
Image Acquisition and Processing Pipeline



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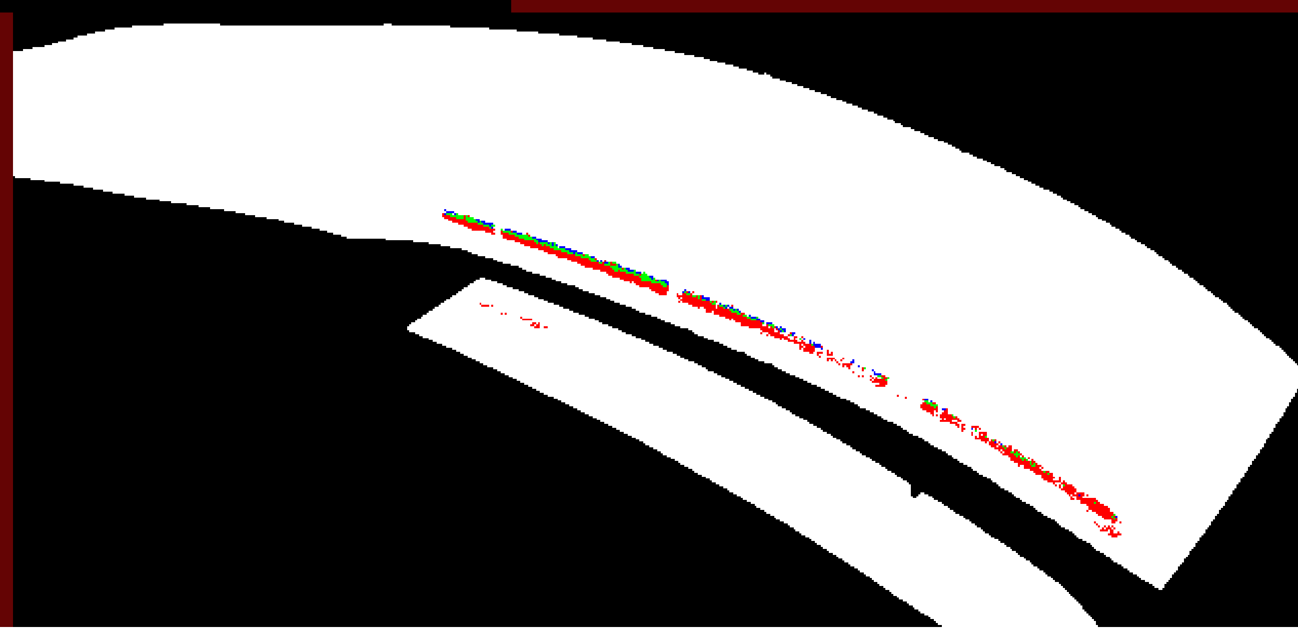
Analysis of 20171114.053 - AEF20 dataset

Segmented Strike-Line
& Hotspots

Surface Layers
During… **Heating**
During… **Cooling**
During… **Both**



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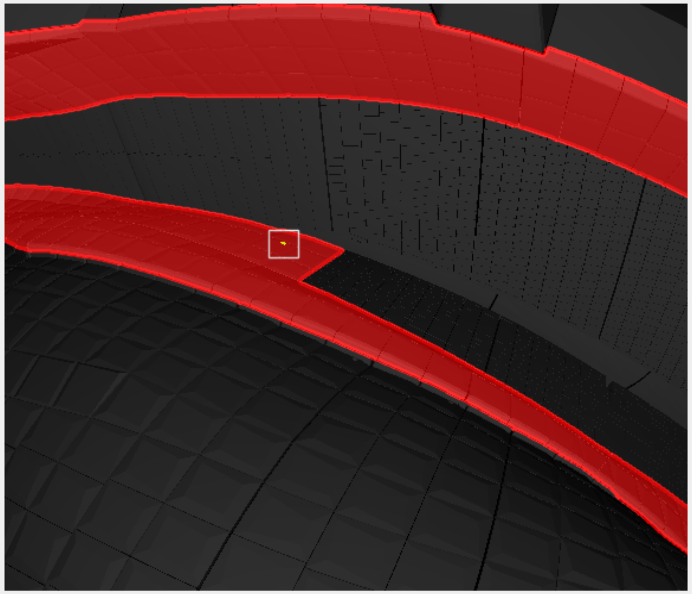
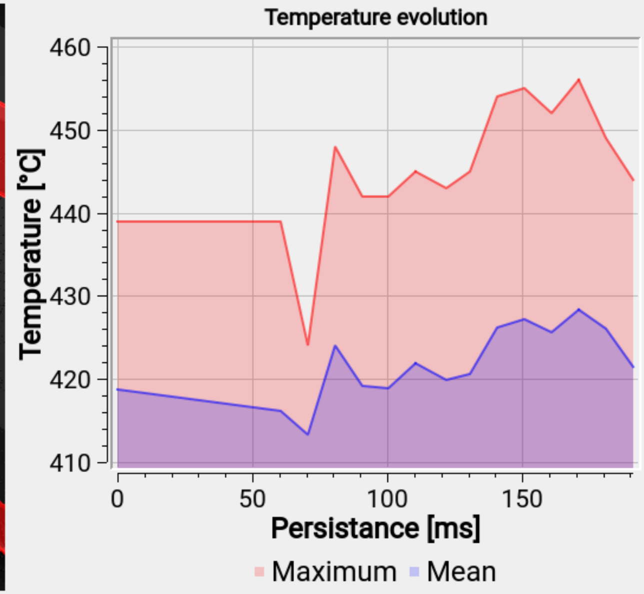
Analysis of W7-X 20171114.053 - AEF20 dataset

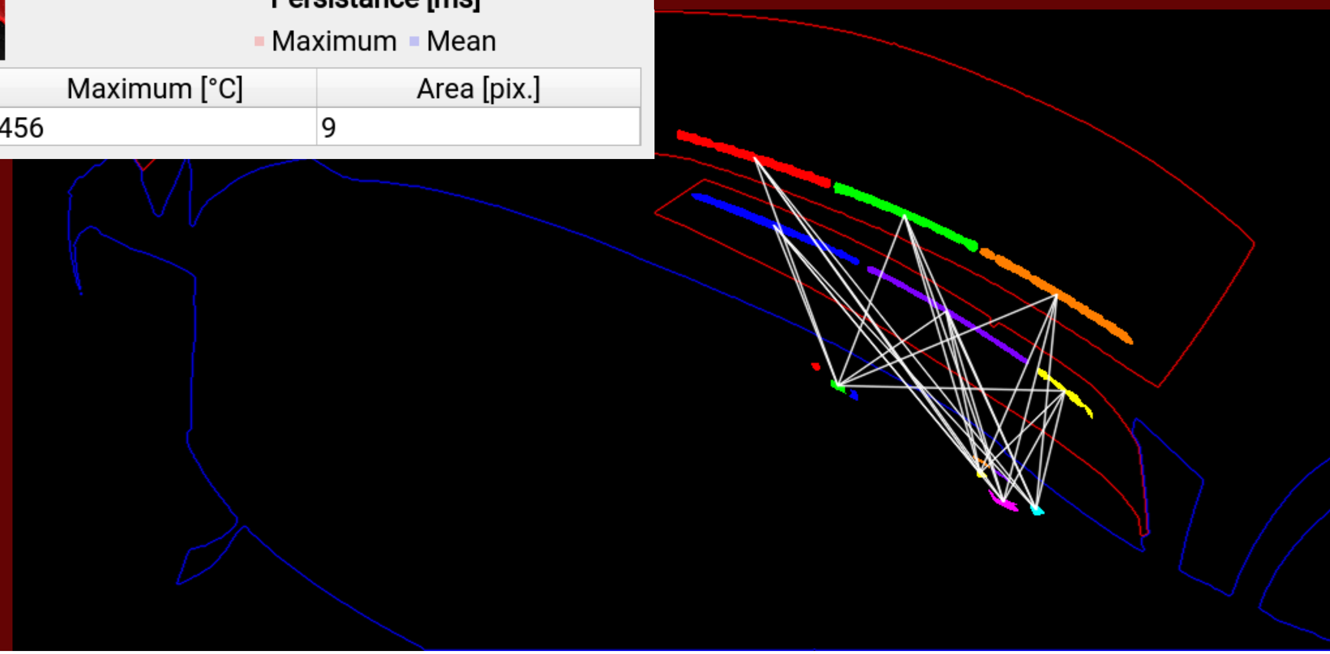




	Begin [ns]	End [ns]	Maximum [°C]	Area [pix.]
1	1510677589505503488	1510677589696637440	456	9

Overload Hotspot
PFC: Baffle
456 °C / 400 °C

Reflections
Divertors (strike-lines) →
Wall Heat Shields (graphite)



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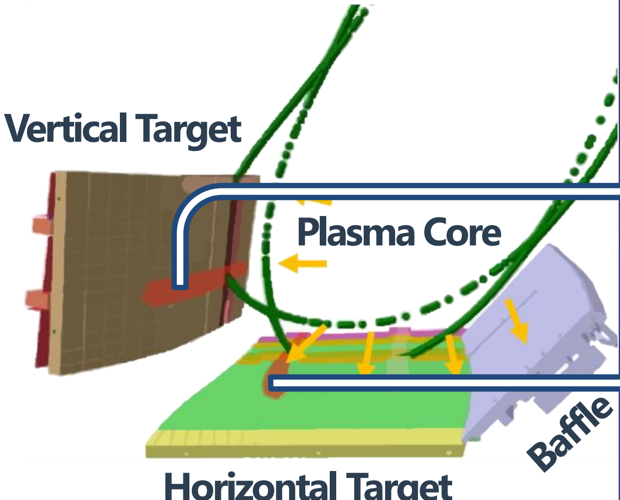
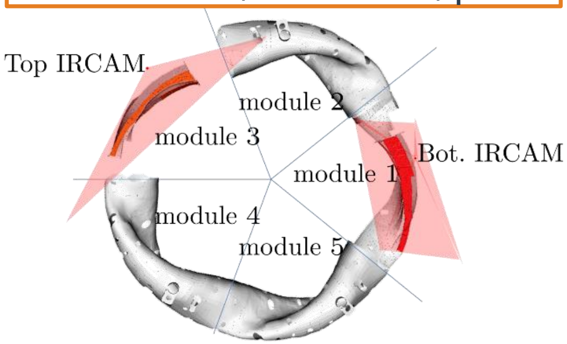
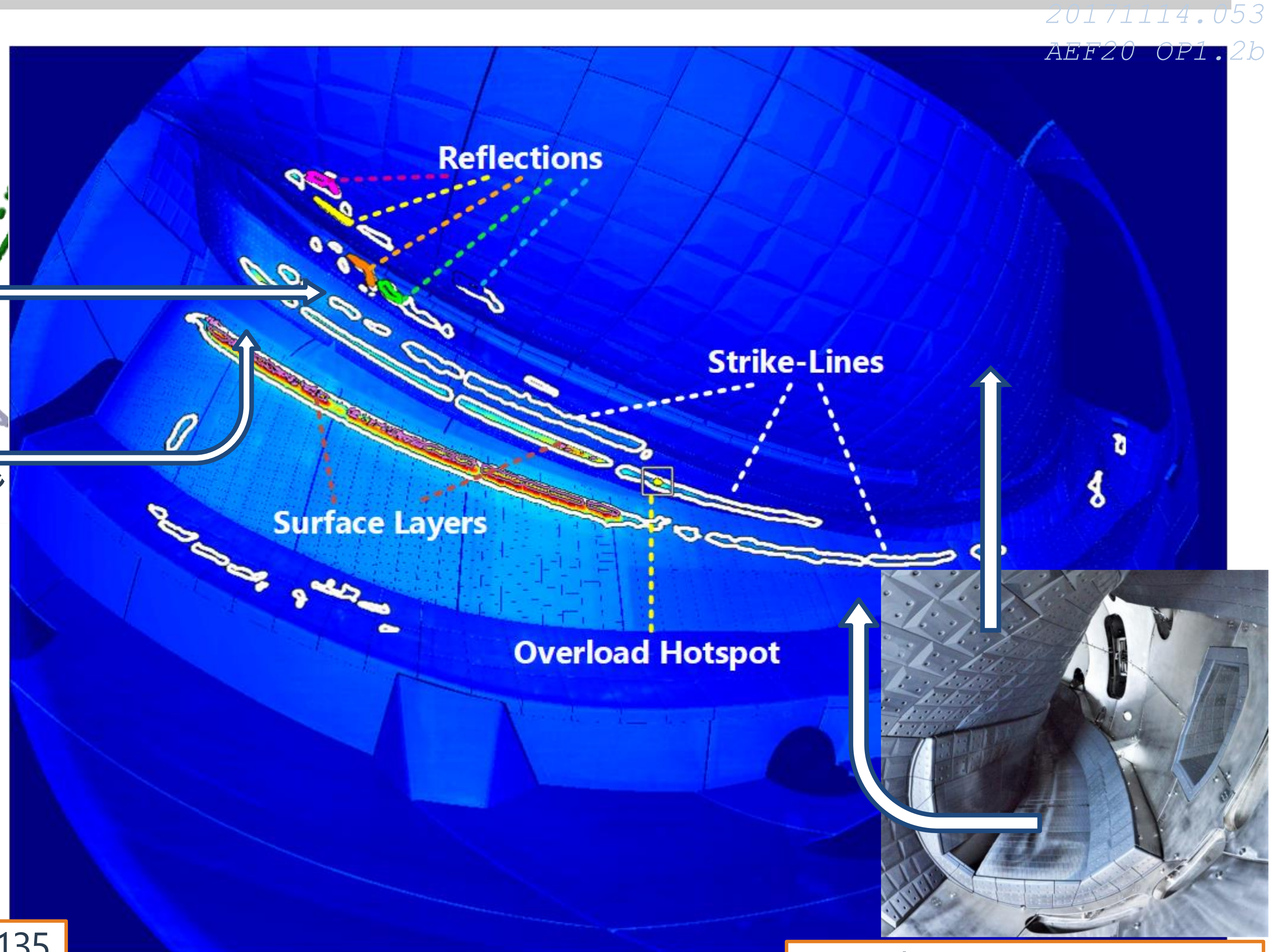
W7-X Stellarator – Machine Protection



TS Pedersen, IAEA 2021, p. 11



H Niemann, PhD Thesis, 2020, p. 135



TS Pedersen, IAEA 2021, p. 11

Future Work – Real-time Image Processing

1. GPU-Accelerated Real-Time Algorithms for Machine Safety

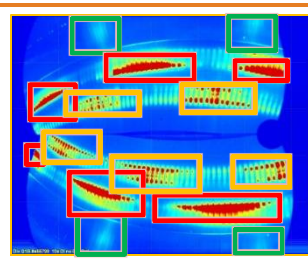
- **Pre-Processing**
- **Real-Time Filtering**
- **Real-Time Analysis**

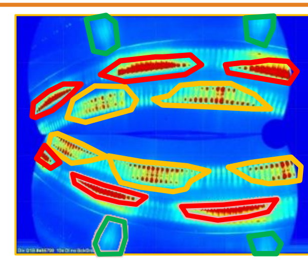
on a GPU

NVIDIA CUDA

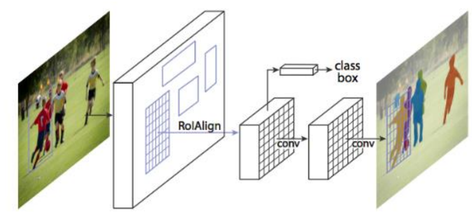
2. Artificial Intelligence for Machine Protection

- **Detection**
- **Instance Segmentation**
- **Classification**



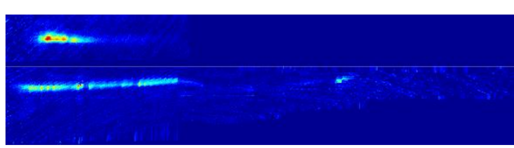


with Mask R-CNN

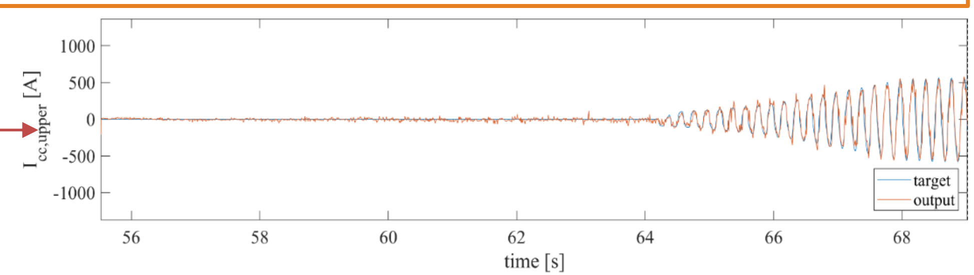


3. Artificial Intelligence for Machine Control

- **Regression**
- **Reinforcement Learning?**



CNN



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Thank you for your attention

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