MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

W7-X Control, Data Acquisition and Communication using mTCA for the 2022/23 campaign

Wendelstein 7-X

A. Winter for the W7-X CoDaC Team

D.Makowski, P. Perek, A. Mielczarek, B Jablonski DMCS Lodz University

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Overview

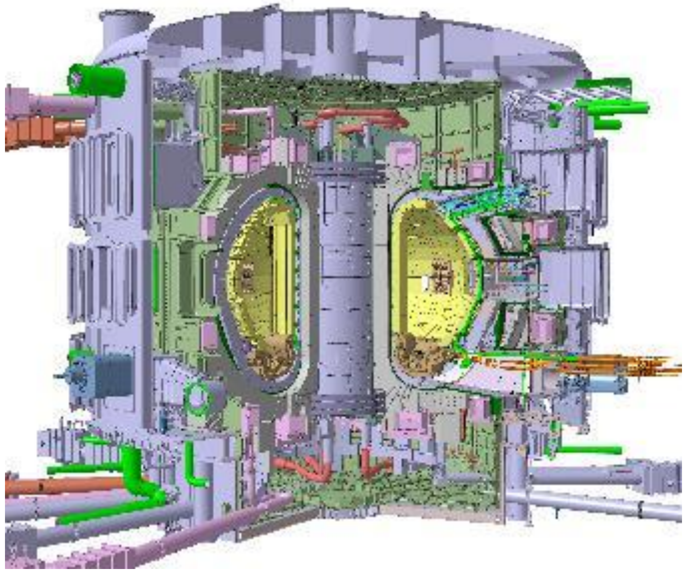
1. **Introduction to W7-X**

2. **Overview and results of work done for the 2022/2023 campaign**

3. **Outlook and Conclusion**

Tokamak and Stellarator

Tokamak (axisymmetric)



Plasma current

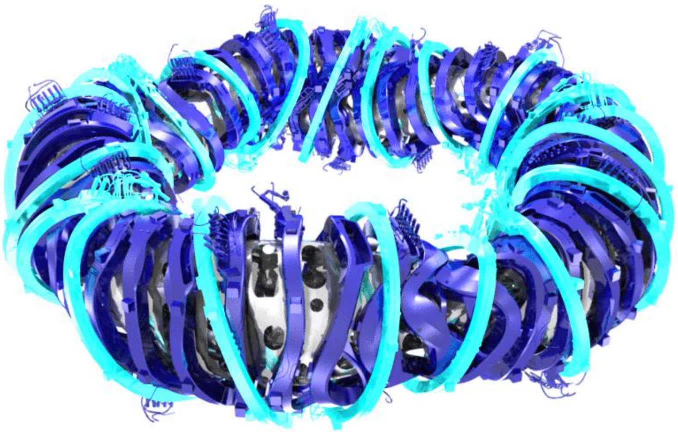
+ good heat isolation

+ high degree of symmetry

- Transient operation (longer pulses with external current drive)

- Current-driven instabilities (active control essential)

Stellarator (3D)



external currents only

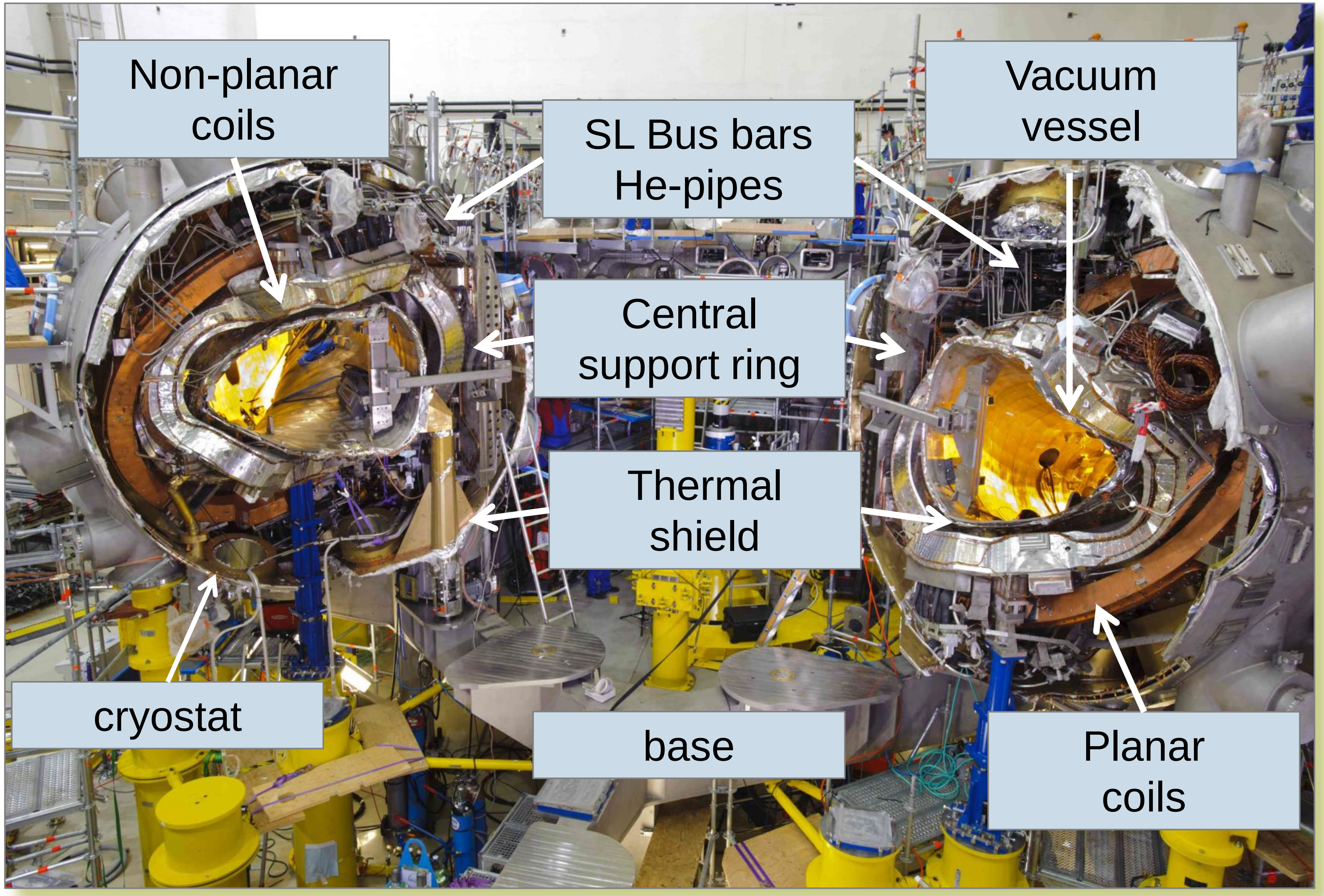
- bad heat isolation (improved by optimizing design)

- no real symmetry (quasi-symmetry with improved design)

+ steady state operation

+ no current driven instabilities

Brief Overview of Wendelstein 7-X



- 10 years assembly
- First plasma 2015
- Actively cooled divertor installation 2018-2022
- Restart of operation 2022

CoDaC state of affairs 2018

- ~ 10 years design phase before first plasma in 2016, followed by 2 actual operation campaigns
  - Key requirements were specified during the “concrete and steel phase”:

1. W7-X will operate few 30 min discharges as standard scenario with few diagnostics
   - Data streaming essential, no local buffering
   - Segment concept essential (sub-dividing discharge into independent experiments)
2. “A Stellarator does not need control”
   - Only very limited real-time control capability (mainly density control, heating & fuelling)

Real life after 2 operational campaigns with lots of lessons learned:

1. Preferred mode of operation: 50+ shorter discharges per day with 40+ systems to orchestrate
2. Real-time protection of actively cooled components required,
3. density feedback with > 5 diagnostic inputs and multiple actuator systems (pellet fuelling and gas)

Our to-do list for the 2018-22 shutdown

- Significantly expand fast interlock system: Divertor and first wall protection
- Expand the central safety system to accommodate new systems and incorporate lessons learned
- Port real-time control from VxWorks to RT-Linux and expand with feedback and protection
- Major refactoring of the central configuration system to accommodate the mass of additional systems
- Double network streaming capacity (40 GB/s) and storage (8 PB)
- Re-implement central safety system to accommodate lessons learned from operation: Need more and different modes of operation for commissioning
- Integrate ~20 new diagnostic systems
  - Set and enforce generic standard hardware platform (mTCA.4) and standard for camera-based diagnostics
  - Integrate 24+ state of the art IR and Vis Cameras as well as the protection algorithms and real-time data compression
  - Develop generic resource interface to facilitate integration of less critical diagnostics

Integration of new systems

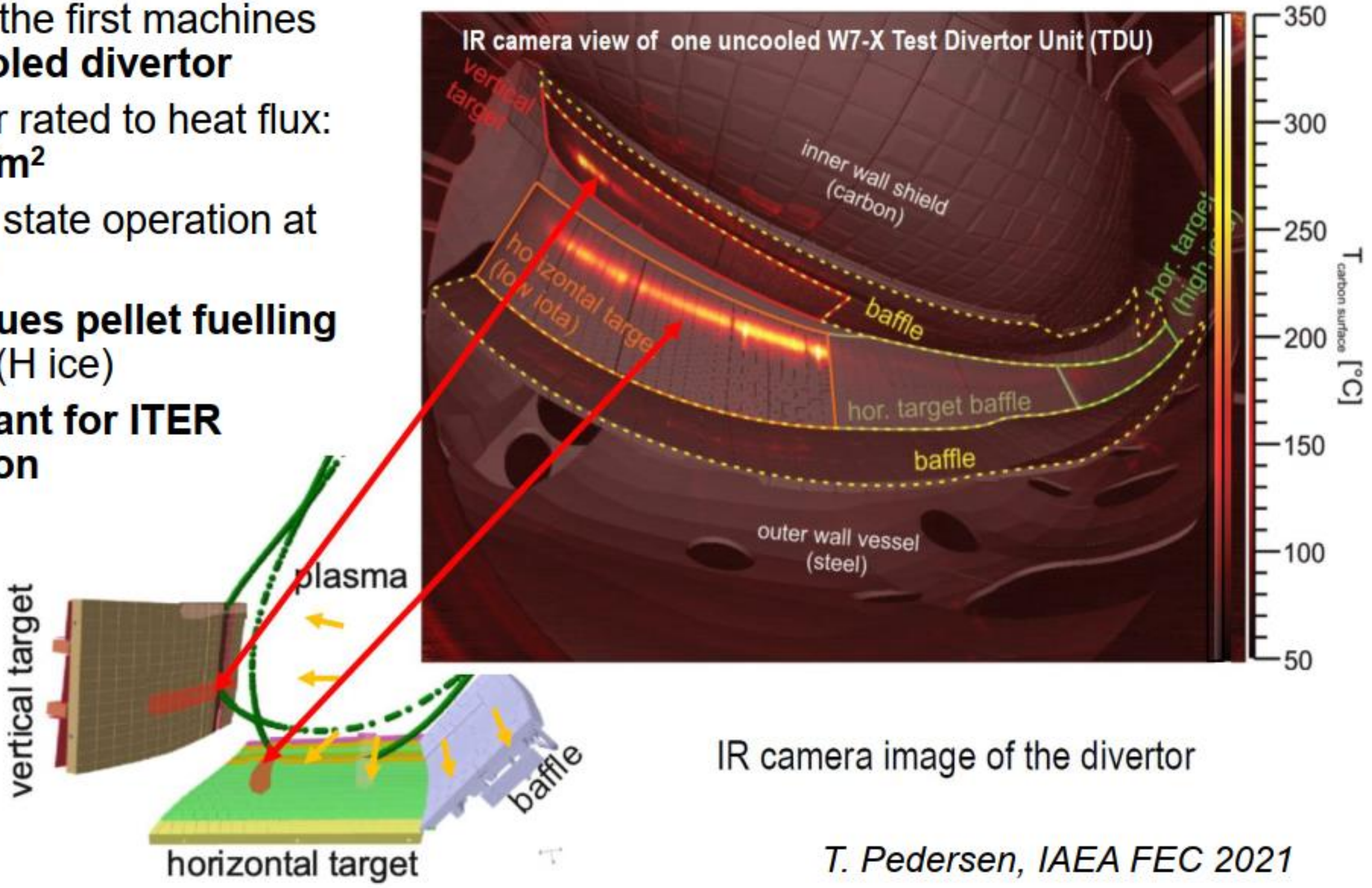
- New heating system: ICRH and extensions to NBI and ECRH
- New fuelling systems: Steady-state pellet injector and divertor gas injection (~20 valves)
- 6 new diagnostics build & integrated by CoDaC
- 15 diagnostics integrated into the CoDaC ecosystem using GeRi

Example: Divertor Protection

- Uses visible and IR cameras and real-time protection algorithms plus the interlock system
- Specs for W7-X 2022/23 campaign
    - 15 visible Cameras Raptor Cygnet (to be replaced with 8 PCO Edge CLHS over time)
    - 2 visible Cameras (PCO Edge CLHS)
    - 9 infrared Cameras IRCAM Caleo (to be replaced with 8 Hercules cameras over time)
    - 4 infrared Hercules cameras
- High-performance hard real-time processing necessary for infrared systems.
- Archiving and live display for visible cameras
- Challenge: How to organize this cost-efficiently, while ensuring performance and flexibility?

W7-X Divertor Protection

- One of the first machines with **cooled divertor**
- Divertor rated to heat flux: **10 MW/m²**
- Steady state operation at 10 MW
- **Continues pellet fuelling** system (H ice)
- **Important for ITER operation**



IR camera image of the divertor

T. Pedersen, IAEA FEC 2021

Complex Structure with complex cooling requirements

- **Divertor tiles**:
  Carbon Fibre Composite (CFC) joined to CuCrZr cooling structure

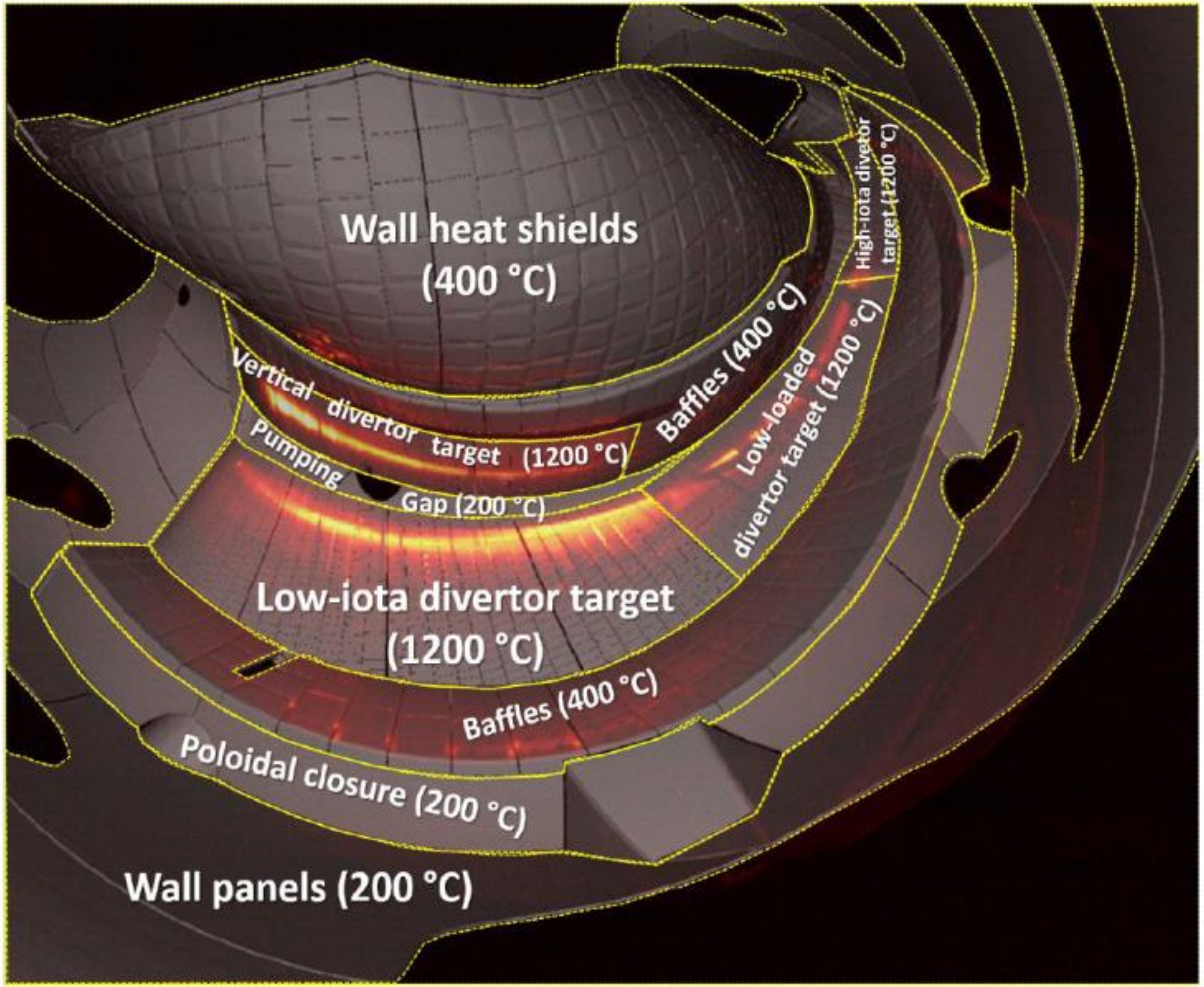
- Max. Operational temperature is limited by a **Cu to 475 °C**

- **Max. surface temperature** is **1200 ° C** for 10 MW/m2

- PFCs (graphite tiles) up to 400 °C

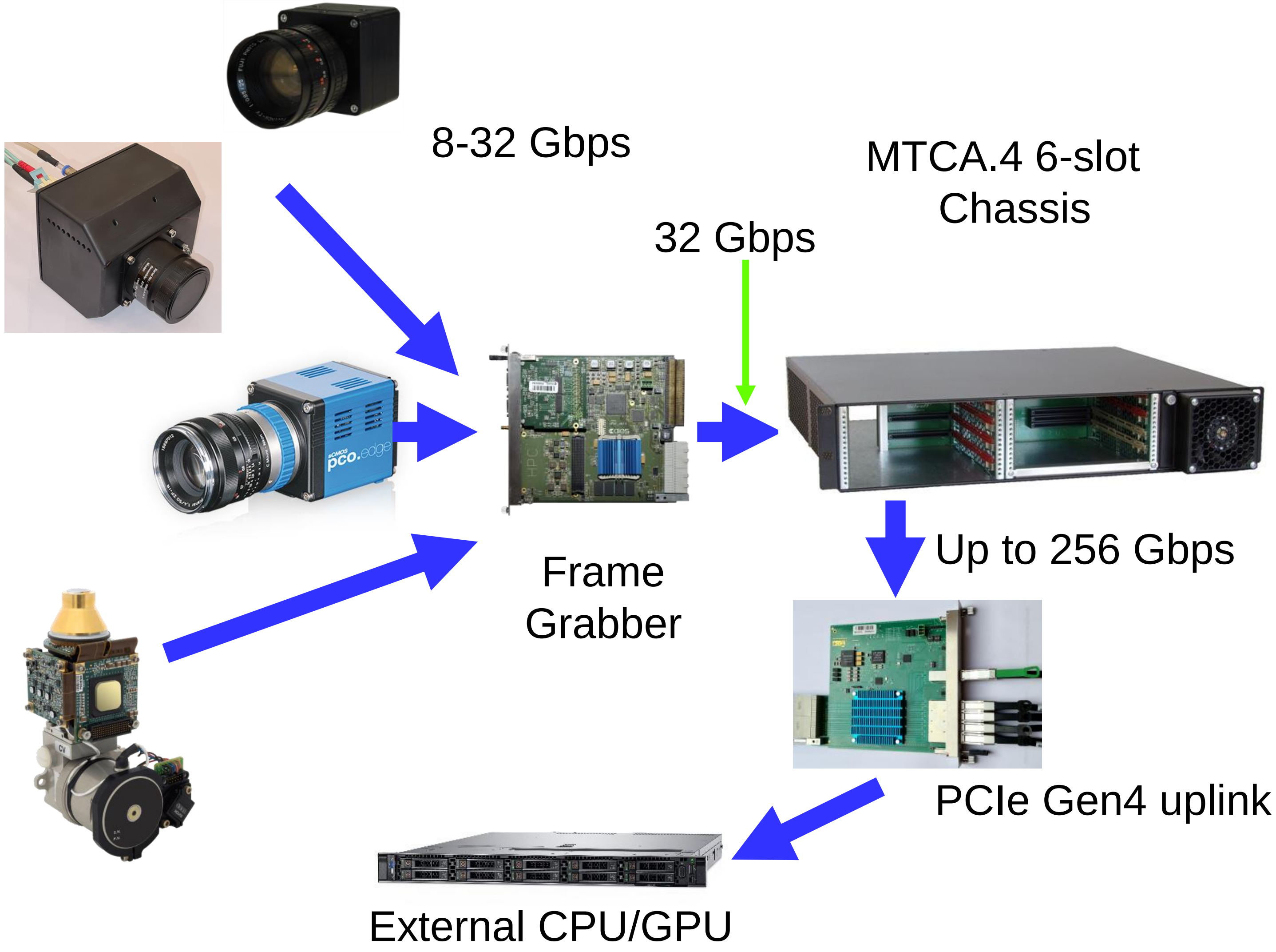
- Wall and pumping gap panels up to 200 °C

A. Puig, IAEA 2021



Highly generic interface required

Image Acquisition and Processing with MTCA.4 – Initial Solution



Micro Telecommunication Computing Architecture:

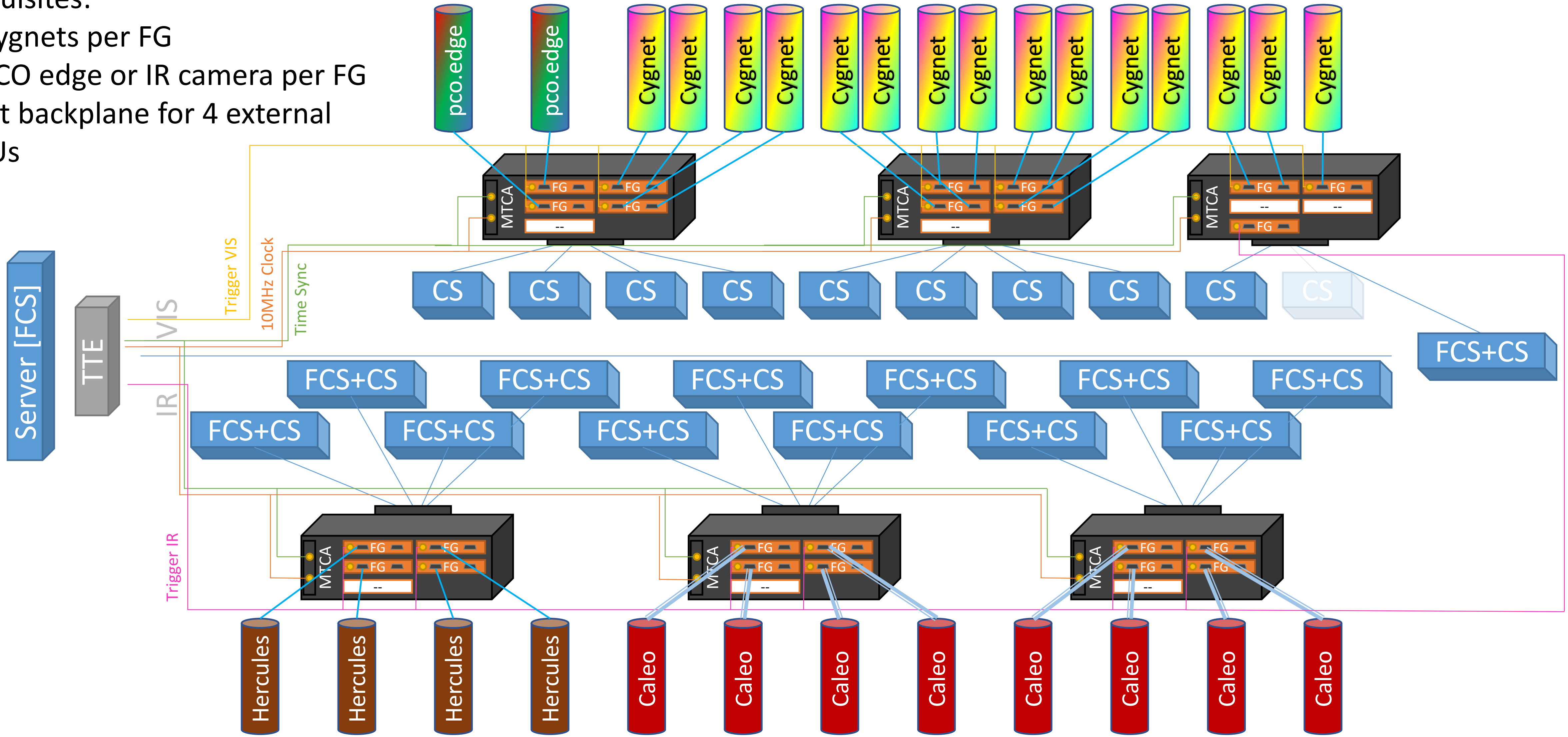
- High RAMI (Reliability, Availability, Maintainability and Inspectability)
- Extensions for precision timing and synchronization
- Intelligent Platform Management
- Good price to performance ratio
- Additional PCIe extender enables use of standard PC with higher throughput
- Now used for practically all new diagnostics with >20 chassis already in use

Courtesy D. Mankowski, DMCS Univ. Lodz

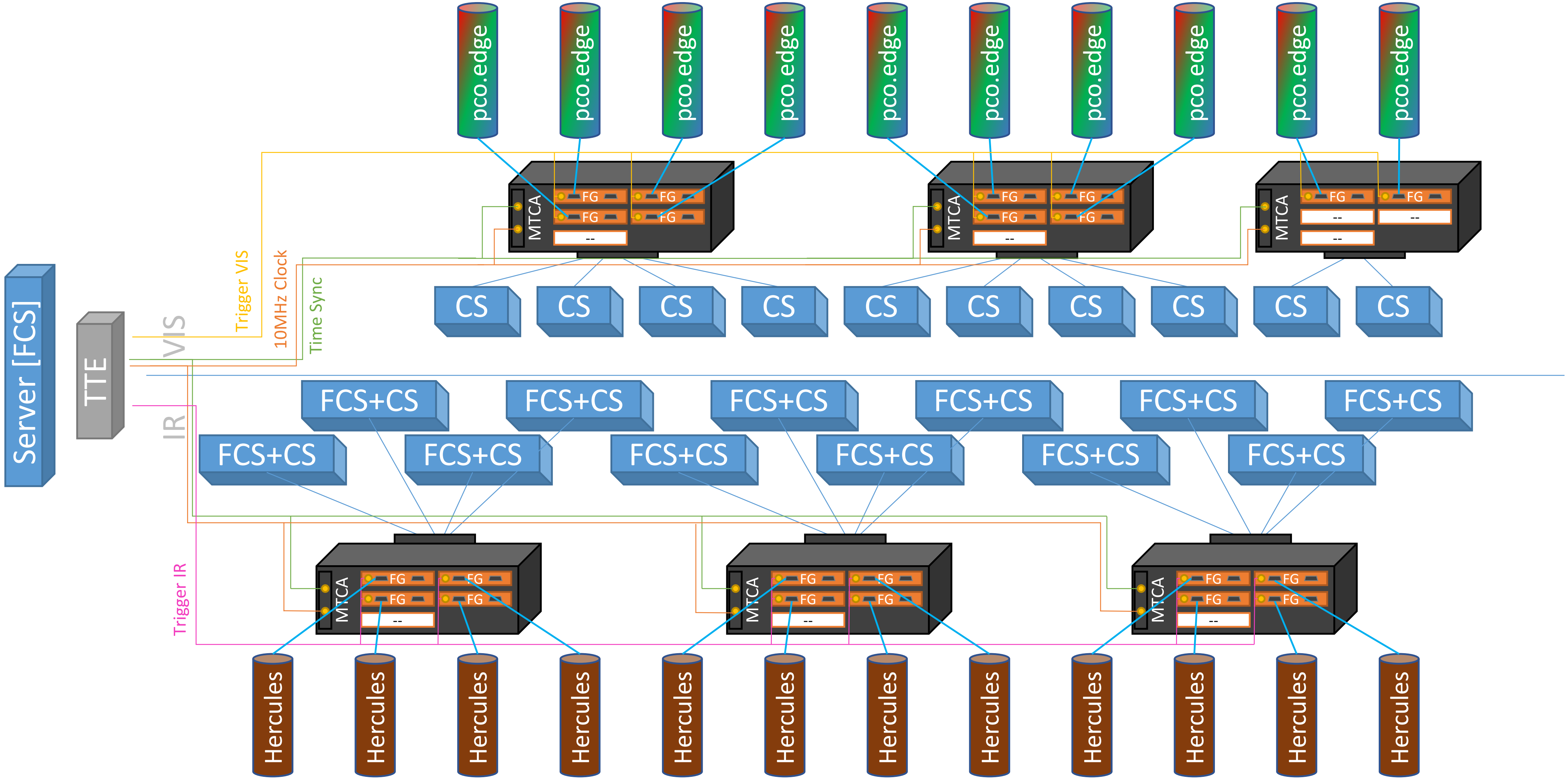
Setup for 2022/2023 campaign

Prerequisites:

- 2 Cygnets per FG
- 1 PCO edge or IR camera per FG
- Split backplane for 4 external CPUs



Final Setup


pco.edge
MTCA
FG
--
CS
Server [FCS]
TTE
VIS
IR
Trigger VIS
10MHz Clock
Time Sync
Trigger IR
FCS+CS
Hercules

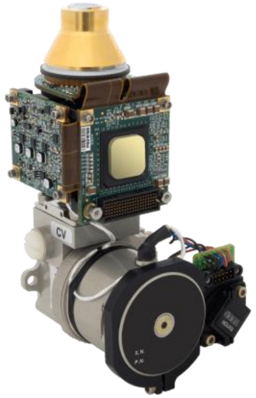
Practically all camera standards supported

- Camera Link — 2.04 Gb/s, 5.44 Gb/s, 6.8 Gb/s
- Camera Link-HS — 2.4 Gbps / 128 Gbps
- CoaXPress 2.0 — n x 6.25/12.5 Gb/s (n=4 → 25/50 Gb/s)
- 1 & 10 GigE Vision — 800M -10 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)

Integration into W7-X done
Integration started

Raptor Cygnet 2.1MP

SCD Hercules (CL)



PCO Edge 5.5

pco.edge Camera Link HS

IRCAM Caleo 768k L

Allied Vision PIKE F-145

Universal Frame Grabber Module

Wendelstein 7-X

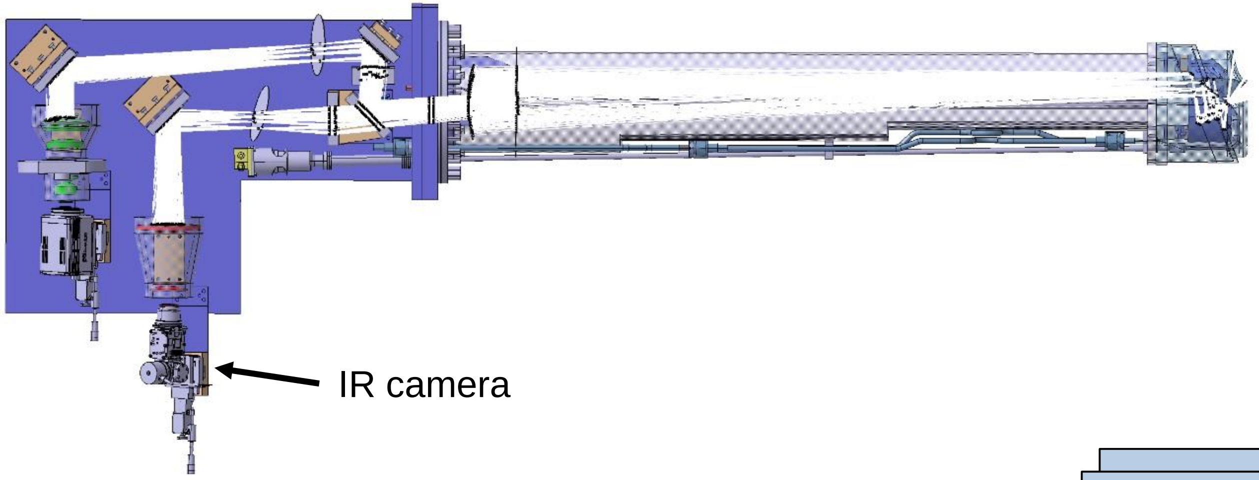
- **Frame grabber** is composed of:
  - FMC carrier
    - **Artix 7 FPGA (<6.5 Gb/s)**
    - **Kintex UltraScale (>6.5 Gb/s)**
  - FMC modules supporting various camera interfaces (8 standards)

- **Software support:**
  - IP core for selected camera interface
  - Common Linux driver
  - Dedicated camera library (GenICam)

Courtesy D. Makowski, DMCS

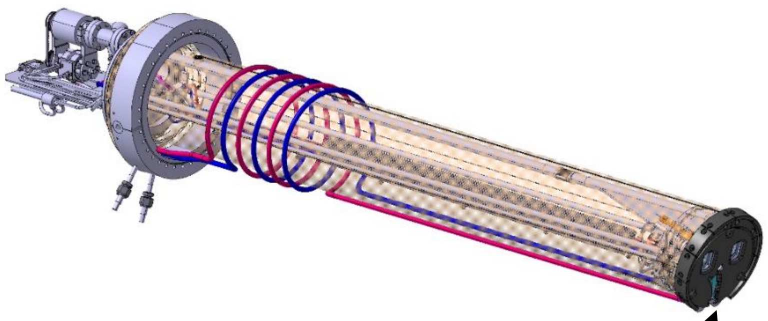
W7-X IR imaging and protection system

High-heat-flux endoscopes

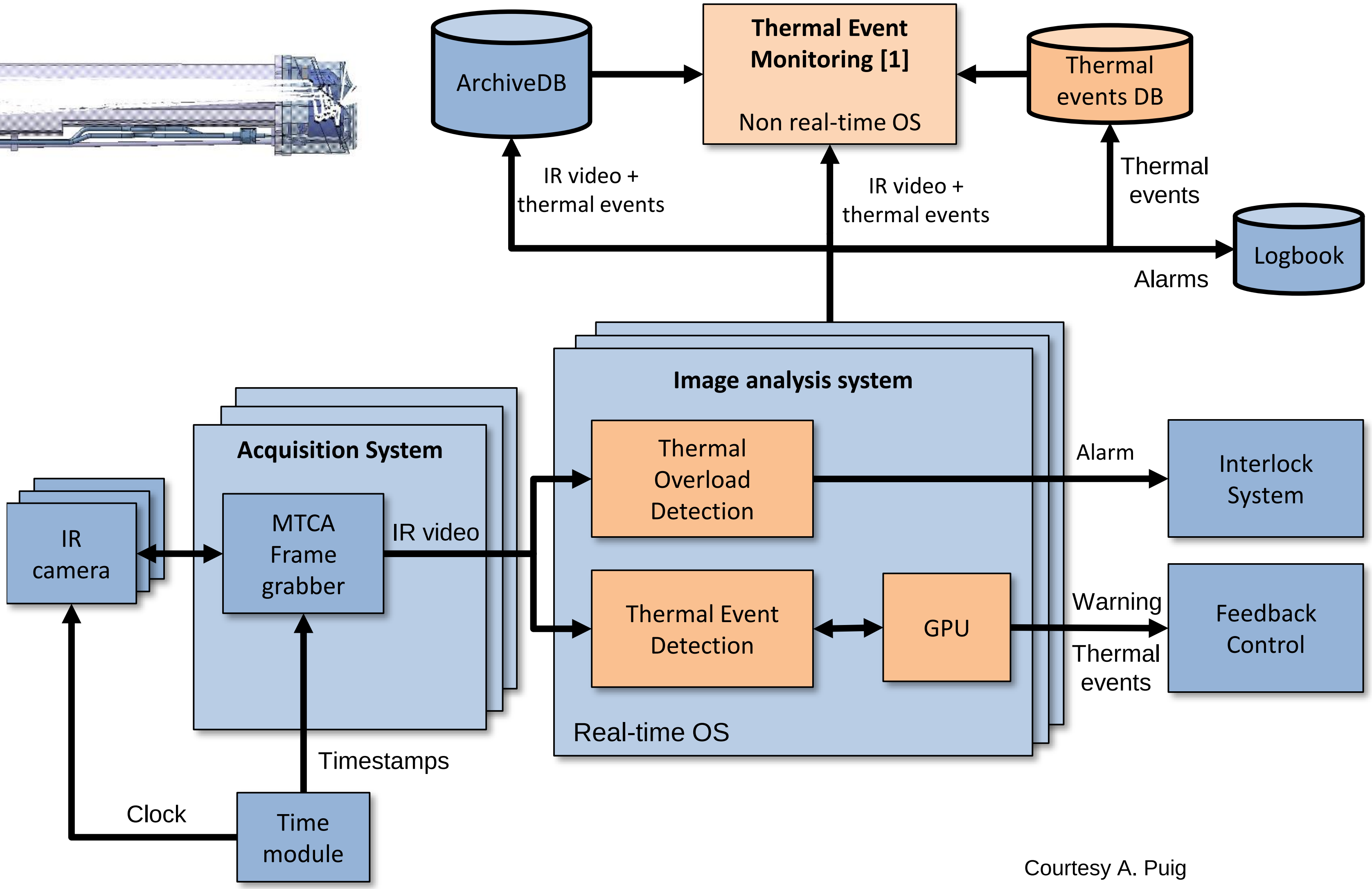


IR camera

Water-cooled immersion tubes

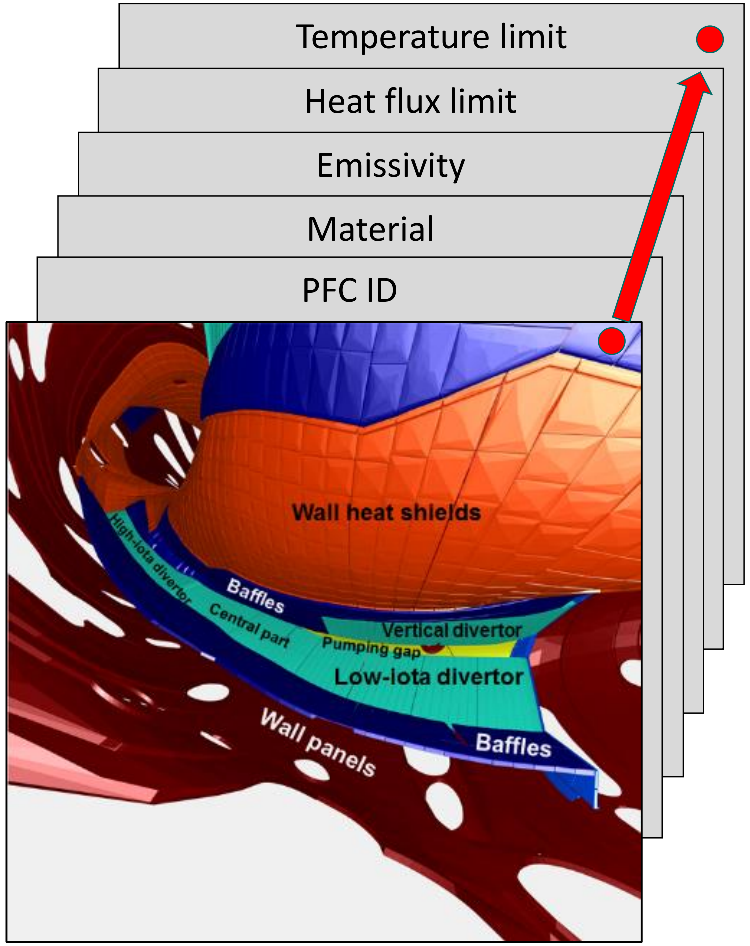


IR camera window



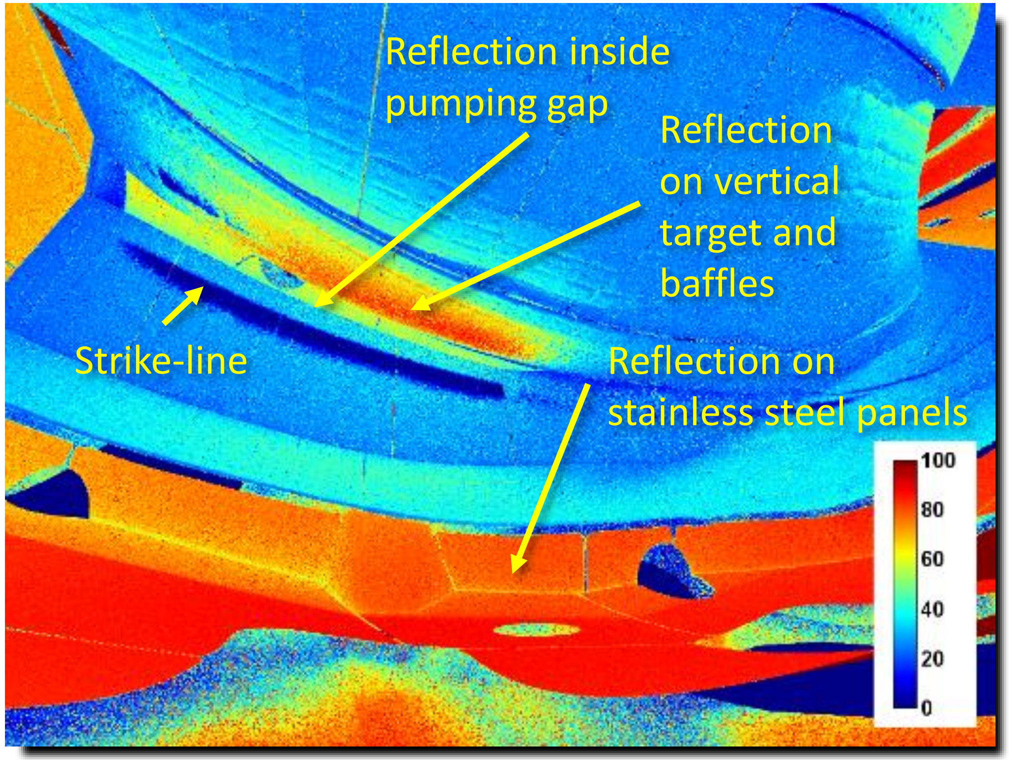
Courtesy A. Puig

Scene models and reflection models



Scene model

- The view is registered against the CAD by modeling the lens distortion [1]
- The scene model provides pixel-wise information of the PFCs properties (emissivity and max. operational temperature)



Reflection model for the standard configuration

- For ech magnetic configuration [2]:

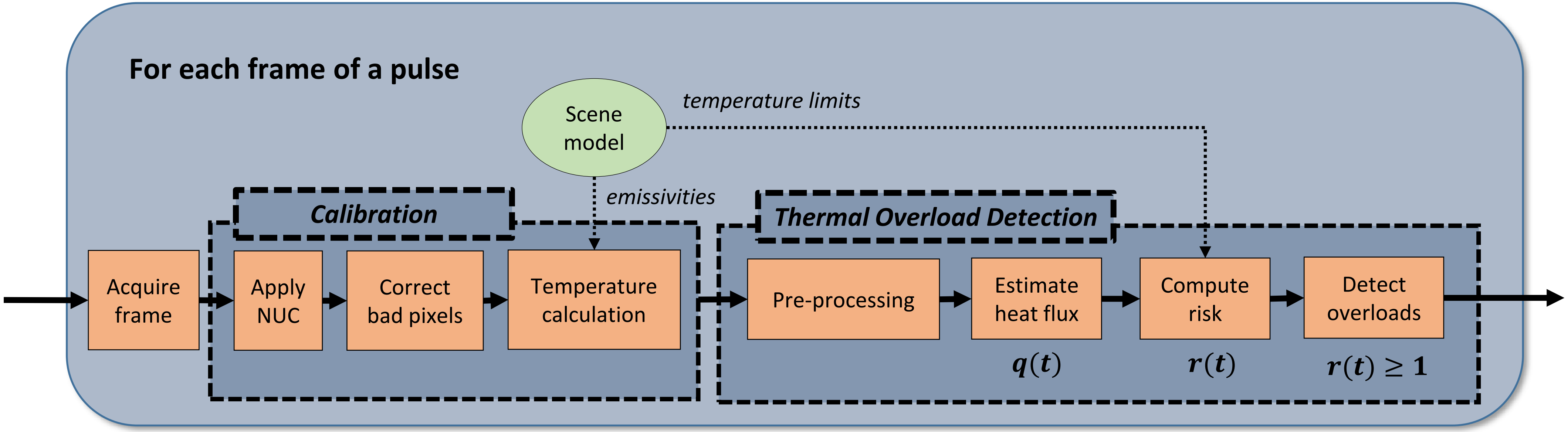
$$\frac{reflected\ flux}{total\ flux}$$

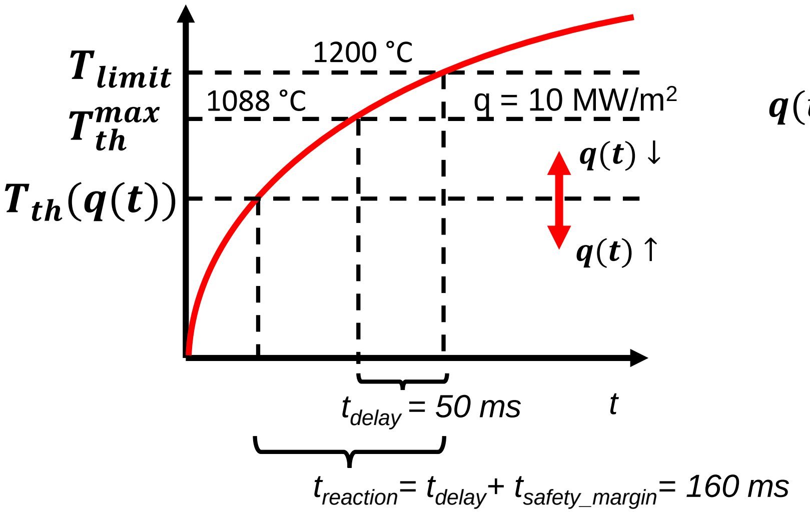
- Static Monte Carlo code
- Long pulse→ dynamic
- AI → real-time

[1] F. Pisano et al., *Tools for Image Analysis and First Wall Protection at W7-X*, Fusion Science and Technology, 933-941, 2020
[2] M-H.Aumeunier et al. *Infrared Thermography in Metallic Environments of WEST and ASDEX Upgrade*, Nuclear Materials and Energy, 2020.

Courtesy A. Puig

Thermal Overload Protection





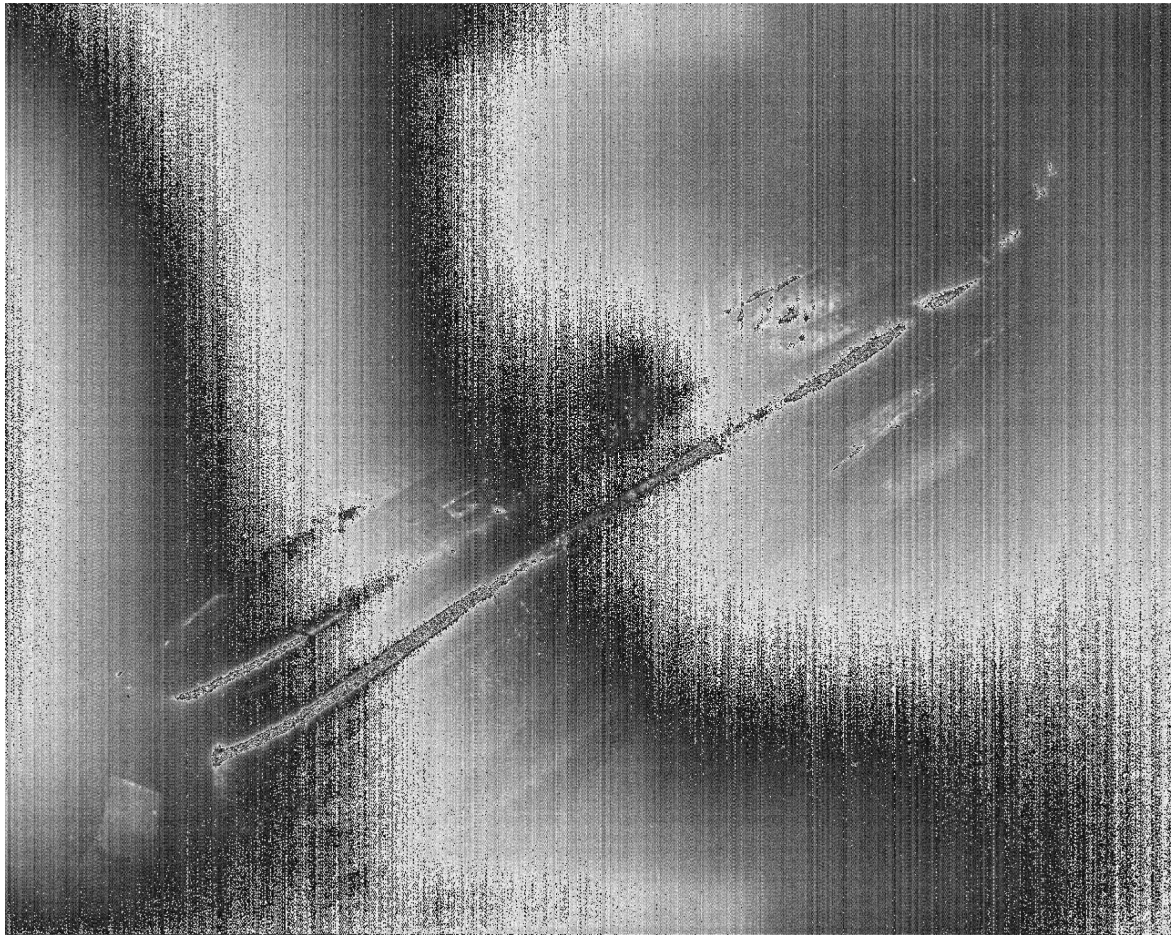
$$q(t) = \frac{\Delta T(t)}{\sqrt{\frac{\Delta t}{C_{material}}}} \Rightarrow T_{th}(t) = min\left\{T_{limit} - q(t)\sqrt{\frac{t_{reaction}}{C_{material}}}, T_{th}^{max}\right\}$$

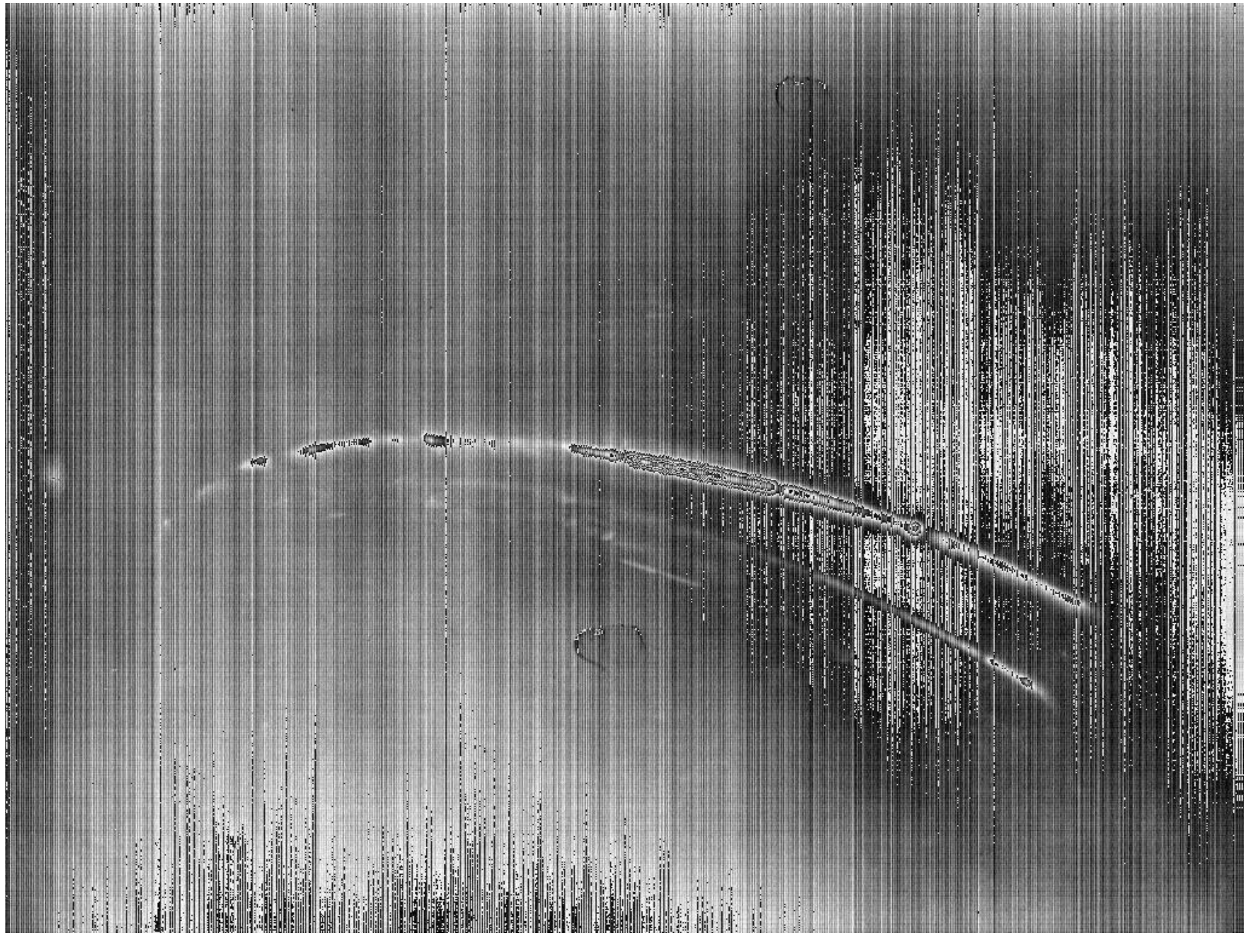
$$\Downarrow$$

$$r(t) = \frac{T(t)}{T_{th}(t)}(1 - S)$$

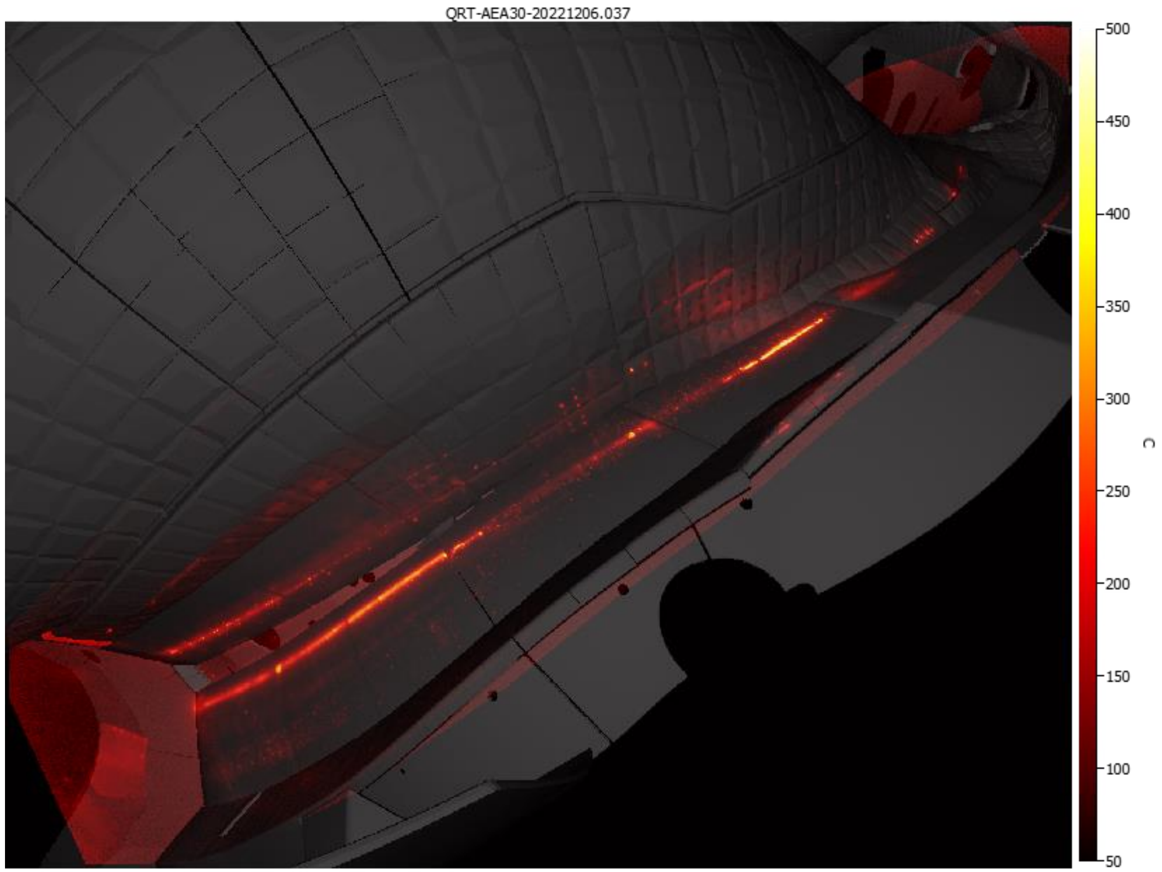
Courtesy A. Puig

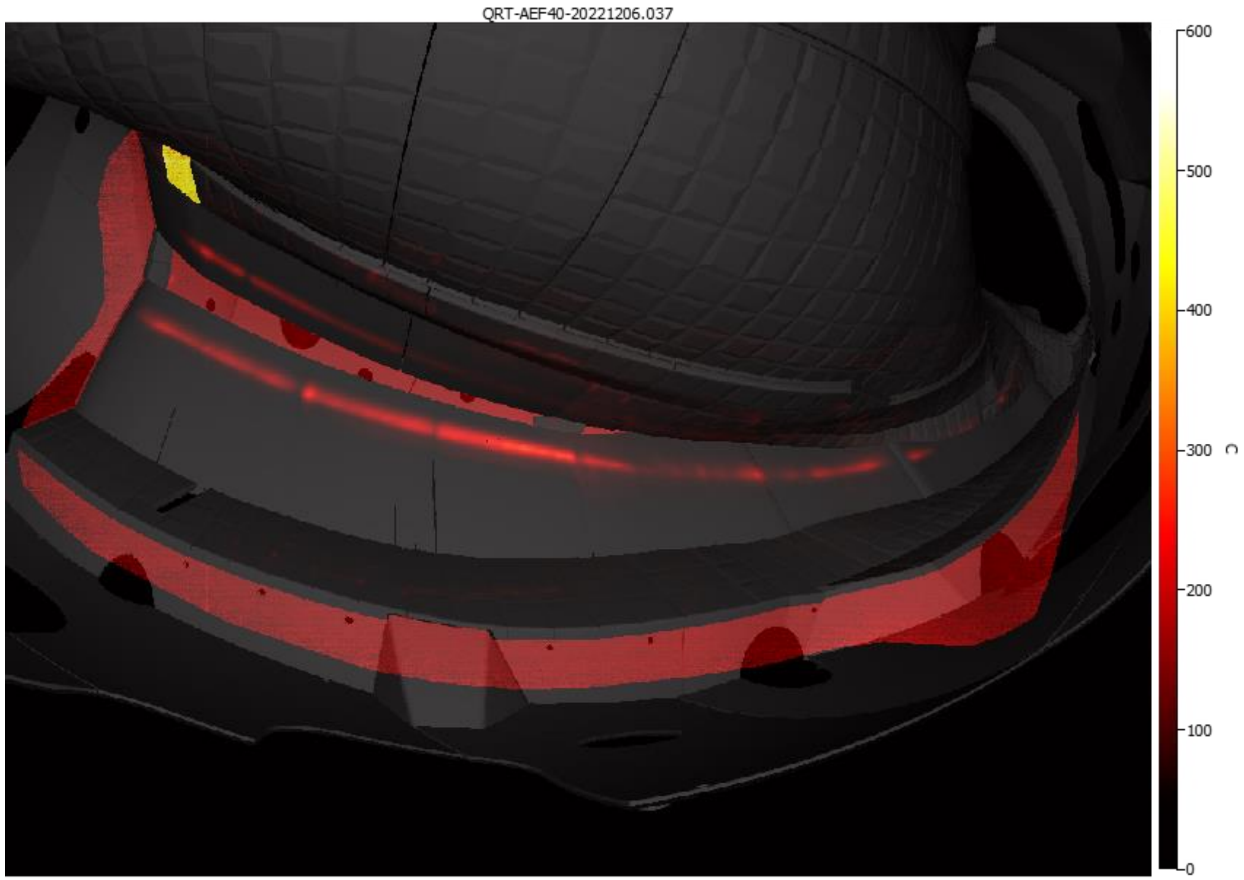
Raw images aka. What is it what we see?



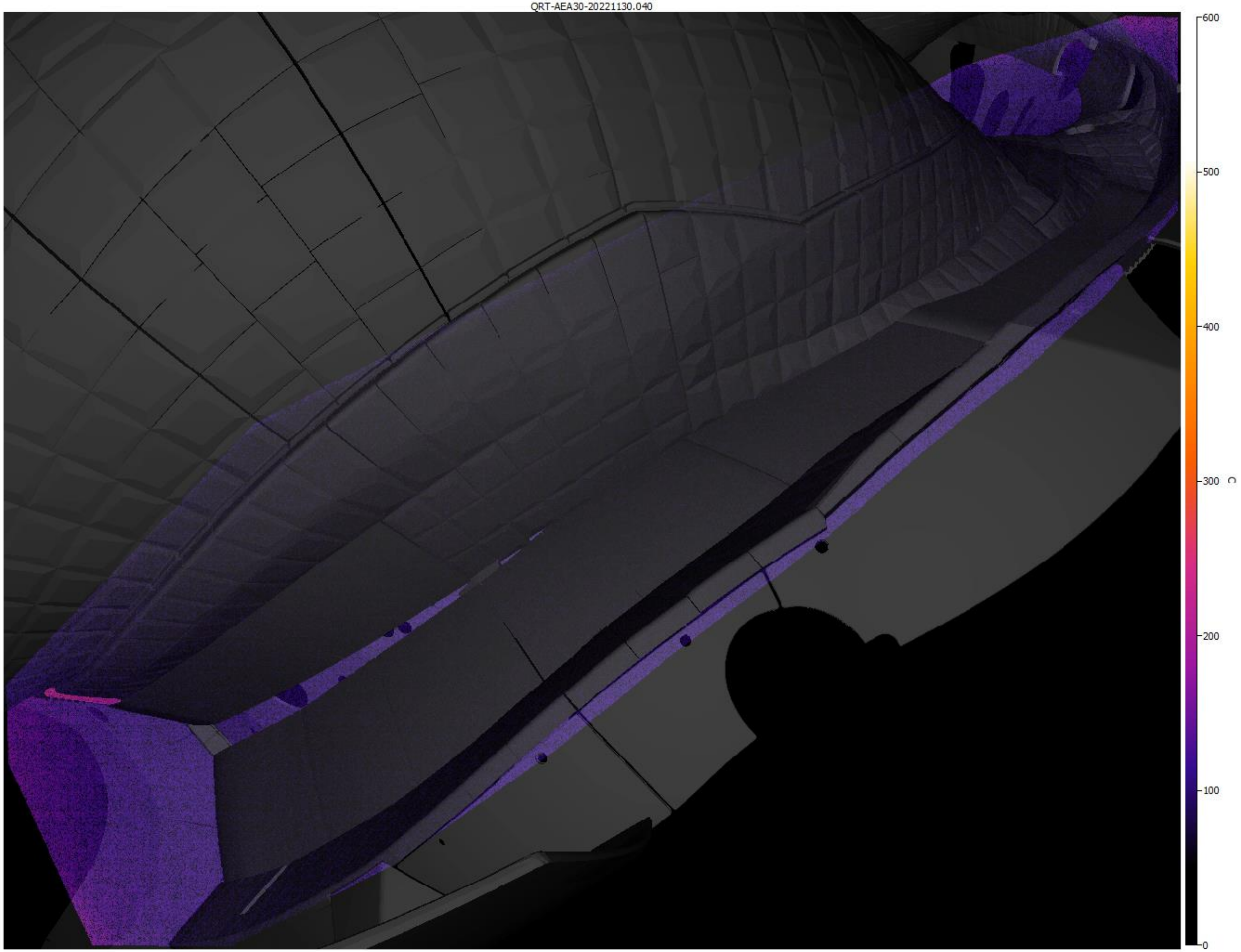


Processed temperature images from the archive





- Courtesy A. Puig Sitjes



- Courtesy A. Puig Sitjes

Legacy Support: Firewire Spectrometer cameras

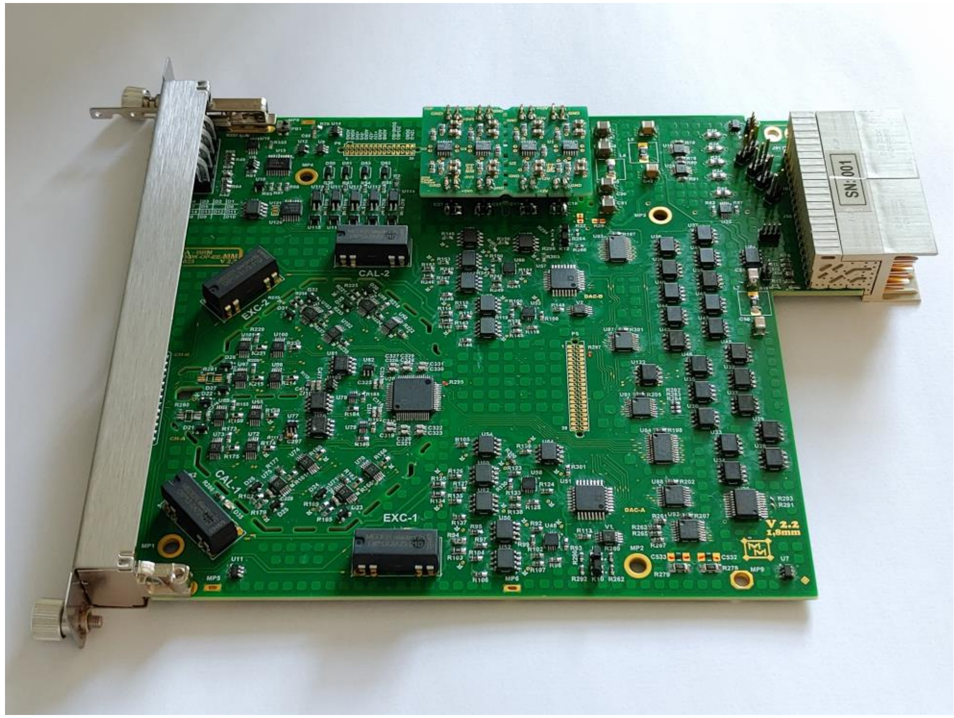
- 25 Firewire based cameras for a “new” spectrometer system
- To help support this, DMCS adapted their Framegrabber and designed the appropriate FMC module to support up to 3 FW cameras per unit.
- Thanks to this, we can implement those cameras using existing drivers and hardware.

Expansion of existing systems: real-time Thomson scattering

- Thomson scattering was a day1 System for W7-X using Teledyne GSPS ADCs and was also our first mTCA system.
- Now, Princeton will add a new set of DAQ to enable real-time analysis of the Thomson scattering data and eventual feedback on temperature profile.
- Thanks to the standardization, this is from the DAQ perspective a very easy extension of the system.

Divertor Bolometer

- 100+ channel bolometer system
- Requires Wheatstone Bridge Data Acquisition with calibration
- IPP internal project to design and manufacture a 2+2 channel analog RTM board
- DMCS provided basicAMC as RTM to PCIe converter with some FPGA processing capability
- Otherwise standard mTCA setup (12 slot shelf, MCH, slot-in CPU)
- Status: prototyping complete, mass production initiated to be operational in the 2024 experimental campaign



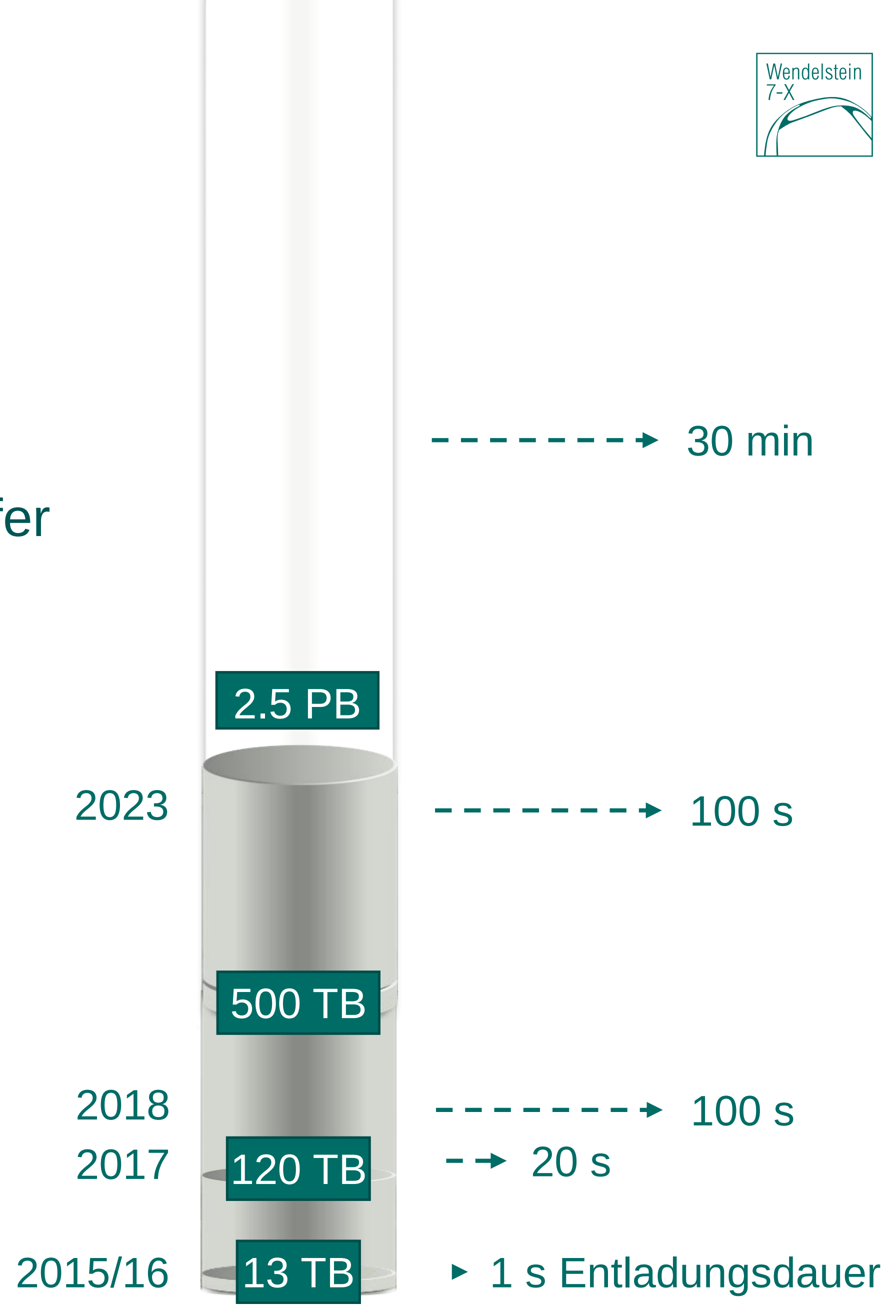
Real-time Data Compression

- Streaming Archiving of raw data necessary due to long-pulses of W7-X (up to 30 mins) → no buffering, average data rate=peak data rate
- To reduce burden and cost on network infrastructure, real-time lossless data compression has been implemented
- Abstracted from user by archive interface
- Using custom built compression codec (https://github.com/google/fusion-power-video)
- Lossless compression of typically 30+ %
- Real-time compression on standard CPU no issue (blade AMC can compress & stream 6.8 Gbit/s without issue)

IR Rohdaten		23.03.2023							
	Breite	Höhe	Anzahl Fram	Rohdaten B	GB	komprimiert B	GB		Kompressionsfaktor
AEK30	1280	1024	392074	1027798466560 B	957,2 GB	418885794723 B	390,1 GB		41%
AEK31	1280	1024	393157	1030637486080 B	959,9 GB	448520930239 B	417,7 GB		44%
AEA30	1280	1024	386930	1014313779200 B	944,7 GB	458254000121 B	426,8 GB		45%
AEA31	1280	1024	385782	1011304366080 B	941,9 GB	516095169961 B	480,7 GB		51%
AEF10	1024	768	381319	599762927616 B	558,6 GB	207098781008 B	192,9 GB		35%
AEF11	1024	768	390163	613673336832 B	571,5 GB	189372308438 B	176,4 GB		31%
AEF20	1024	768	392745	617734471680 B	575,3 GB	185079752095 B	172,4 GB		30%
AEF21	1024	768	389711	612962402304 B	570,9 GB	190338844276 B	177,3 GB		31%
AEF40	1024	768	386145	607353569280 B	565,6 GB	183343113832 B	170,8 GB		30%
AEF41	1024	768	393135	618347888640 B	575,9 GB	192595837970 B	179,4 GB		31%
AEF50	1024	768	387569	609593327616 B	567,7 GB	208497721721 B	194,2 GB		34%
AEF51	1024	768	389176	612120920064 B	570,1 GB	226998324037 B	211,4 GB		37%

W7-X Data Archive

- High Performance GPFS Storage
- 7.9 PB of usable space // 40GB/s continuous data streaming
- Data is directly streamed from the diagnostics via 40G/100G Ethernet to 25 „archive servers“ which transfer the data into the storage
- 3 tier design for a balance of high performance and economic scalability
  - 1st tier for small data and meta data based on NVME connected via Infiniband
  - 2nd tier for large data based on HDD connected via Infiniband
  - 3rd tier for warm data based on HDD connected via 32G Fibre Channel
- Local backup via tape library and distributed backup at another site of MPG



Conclusions

- Operational experience led to a massive change in top-level requirements
- All parts of the central software stack had to be upgraded to address the operation model → massive amount of work
- Implementation of a global hardware standard using mTCA
- Developed camera DAQ system for practically all common camera standards which is deployed for ~25 cameras now and ~50 cameras for the next operational campaign
- 6 new fully developed large scale diagnostic systems
- 20 further systems integrated using a higher-level Interface to central systems
- Real-time data compression implemented in routine operation
- Doubled network streaming bandwidth and storage

Thank you for your attention!

Questions ?