Image Acquisition and Processing with MicroTCA.4

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CONTROL AND DATA ACQUISITION LABORATORY

Imaging Plasma Diagnostics

Diagnostic Systems provide data for:

- **Plasma Diagnostics, physics study (non-real-time)**
  - Physical studies, observation, measurements
  - Archiving measurements, raw data – **could be challenging** (transferring and archiving ~TBs of data)
    - **Stored data:** raw data, pre-processed, calibrated, measurements, meta-data (labels, tags)
    - **Important for ML and AI**
- **Machine and Plasma Control (real-time, soft real-time)**
  - Diagnostic systems supply information for Plasma Control System
  - Primary and supplementary systems
  - **Latency from 10 - 100 ms**
- **Machine Protection (hard real-time)**
  - Trigger interlocks to protect machine against damage
  - **Latency from 100 - 1000 ms**

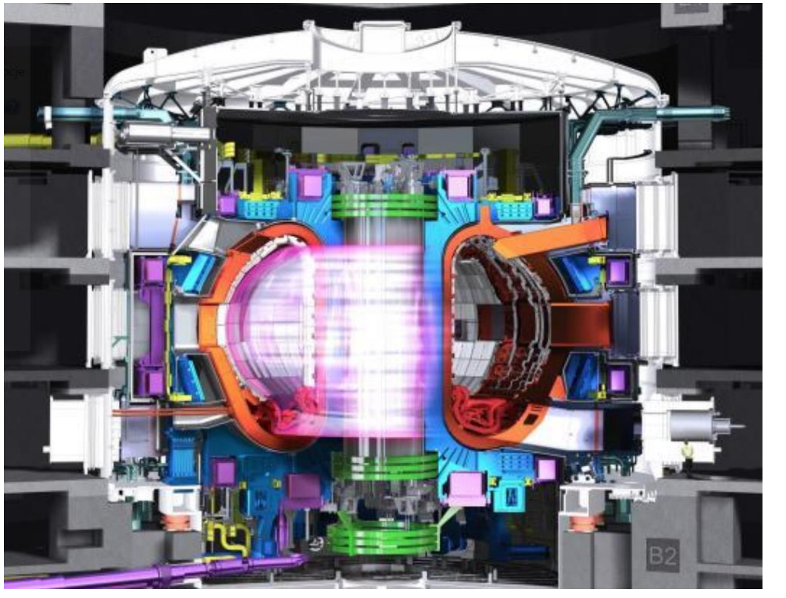
Fusion Projects - Plasma Diagnostics

Imaging diagnostics:

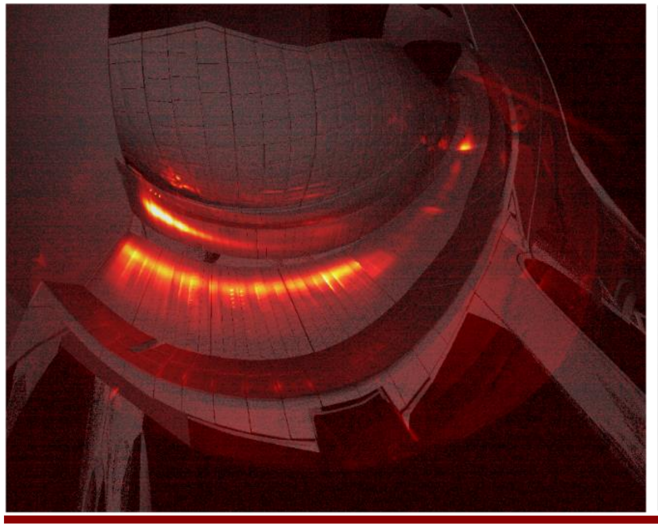
- **W7-X:**
  17 VIS and 13 IR cameras (OP2.1-OP2.4)

- **ITER:**
  more than 200 cameras

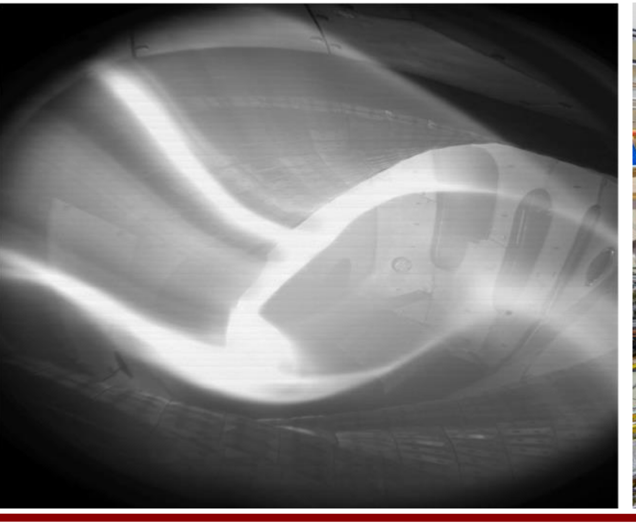
ITER Tokamak



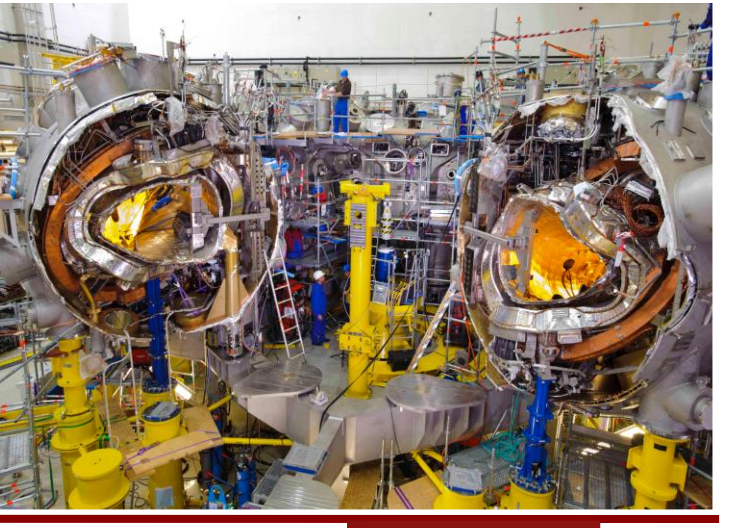
IR Diagnostics



VIS Diagnostics



Wendelstein 7-X Stellarator



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Imaging Diagnostics – Image Acquisition and Processing (1)

- A single camera provides **one or more streams** of images
- **Frame grabber** configures camera, start and stop DAQ
- **All operations must work in real-time (hard real-time system)**
- Looking for **reliable, scalable and standardized solution (hardware/software)** suitable for **AI and ML real-time** applications
- Looking for a **methodology** to build **complex** (more than 50 cameras) and **scalable imaging systems** with improved **reliability**

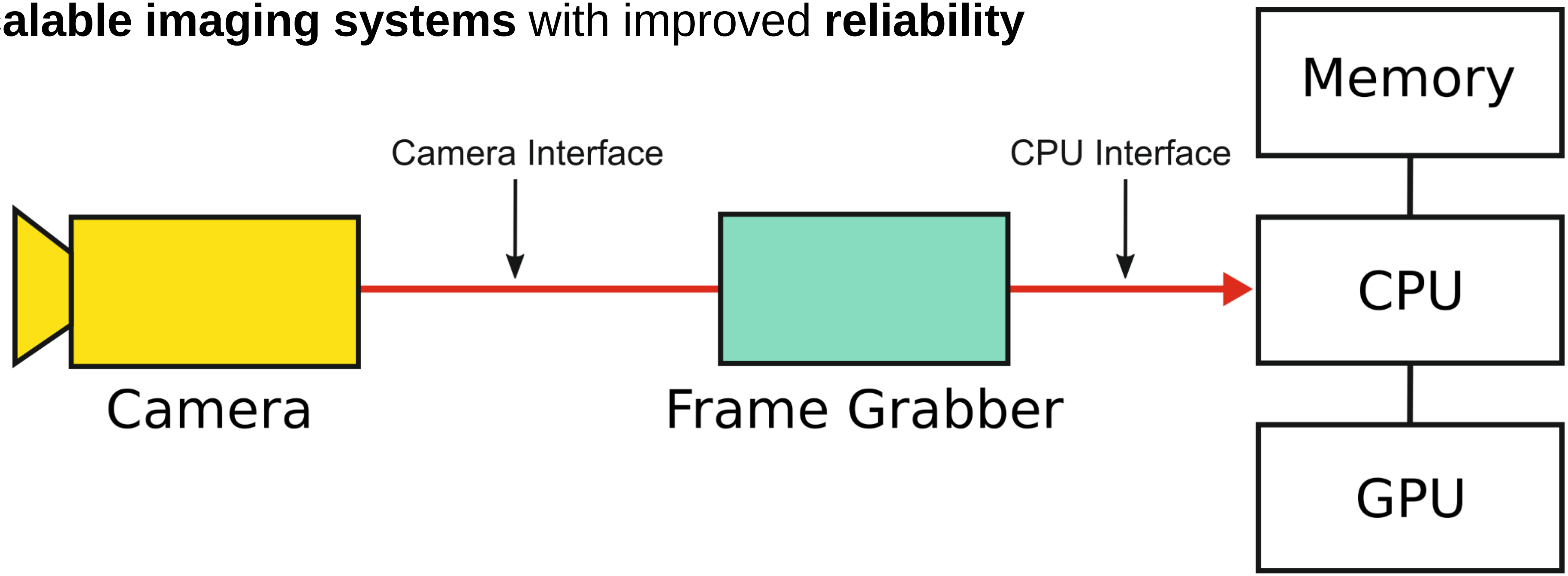
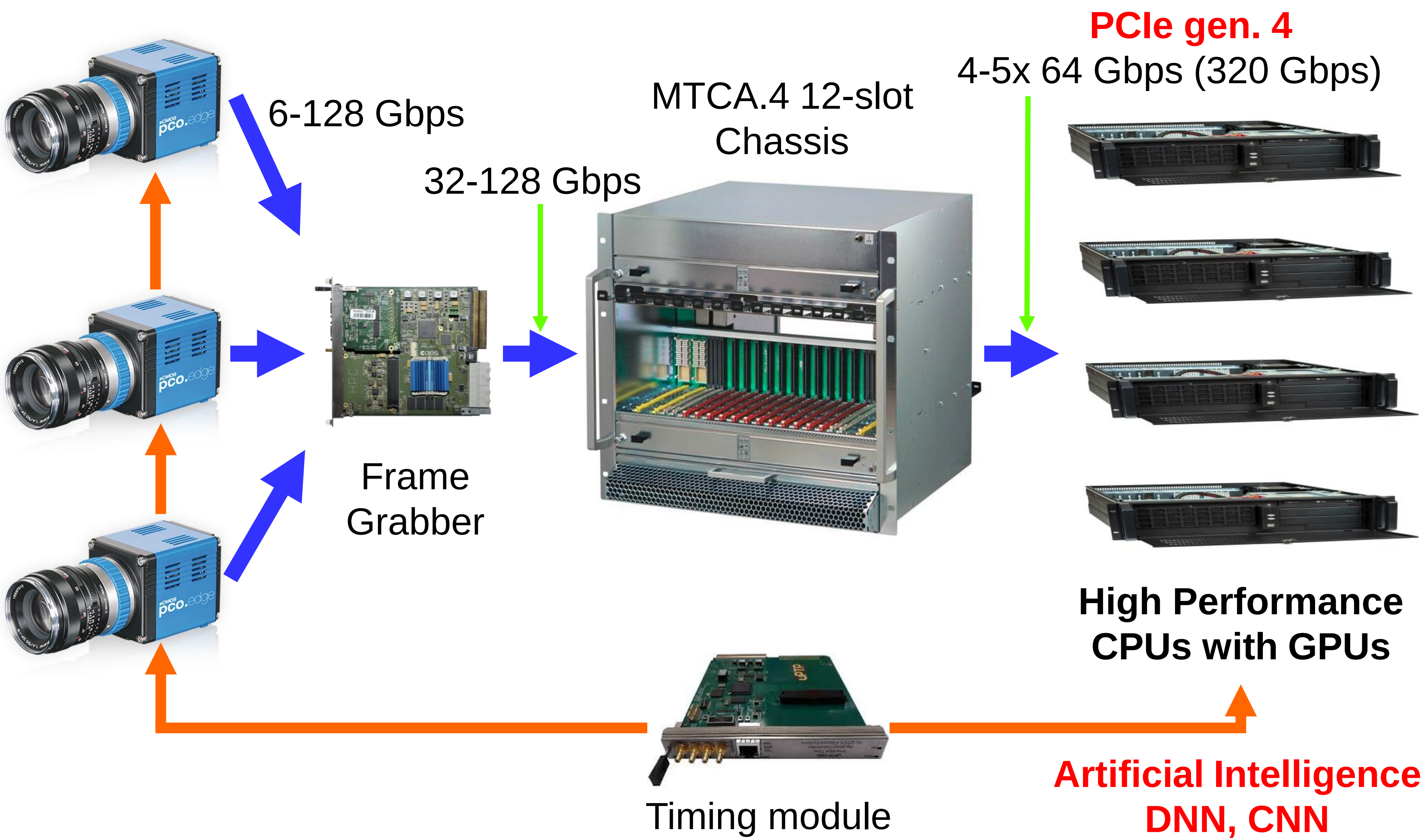


Image Acquisition and Processing with MicroTCA.4 (2)



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Universal Frame Grabber Module for MicroTCA.4

Frame grabber is composed of:

- **FMC carrier** (FPGA, DDR, PCIe, trigger, etc.)
- **FMC modules** supporting various camera interfaces (8 standards)

In addition, we need (**software**):

- **FPGA firmware**
  - **IP core** for selected camera interface
  - **Xilinx (IP Cores, Vivado)**
- **Linux driver**
  - Dedicated camera library
- **Image processing framework**
- **Additional tools**
  - Visualisation, archiving, verification, latency measurements, integrity, more

Mezzanine module

Carrier module

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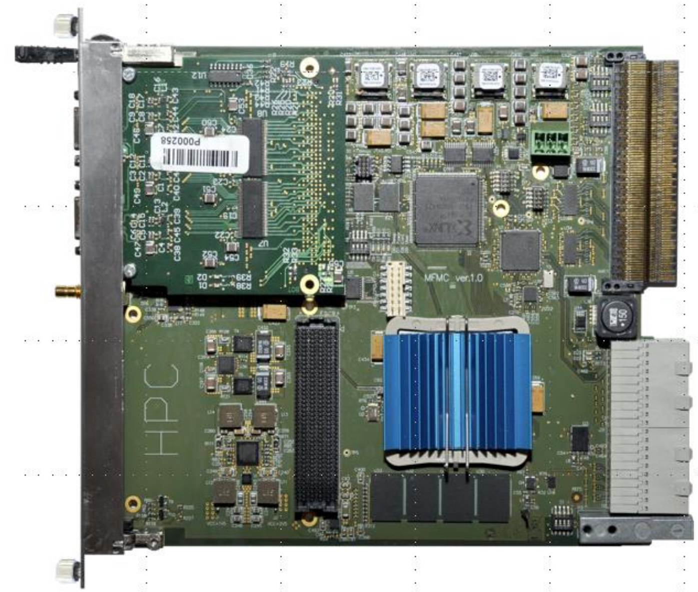
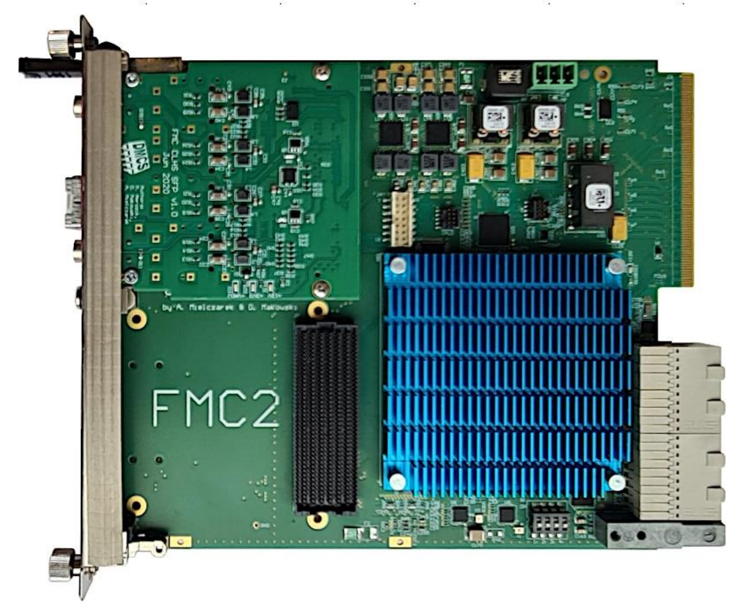
FMC Carrier Modules

Frame grabber is composed of:

- FMC carrier
  - Artix 7 FPGA (<6.5 Gb/s)
  - **Kintex US+ (>6.5 Gbps, 32 Gb/s per lane)**
- Mezzanine modules (FMCs) supporting various camera interfaces (8 standards)





Software support:

- **IP cores** for selected **camera interfaces**
- Common Linux driver
- **Dedicated camera library (GenICam)**
- Real-time processing software
- **Algorithms (FPGA, CPU, GPU)**

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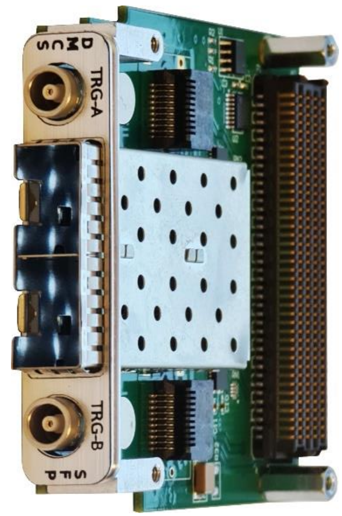
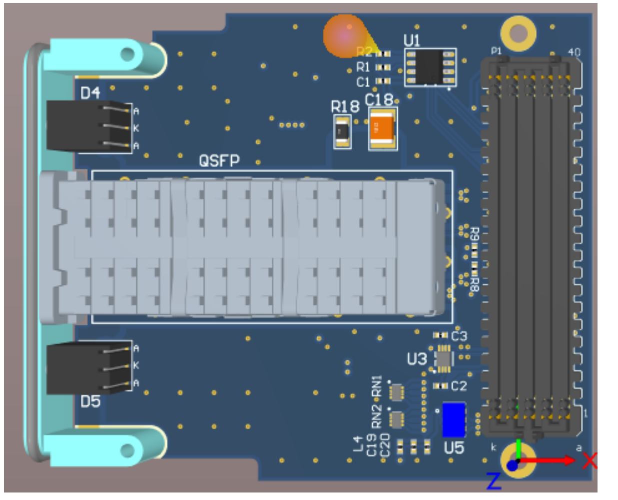
FMC Modules – Camera Interface (Selected Modules)

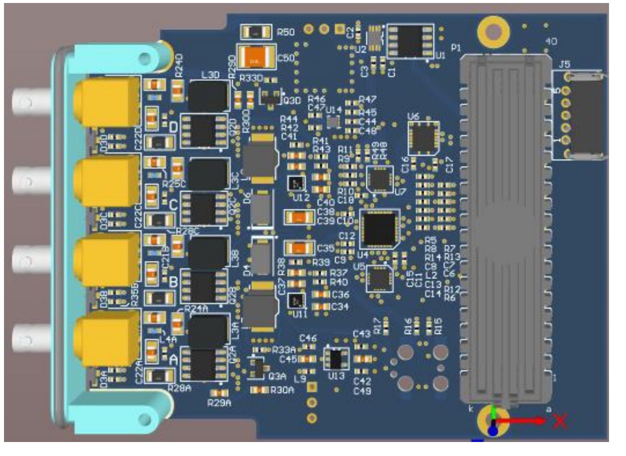




CAMERA Link

CAMERA Link HS

GiGE VISION



IEEE1394

CoaXPress

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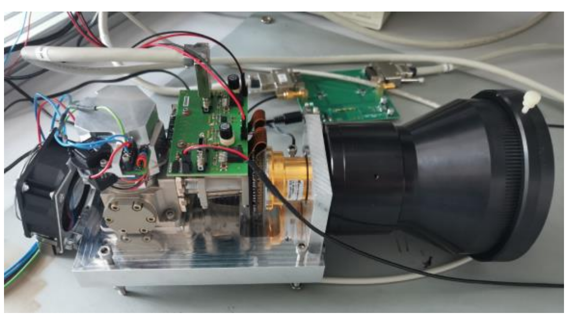
Camera Interfaces

✓ Camera Link	2.04 Gb/s, 5.44 Gb/s, 6.8 Gb/s
✓ Camera Link-HS	2.4 Gb/s - 128 Gb/s
✓ CoaXPress 2.0	n x 6.25/12.5 Gb/s (n=4 → 25/50 Gb/s)
✓ 1 GigE Vision	800 Mb/s
✓ 10/25 GigE Vision	10/25/100 Gbps
✓ IEEE1394/Fire Wire	0.4 Gb/s (1394a) or 0.8 Gb/s (1394b)
✓ HD-SDI	1.45 Gb/s (max. 2.9 Gb/s)

SCD Hercules (CL)



Active Silicon (CXP-12)

Imperx Cheetah (10GigE Vision)

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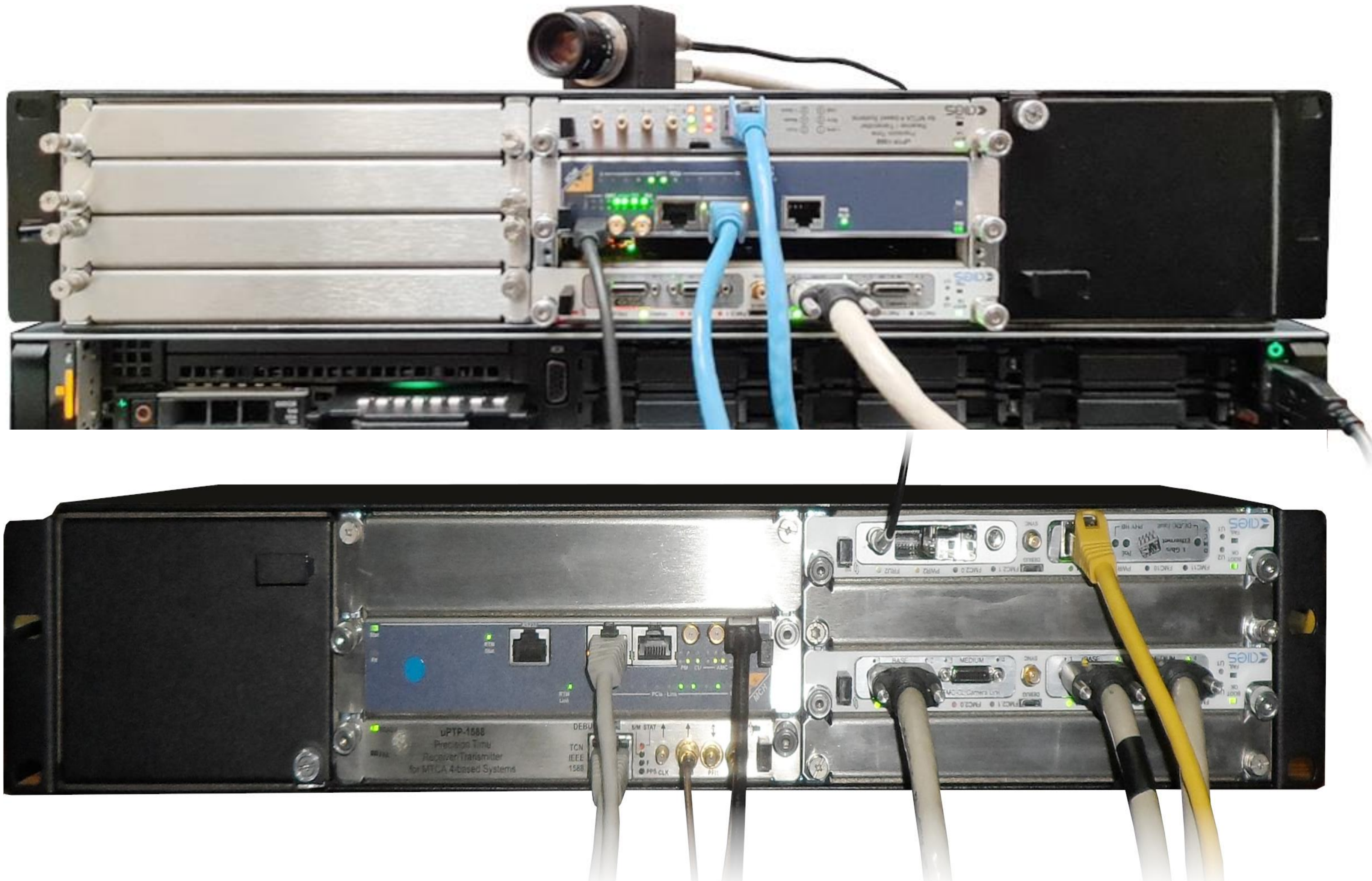
Image Acquisition and Processing System



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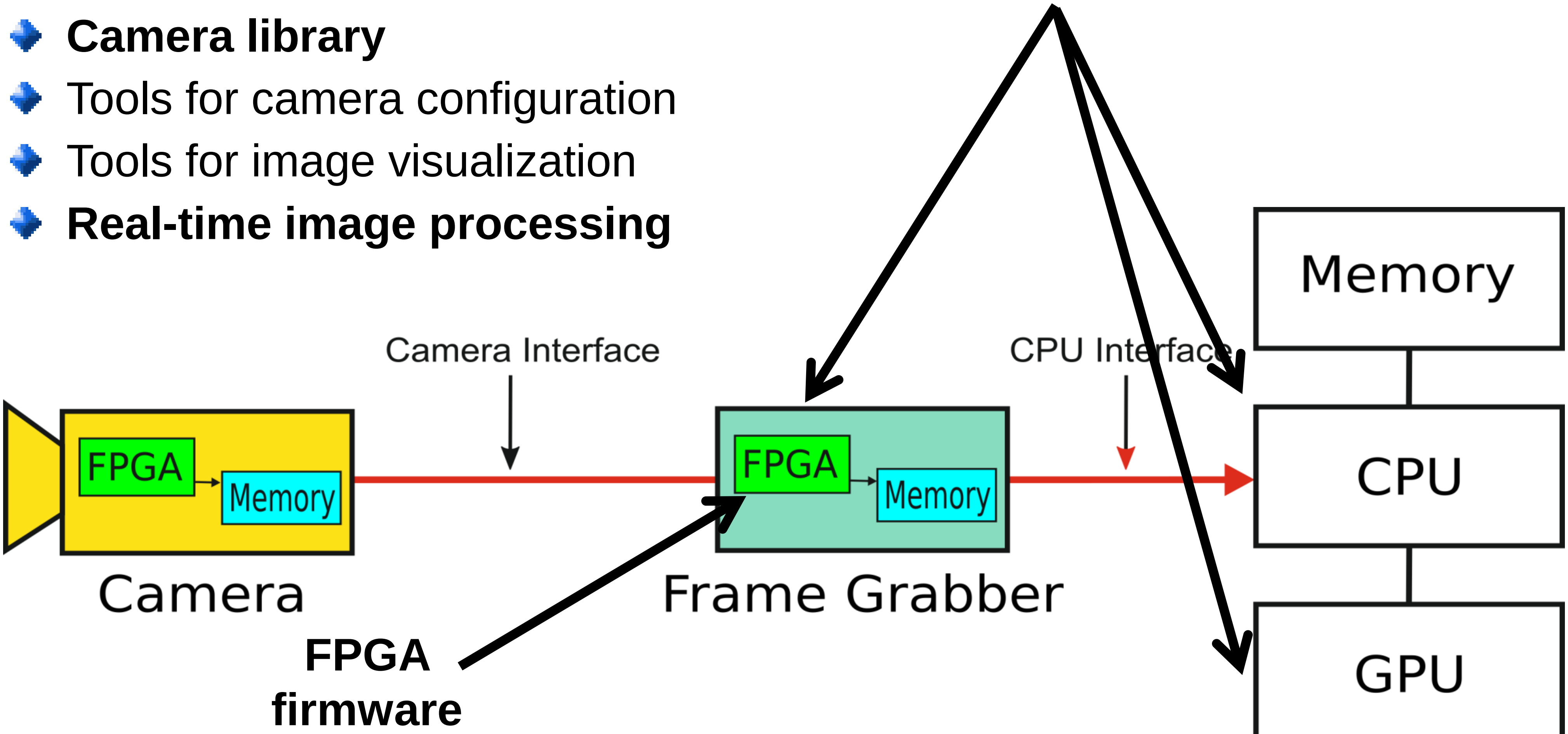
Universal Frame Grabber Module - Software

- **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 IA and IP framework**



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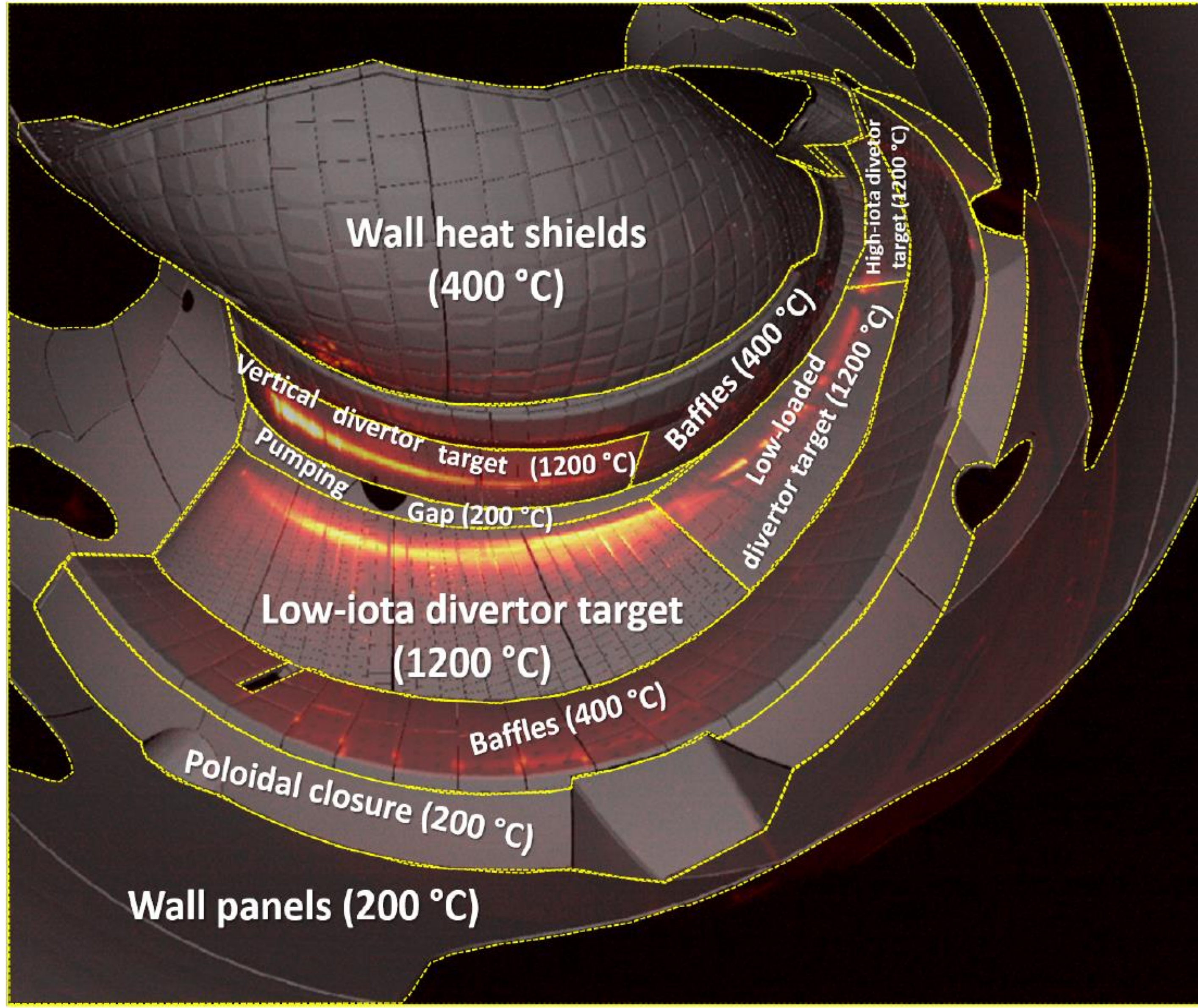
Protection of Plasma Facing Components

- **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



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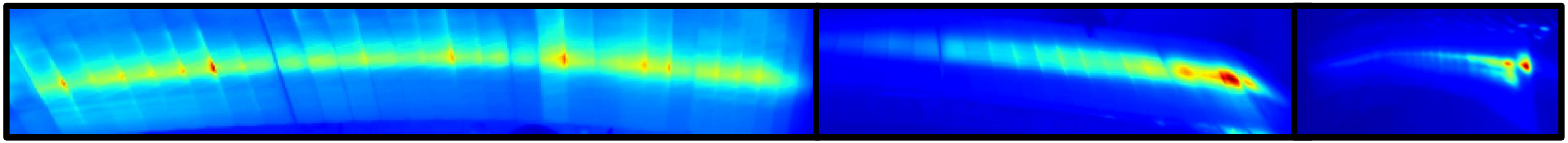
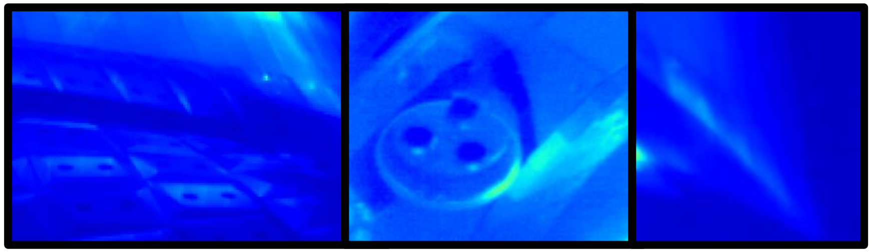
Thermal Events in Infrared Images

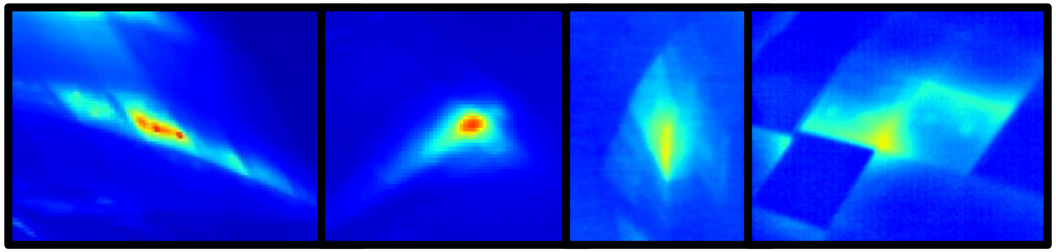
Strike-line



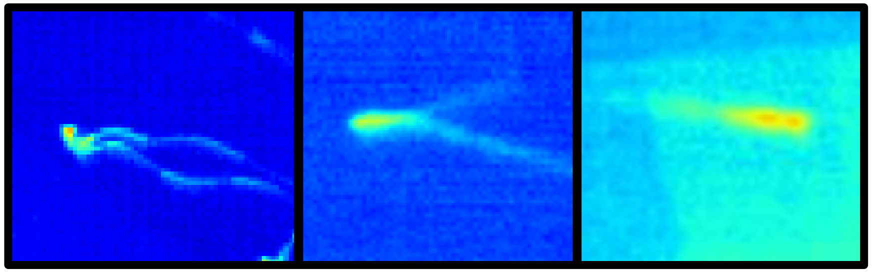
Reflection



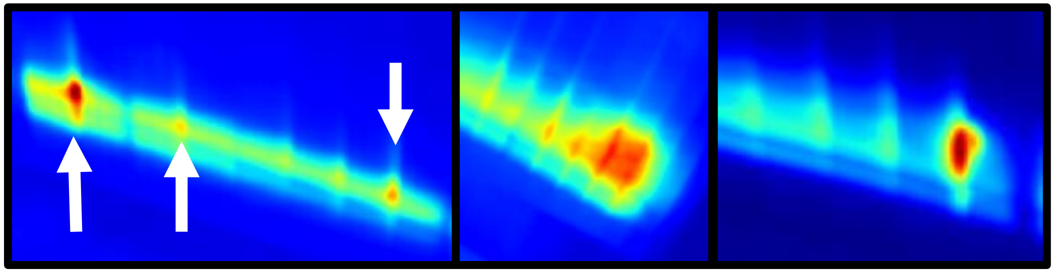
Hot-spot



UFO

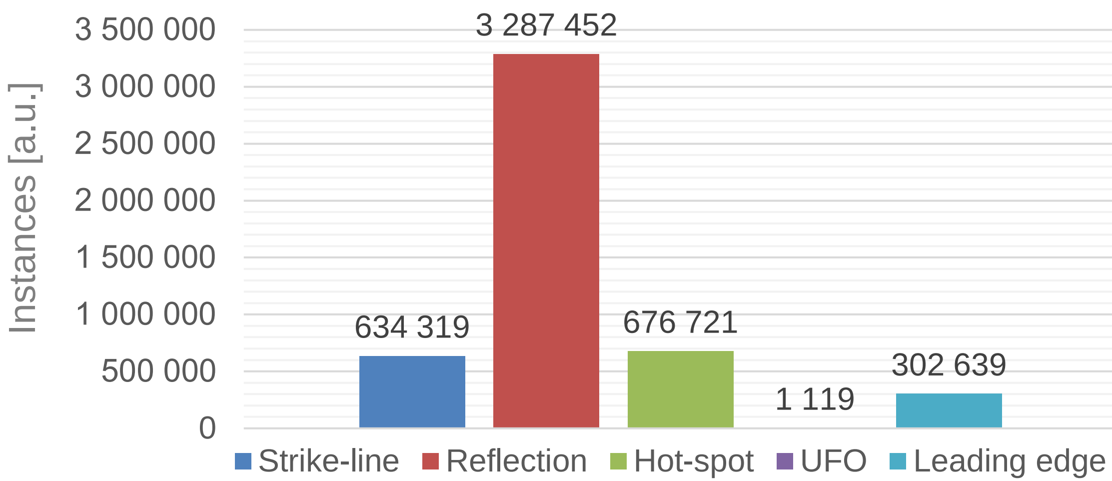


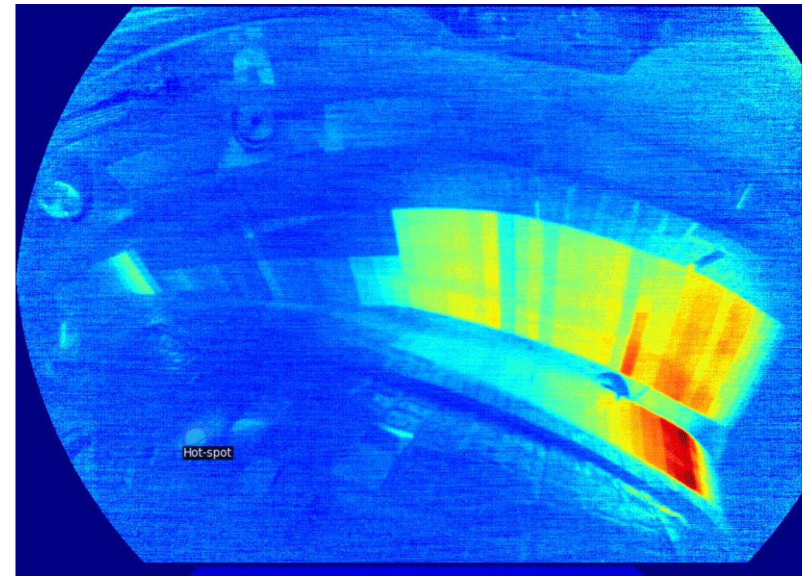
Leading edge

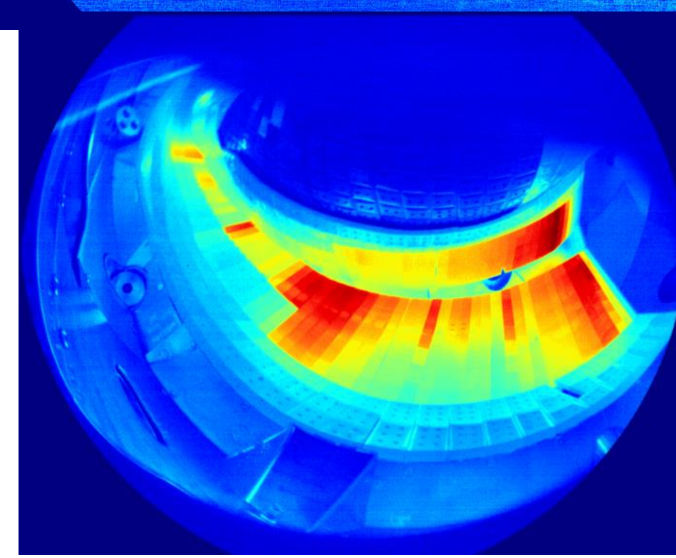


Annotated Dataset

- 109 training/21 test discharge sequences (**178 402** images from OP1.2)







- COCO and YOLO annotation formats
- High similarity to ground truth (manual) annotations
- Annotation method described in B. Jabłoński, D. Makowski, A. Puig Sitjes, M. Jakubowski, "***Enabling Instance Segmentation: A Semi-Automatic Method for Thermal Event Annotation***", IEEE Transactions on Plasma Science

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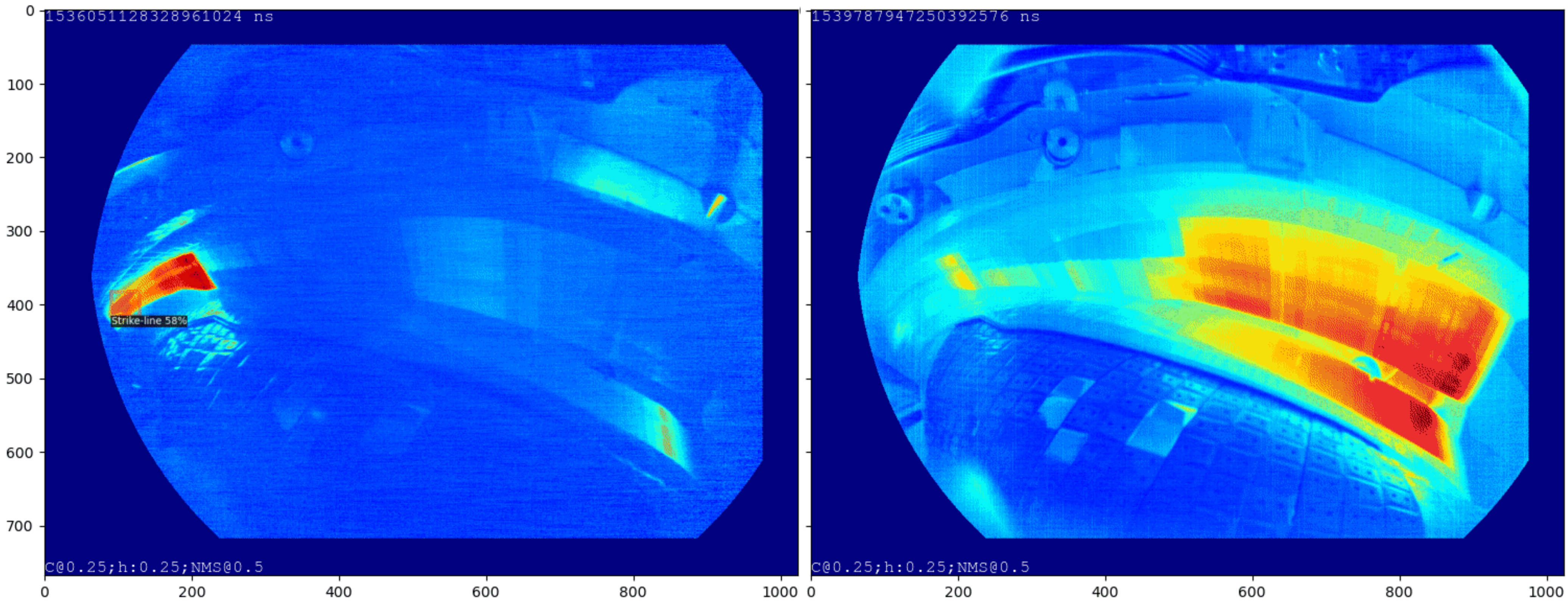
Instance Segmentation - Qualitative Results

20180904.007 (AEF10)
High-iota (FTM) configuration

20181017.038 (AEF10)
Standard (EJM) configuration



Mask R-CNN: T1 (heating start) → T4 (heating termination)
Visualize every 5th image

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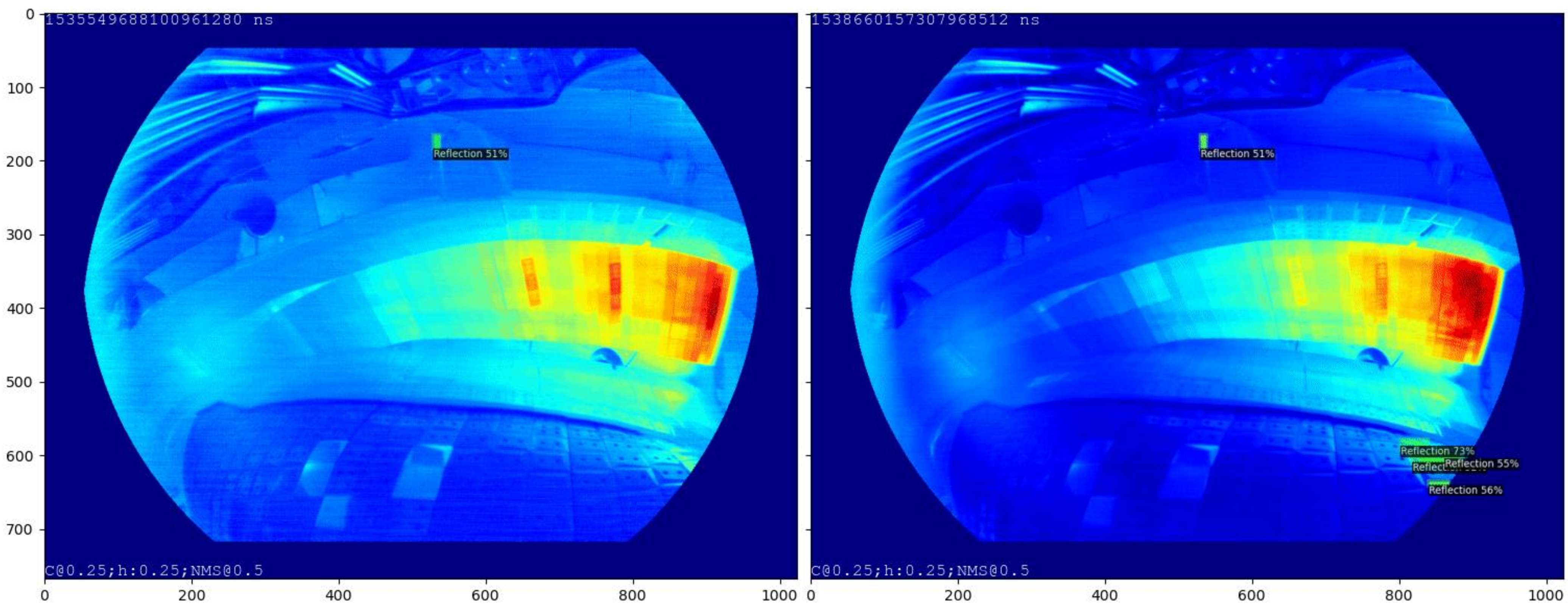
Instance Segmentation - Qualitative Results

20180829.040 (AEF51)
Low-iota (DBM) configuration

20181004.032 (AEF51)
Low-iota (DBM) configuration



YOLOv8: T1 (heating start) → T4 (heating termination)
Visualize every 5th image

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Instance Segmentation - Quantitative Results

Model	# Params	Bounding-Box		Mask		TensorRT inference [ms] w/o pre- & post-processing
		mAP	AP@50	mAP↓	AP@50	
Mask R-CNN	45.3 M	29.89	62.92	**34.23**	66.58	-
YOLOv8 (medium)	27.2 M	**43.90**	71.10	33.20	63.50	20.76
Cascade Mask R-CNN	71.8 M	30.54	61.52	33.19	64.21	-
YOLOv8 (small)	11.8 M	41.60	68.90	31.50	62.20	**9.39**
MaskDINO (DETR)	43.8 M	22.66	54.62	25.43	62.05	-

- Smaller models with not significantly reduced performance might achieve **real-time processing**, i.e. faster than the acquisition rate: 100 Hz (10 ms)
- More annotated discharge sequences will be used for training to advance the performance
- Leading edges (few pixels) are significantly harder to detect/segment than other events; their annotations will be improved
- Transfer to different devices and experimental campaigns
- Additional data sources might be included

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Summary

- Processing of images from VIS or IR cameras requires a **flexible and scalable hardware platform**
- **FPGA and GPU** could be used for executing AI-based algorithms
- Looking for **low latency solutions** working with MPx cameras
- Developed frame grabbers supporting various camera interfaces
- Developed universal software framework based on GenICam
- Developed a dedicated solution based on **NVIDIA GPUDirect RDMA** solution that significantly reduces the total image processing latency and releases the CPU
- Working on real-time AI algorithms and design methodology

Looking for imaging solution – contact with us ☺

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Thank you for your attention

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