

Thermal loads control with infrared imaging at W7-X

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on behalf of W7-X IR team and

our EUROfusion collaborators at CEA, UniCa, UPC and Lodz Univ.

MAX PLANCK
GESELLSCHAFT



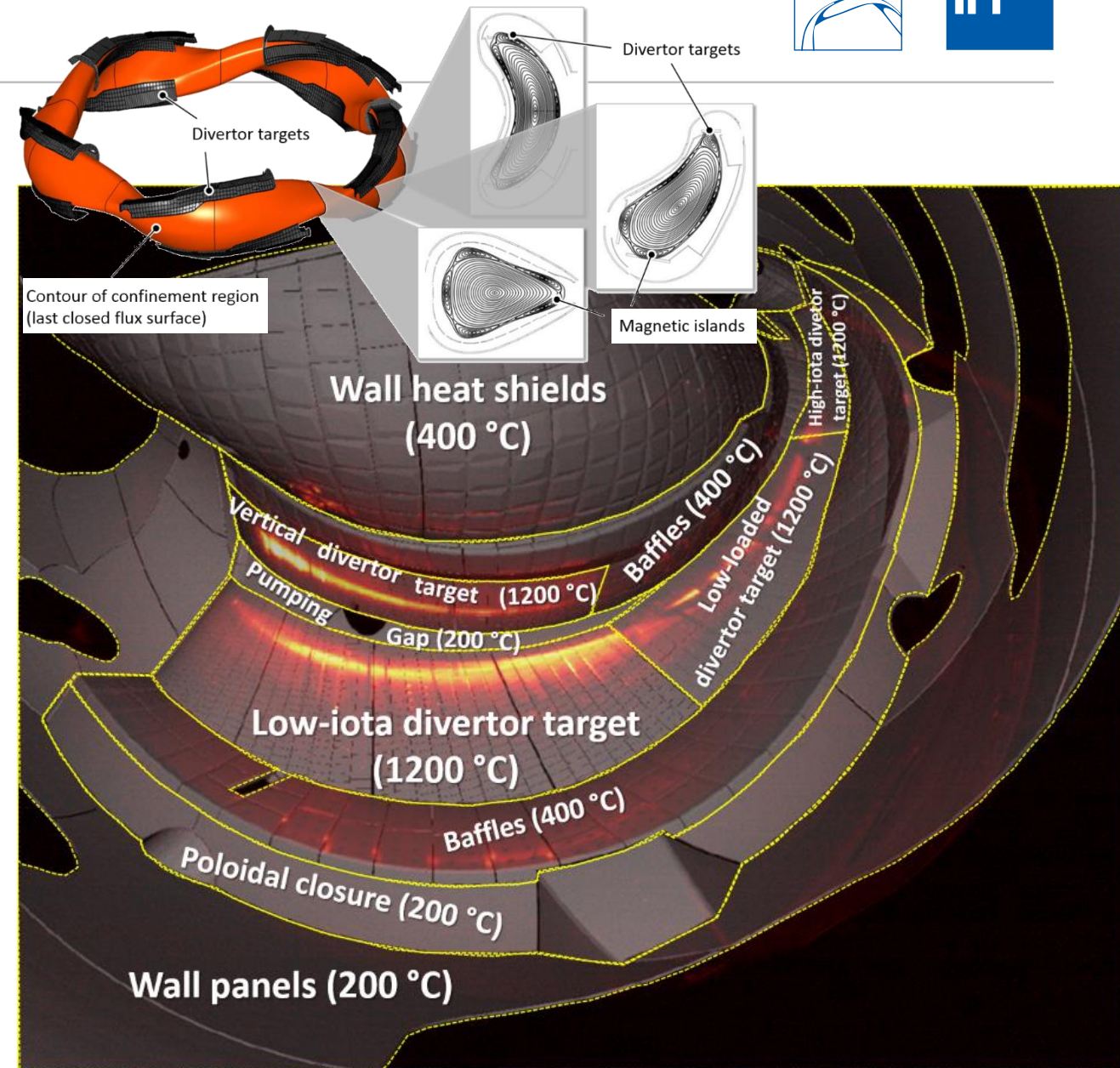
EUROfusion



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Outline

- PFC protection in steady-state
- W7-X IR imaging system
- Towards thermal loads control
- W7-X Thermal Event Detection
- WEST Thermal Event Detection
- WEST + W7-X thermal event database
- Roadmap for OP2
- W7-X strike-line control
- Conclusions

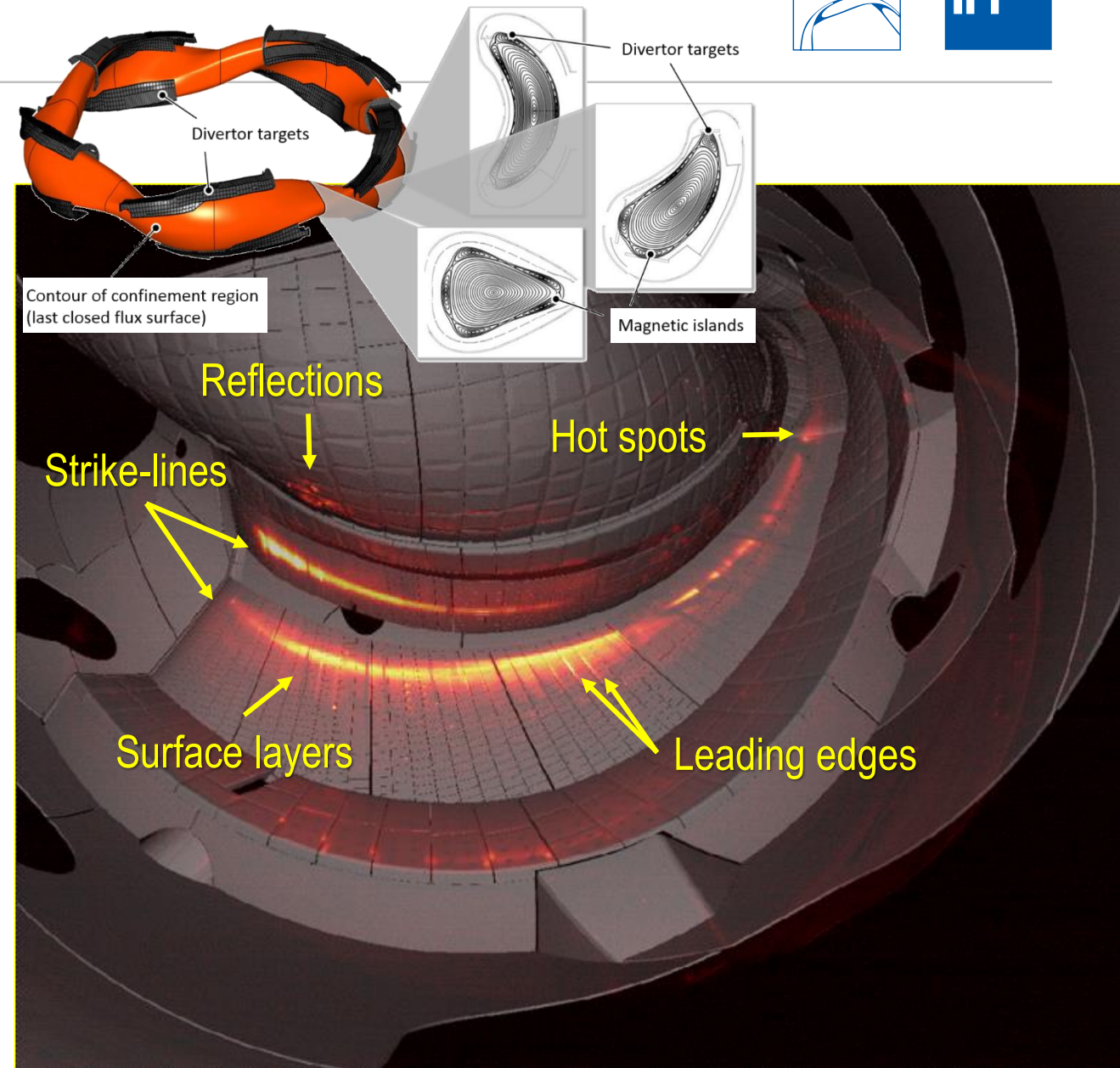


PFC protection in steady-state

- **Current IR protection systems :**
 - Tungsten emissivity issue → **Near IR** ($> 700\text{ °C}$)
 - **ROI-based:** the limits are pre-defined in regions where heat-loads are expected
 - **Reactive:** some action triggered when the temperature reaches the limit.
- **High-performance steady-state** operation poses new challenges:
 - **Thermal loads protection:** Guarantee in real-time that limits of PFCs are not exceeded
 - **Thermal loads control:** intelligently mitigate the overheating threat to avoid premature terminations and achieve long-plasma operation.

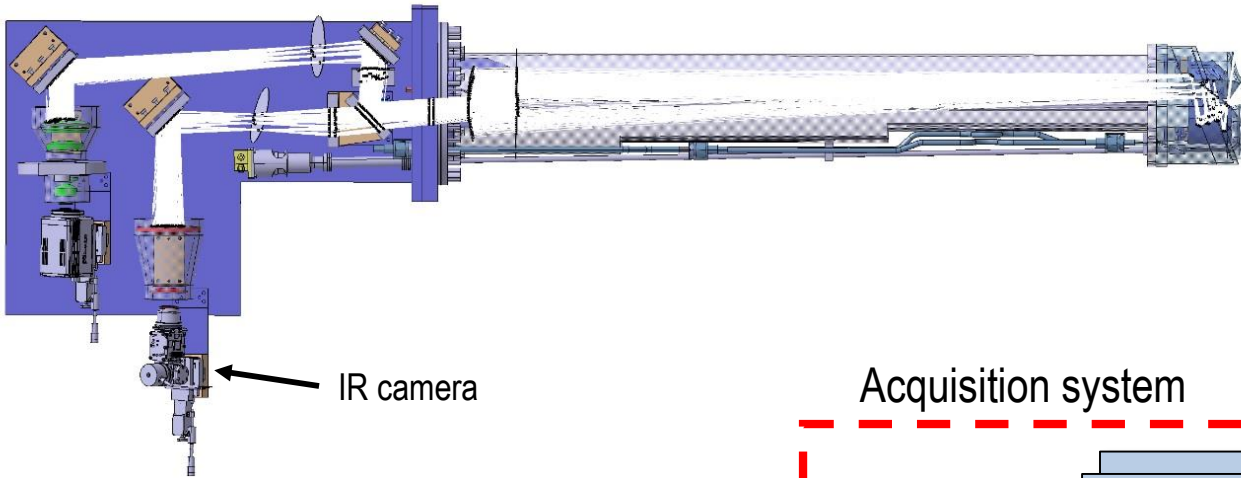


MWIR + predictive



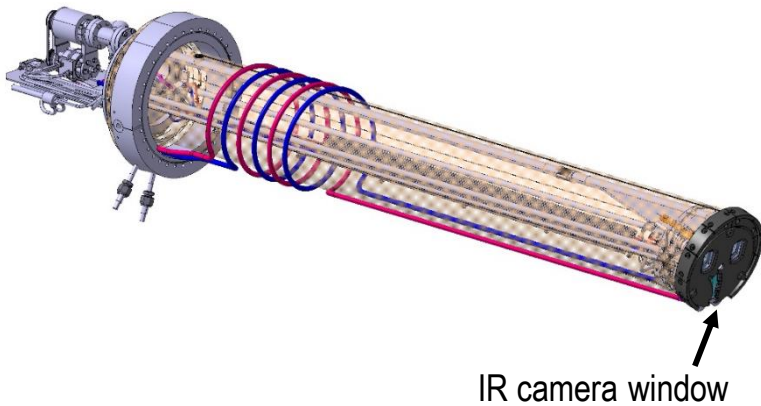
W7-X IR imaging system

High-heat-flux endoscopes



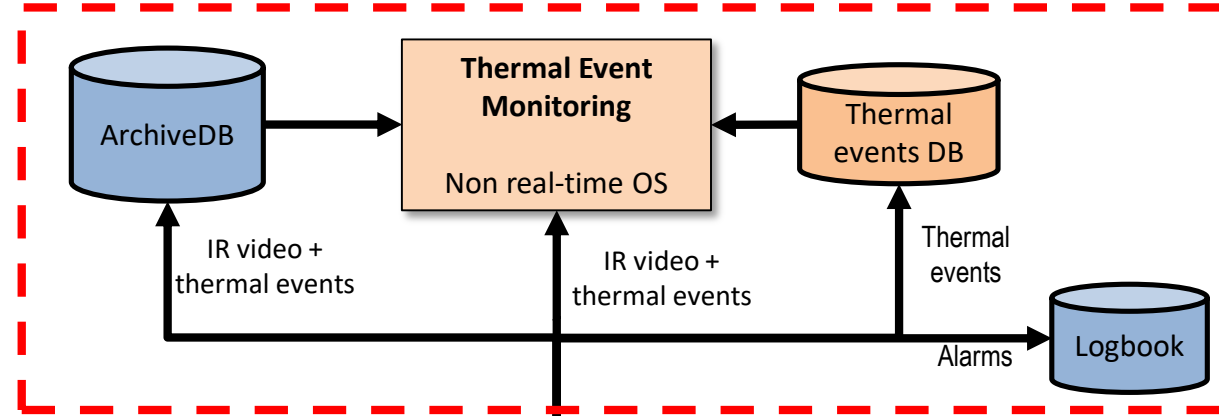
IR camera

Water-cooled immersion tubes

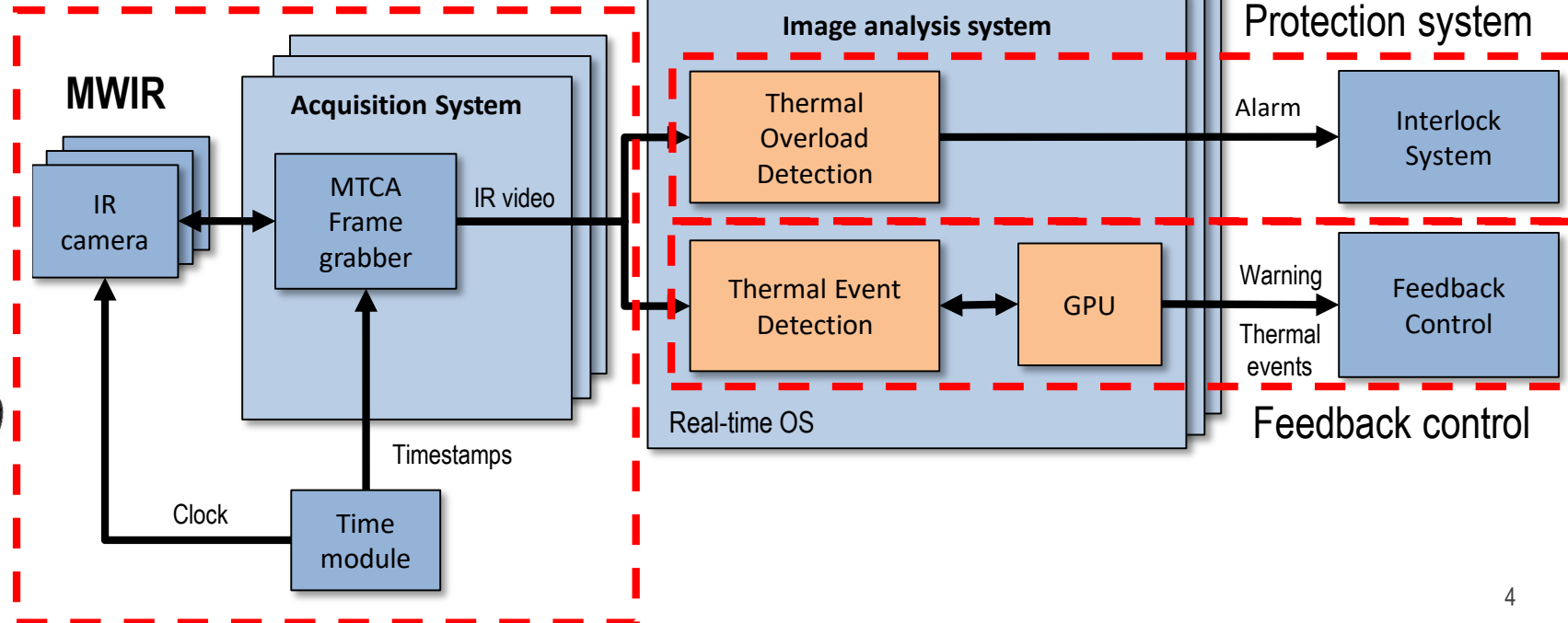


IR camera window

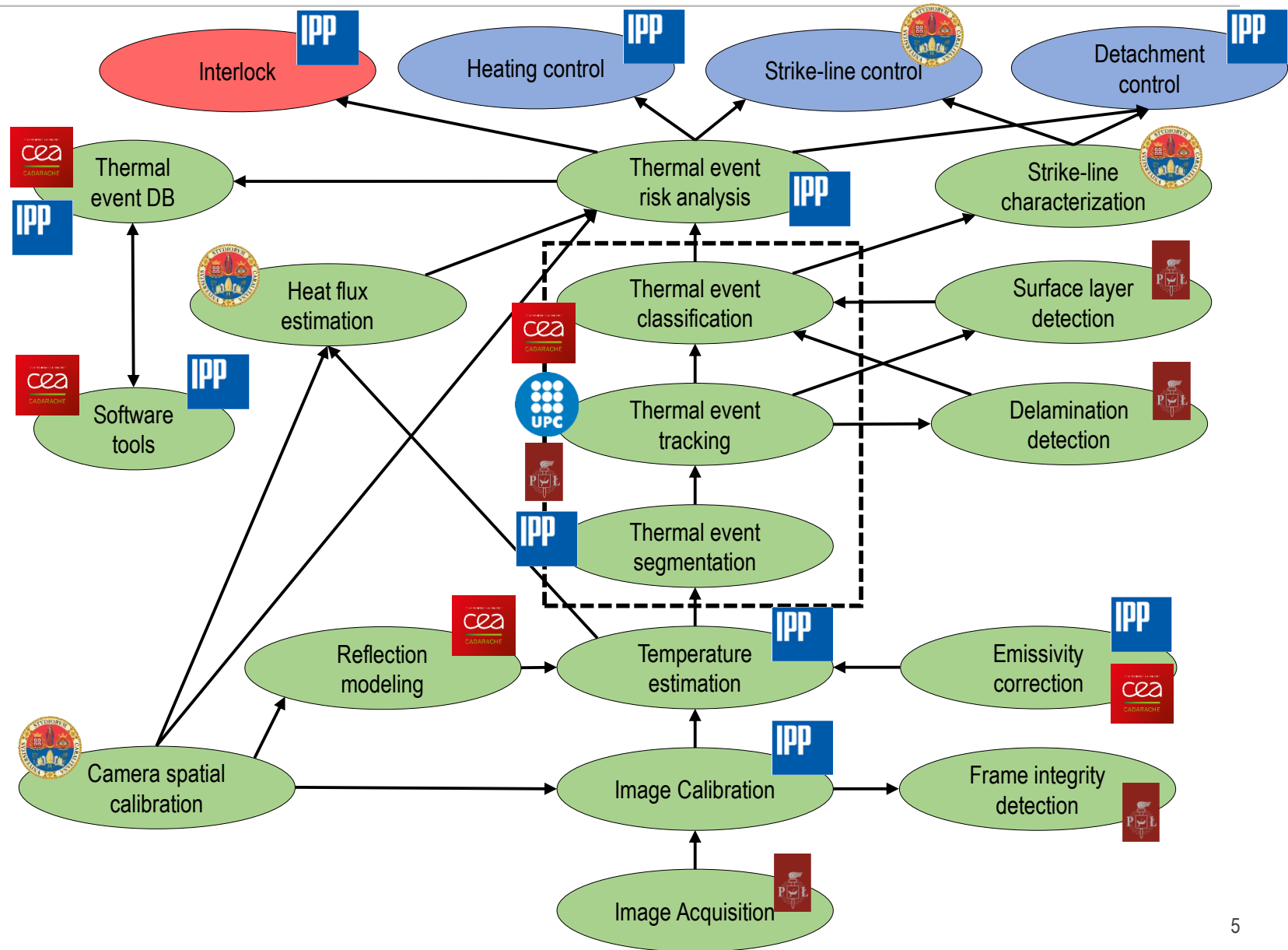
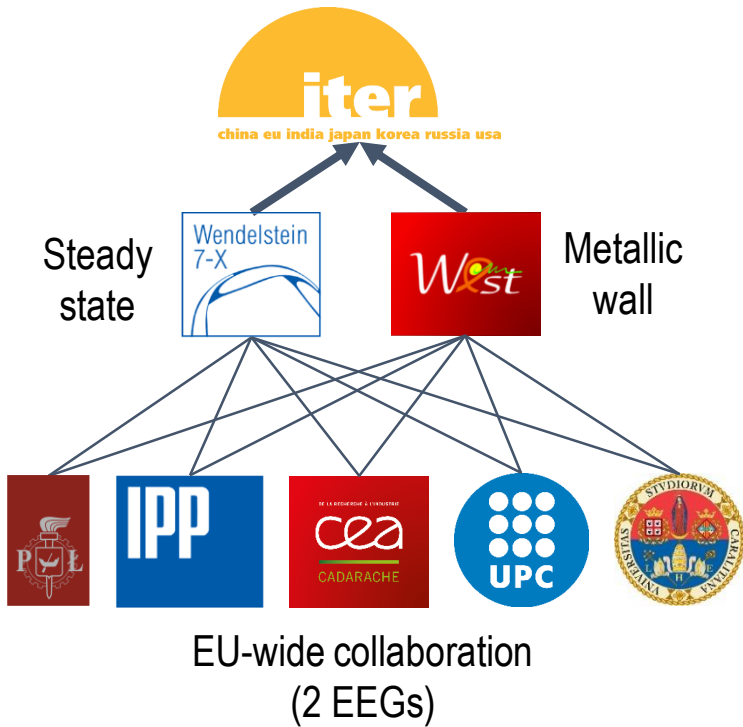
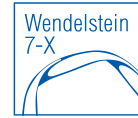
Visualization system



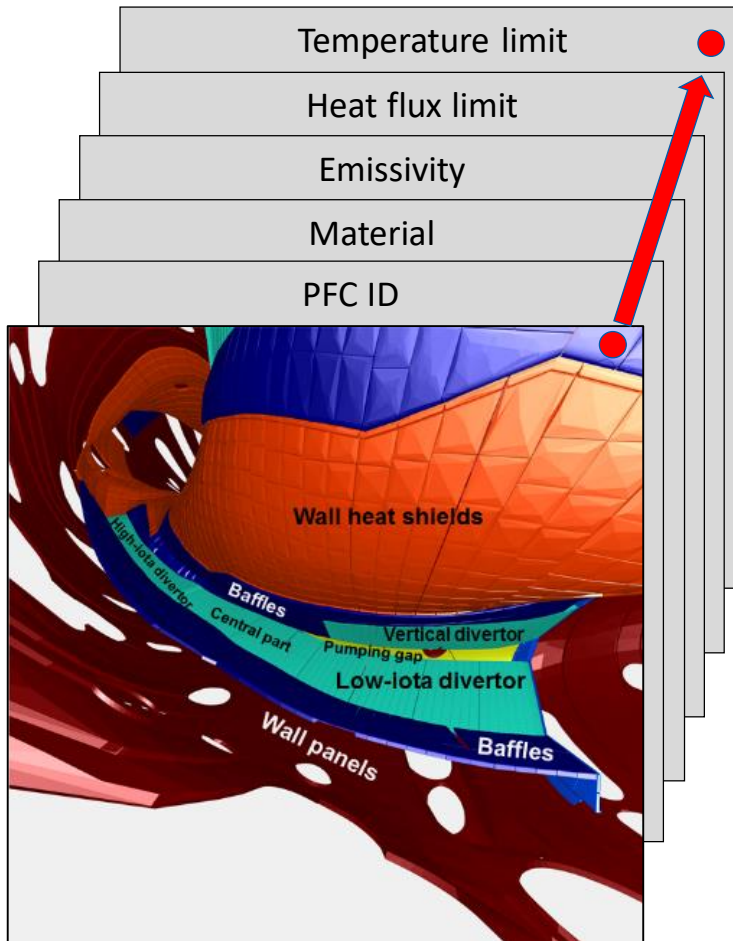
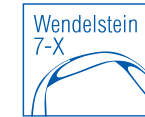
Acquisition system



Towards thermal loads control

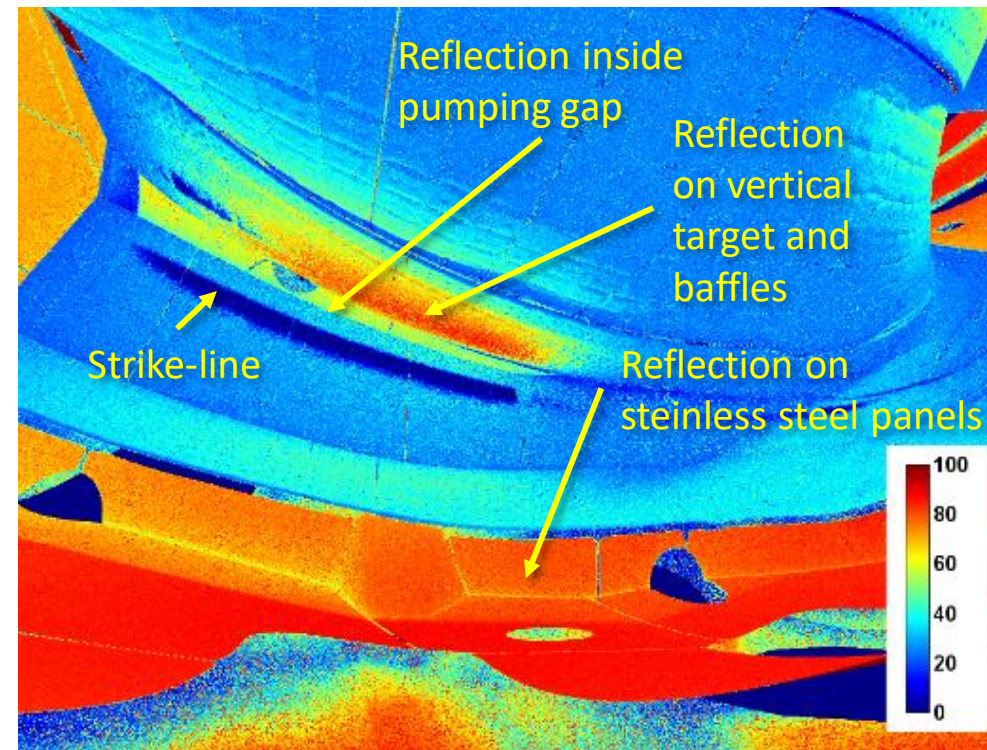


Scene models and reflection models



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

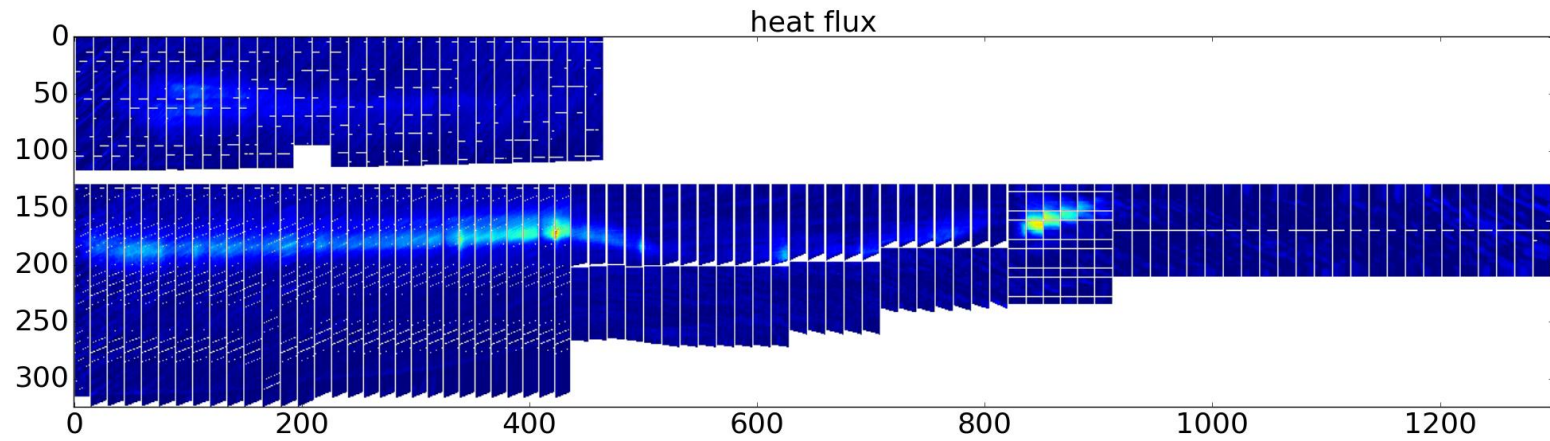
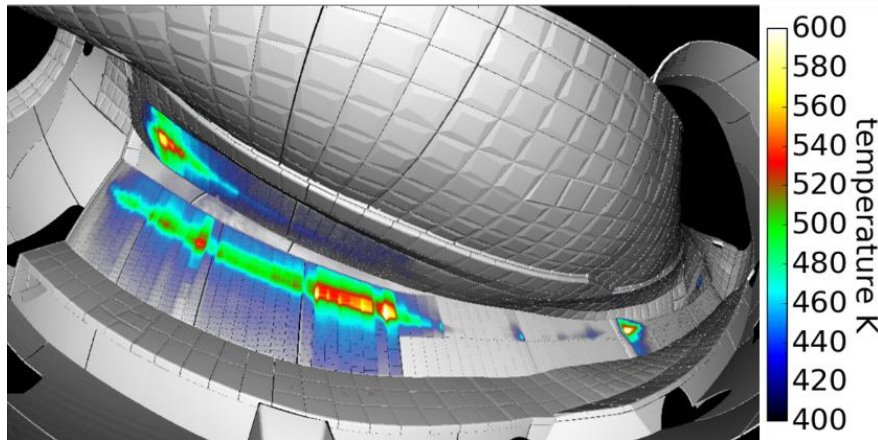
- For each magnetic configuration [2]:

$$\frac{\text{reflected flux}}{\text{total flux}}$$
- Static Monte Carlo code
- Long pulse \rightarrow **dynamic**
- **AI** \rightarrow 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

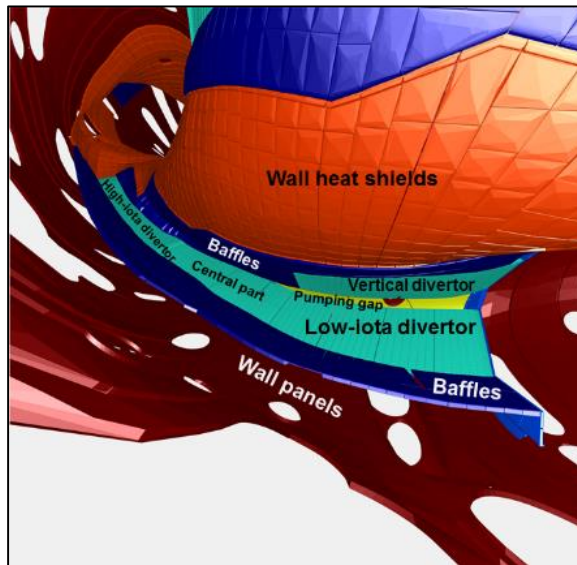
[2] M-H.Aumeunier et al. *Infrared Thermography in Metallic Environments of WEST and ASDEX Upgrade*, Nuclear Materials and Energy, to be published.

Real-time heat flux estimation

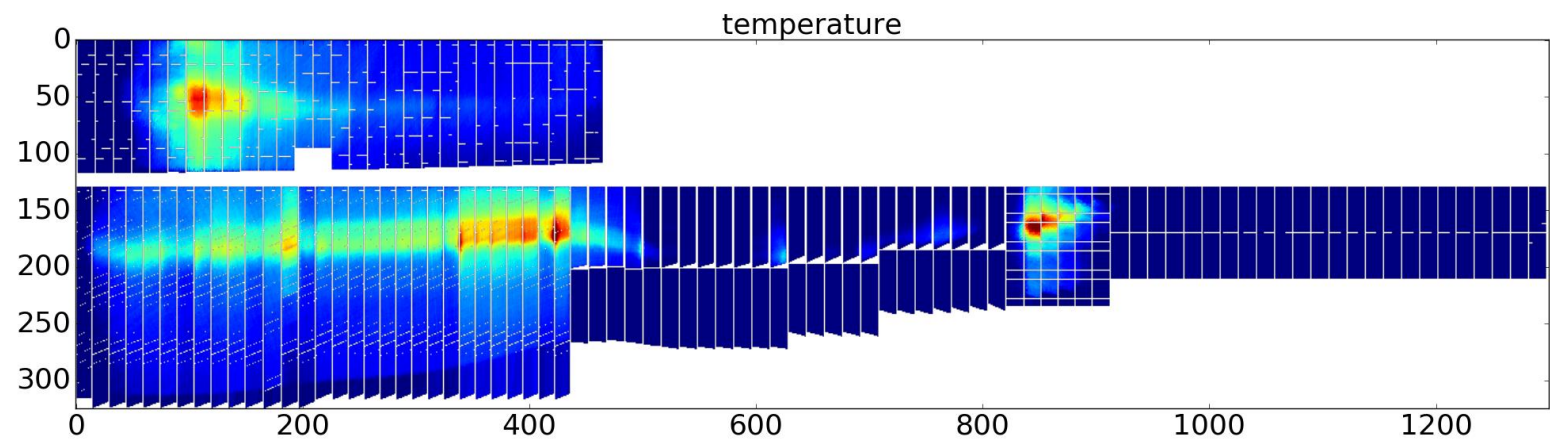


THEODOR 3D
(not real-time capable at W7-X)

Neural Net
(real-time)

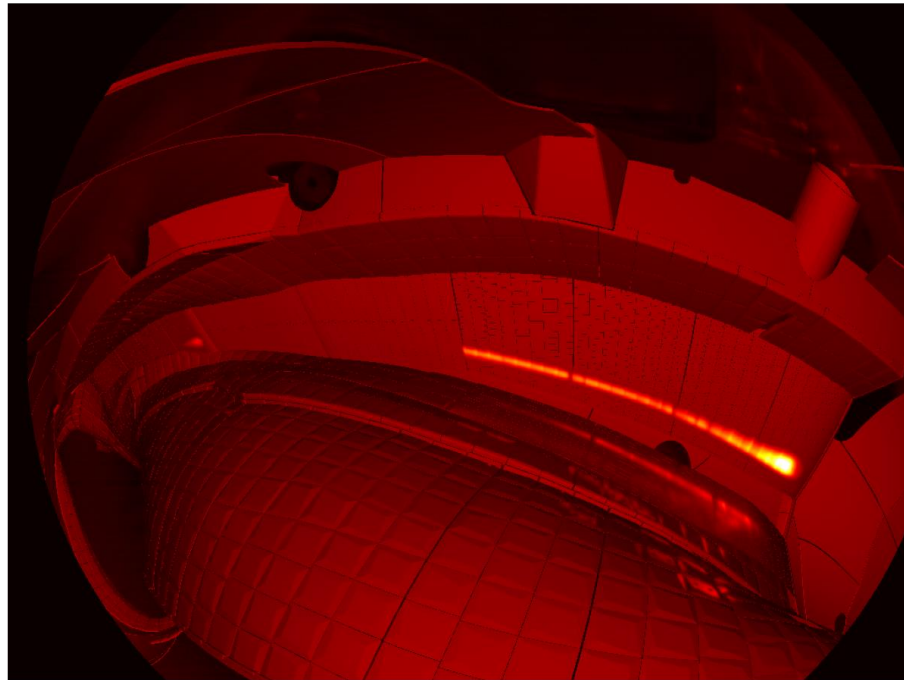


Scene model

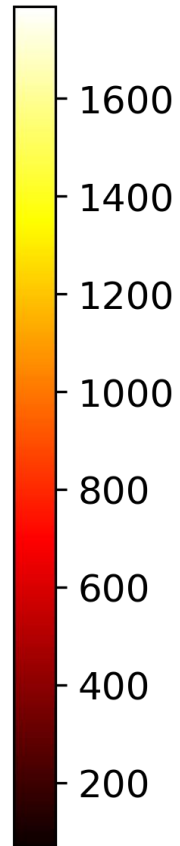


W7-X Thermal Overload Detection (protection)

20181017.041 - AEF40

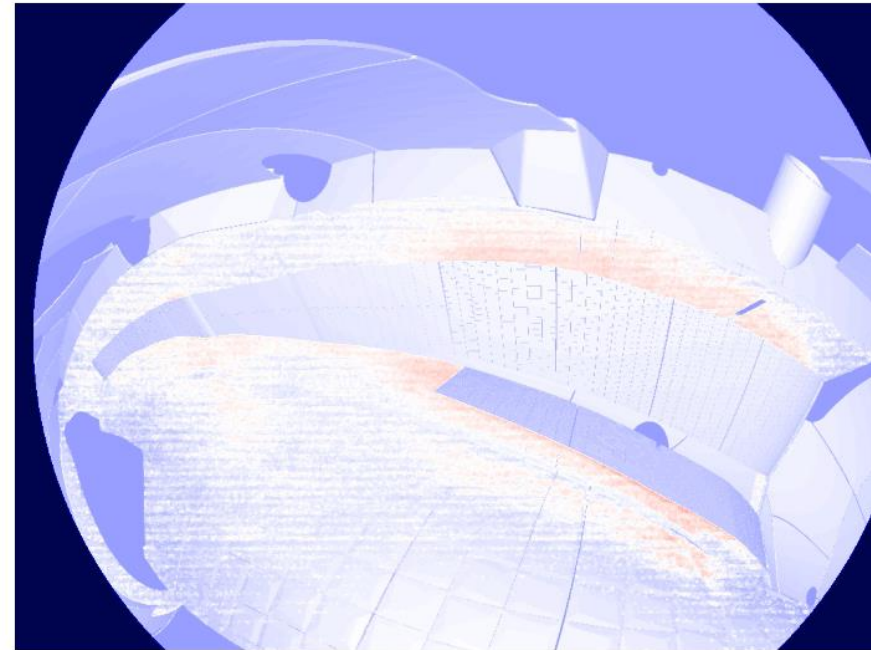


t=1539790125526392320 (2.13s)

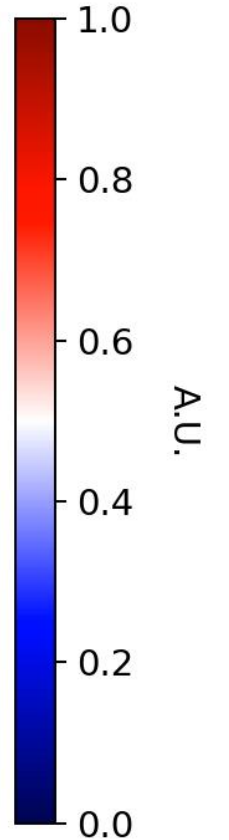


Risk

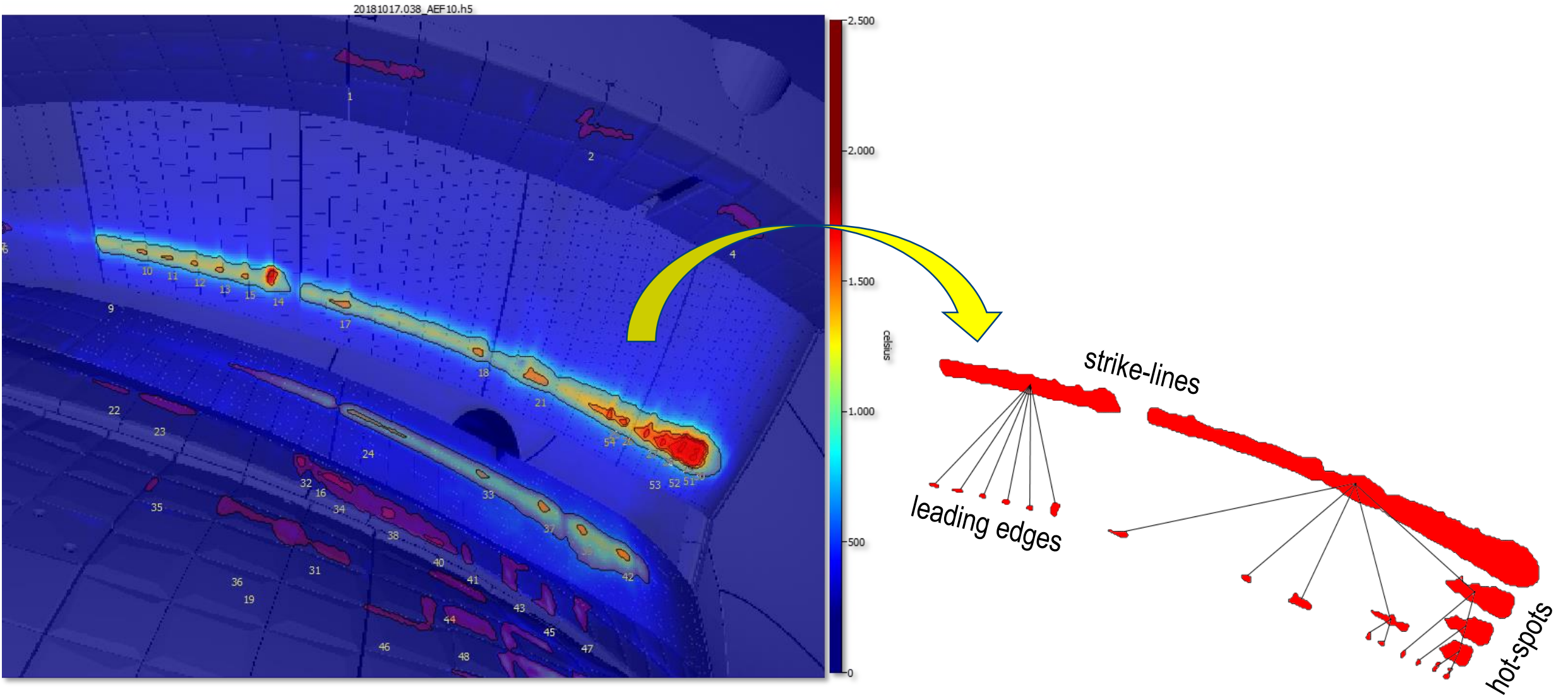
20181017.041 AEF40



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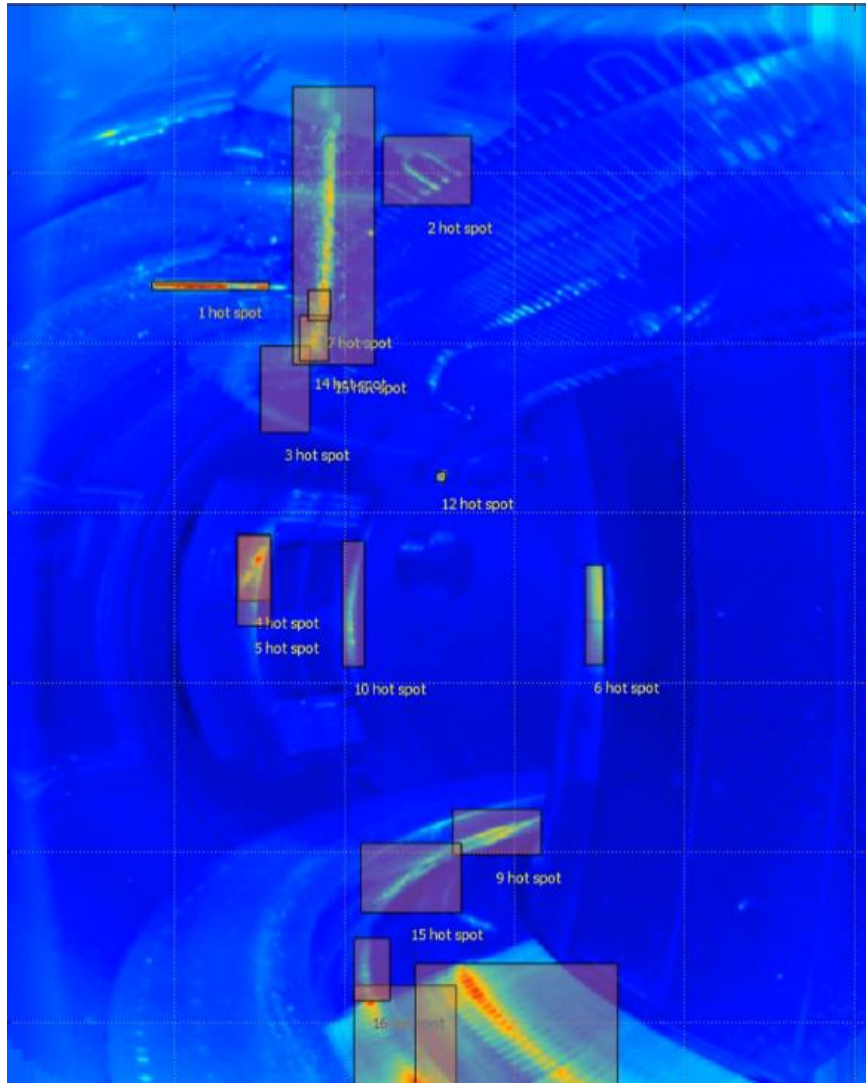


W7-X Thermal Event Detection (feedback control)



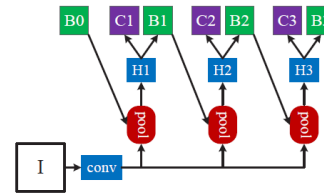
Hierarchical thermal event segmentation with Max-Tree algorithm

WEST Thermal Event Detection



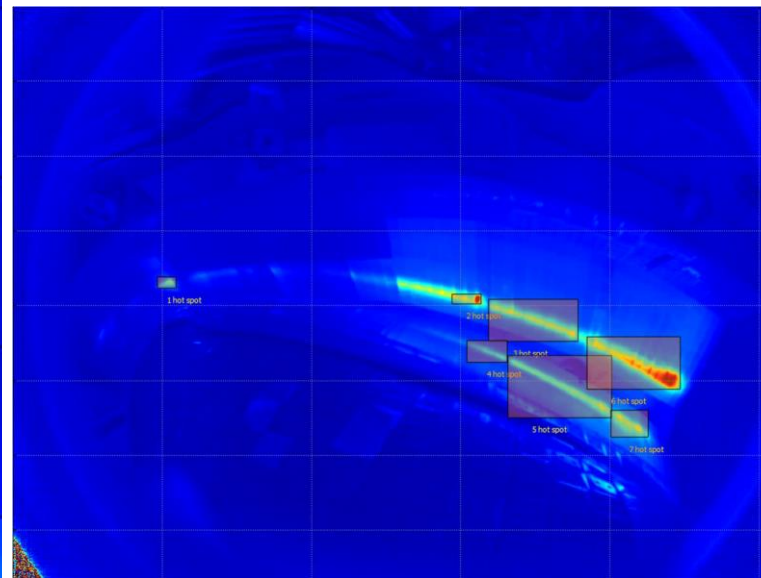
WEST thermal event detection and classification (EEG)

WEST DB

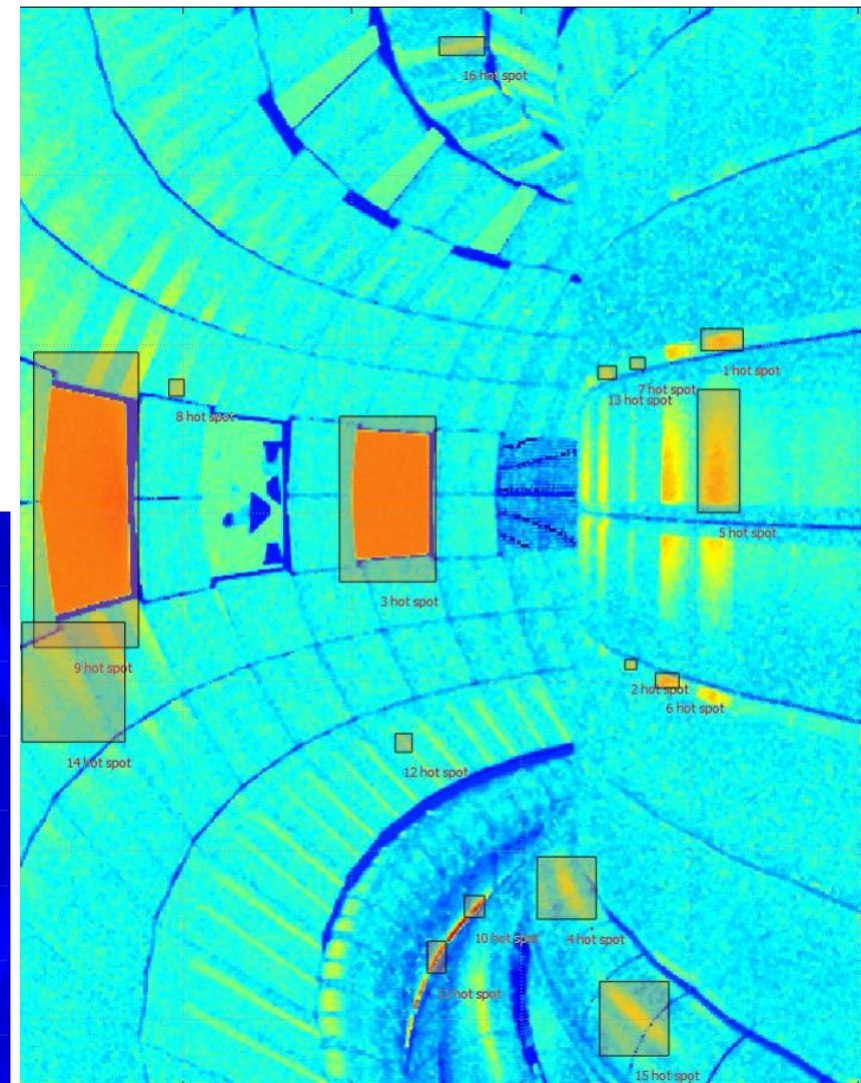


Cascade R-CNN deep model

Transfer learning

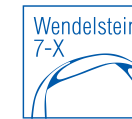


W7-X dataset



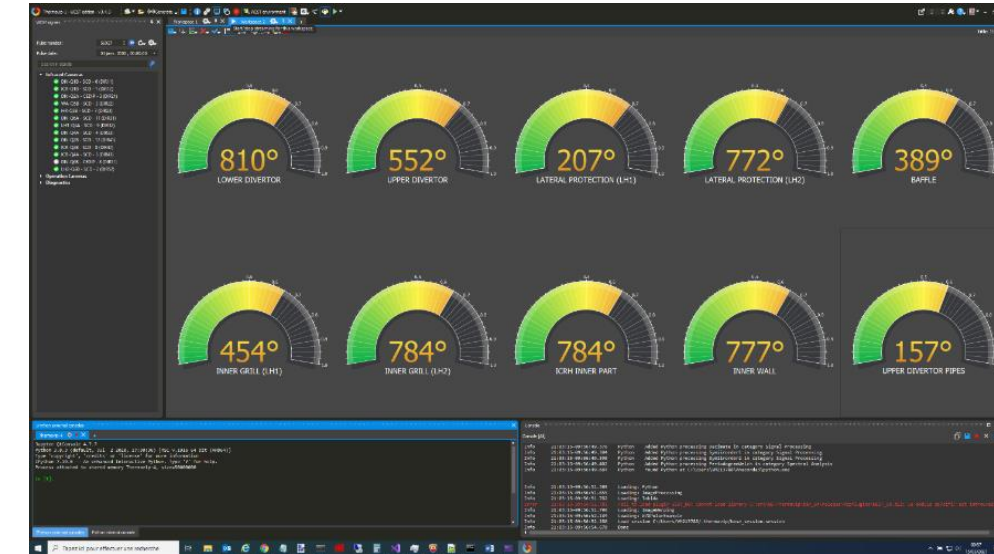
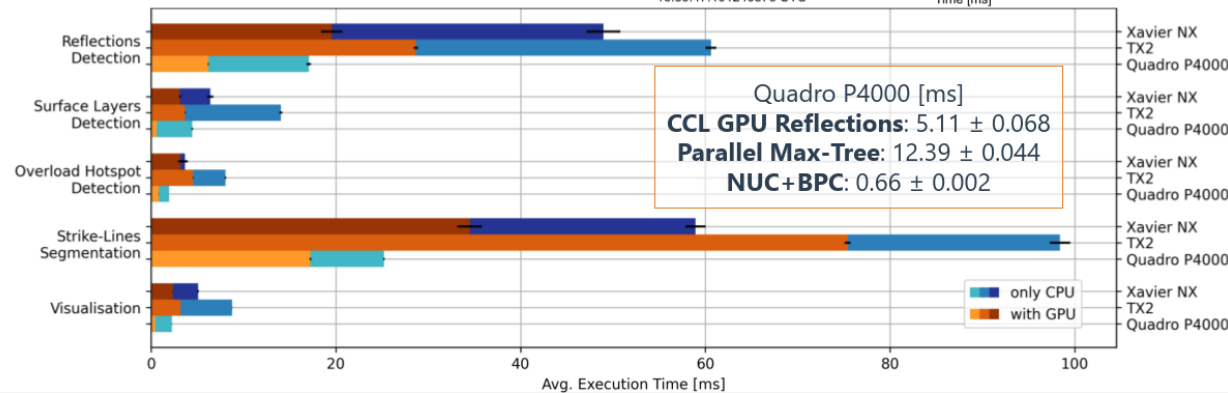
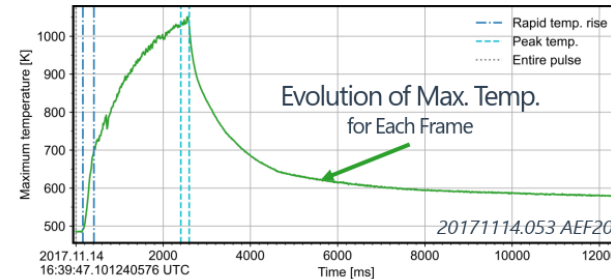
ITER synthetic diagnostic

W7-X + WEST thermal event database



Algorithm Benchmarks

Benchmarked Pulse Sections	
Entire Pulse	Visualisation, NUC+BPC (20180807.029 AEF11)
Rapid Temperature Rise	Surface-Layers
Peak Temperature	Strike-Lines, Overload Hotspots, Reflections



Real-time GPU optimization (Lodz Univ. EEG)

Min pulse	55058	Pulse	Camera	Start(s)	Duration(s)	Type	MaxT(C)	CT (ramp-up)	CT (ramp-down)	Automatic
Max pulse	55058	1	55058 LH1Q6A	26.32	15.26	unknown	330	0	0	yes
ID ThermalEventInfo	0	2	55058 LH2Q6B	26.919	14.66	hot component	164	0	0	yes
PPO name	All	3	55058 WAQ5B	3.619	22.64	hot component	205	0	0	yes
Camera name	All	4	55058 WAQ5B	5.3	36.259	localized heat flux	445	0	0	yes
Thermal event	All	5	55058 WAQ5B	6.859	34.7	localized heat flux	395	0	0	yes
Component		6	55058 WAQ5B	8.479	33.08	reflection	264	0	0	yes
Sector		7	55058 WAQ5B	11.139	30.42	reflection	232	0	0	yes
Min duration (s)	0.00	8	55058 WAQ5B	15.819	25.74	reflection	235	0	0	yes
Max duration (s)	1000.00	9	55058 LH2Q6B	19.279	22.3	localized heat flux	279	0	0	yes
Min temperature	0.00	10	55058 LH2Q6B	26.579	9.2	localized heat flux	193	0	0	yes
Max temperature	5000.00	11	55058 LH2Q6B	27.359	12.34	localized heat flux	172	0	0	yes
Min TC (ramp up, s)	0.00	12	55058 LH2Q6B	27.899	8.48	localized heat flux	159	0	0	yes
Max TC (ramp up, s)	1000.00	13	55058 LH2Q6B	28.219	4.64	localized heat flux	151	0	0	yes
Min TC (ramp down, s)	0.00	14	55058 LH1Q6A	5.48	23.519	localized heat flux	719	0	0	yes
Max TC (ramp down, s)	1000.00	15	55058 LH1Q6A	6.78	20.08	localized heat flux	510	0	0	yes
Min I ² (kA)	-1.00	16	55058 LH1Q6A	12.68	28.9	hot component	624	0	0	yes
Min density (1E19 p/m ³)	-1.00	17	55058 LH1Q6A	5.92	35.66	hot component	331	0	0	yes
Min LH power (MW)	-1.00	18	55058 LH1Q6A	12.68	28.9	hot component	624	0	0	yes
Min ICRH power (kW)	-1.00	19	55058 LH1Q6A	26.66	14.92	hot component	409	0	0	yes
Text in comments	Search in comments	20	55058 LH1Q6A	5.48	23.519	localized heat flux	719	0	0	yes
Text in surname	Search in surname	21	55058 LH1Q6A	6.78	20.08	localized heat flux	510	0	0	yes
Detection method	Search in method	22	55058 ICR3Q4A	4.22	22.02	unknown	2815	0	0	yes
Automatic detection	All	23	55058 DIVQ1B	5.779	8.12	localized heat flux	317	0	0	yes
Min confidence	0	24	55058 DIVQ1B	6.319	8.72	localized heat flux	354	0	0	yes
		25	55058 DIVQ1B	6.359	5.4	localized heat flux	318	0	0	yes
		26	55058 DIVQ1B	6.359	4.84	localized heat flux	302	0	0	yes

thermalevent_realtime	
ID_ThermalEvent_RealTime	bigint
CurrentTimestamp	bigint(20)
RecordTimestamp	bigint
ID_ThermalEventInfo	bigint
LeftBox	int(11)
TopBox	int(11)
WidthBox	int(11)
HeightBox	int(11)
MaxIntensity	double
MinIntensity	double
MeanIntensity	double
StandardDeviation	double
MaxLocationX	int(11)
MinLocationX	int(11)
MaxLocationY	int(11)
MinLocationY	int(11)
Area	int(11)
CentroidX	double
CentroidY	double
Orientation	double
Eccentricity	double

thermaleventinfo	
ID_ThermalEventInfo	bigint
Pulse	int(11)
PulseDate	bigint
CameraName	varchar(255)
InitialTimestamp	bigint(20)
LastTimestamp	bigint(20)
Duration	bigint(20)
ThermalEvent	varchar(255)
IsAutomaticDetection	tinyint(1)
Maximum	double
TimeConstantIncrease	double
TimeConstantDecrease	double
Method	varchar(255)
Polygon	varchar(600)
Confidence	int(1)
DateValidation	datetime
NamePPO	varchar(255)
Comments	varchar(255)

cameraname	
CameraName	varchar(255)

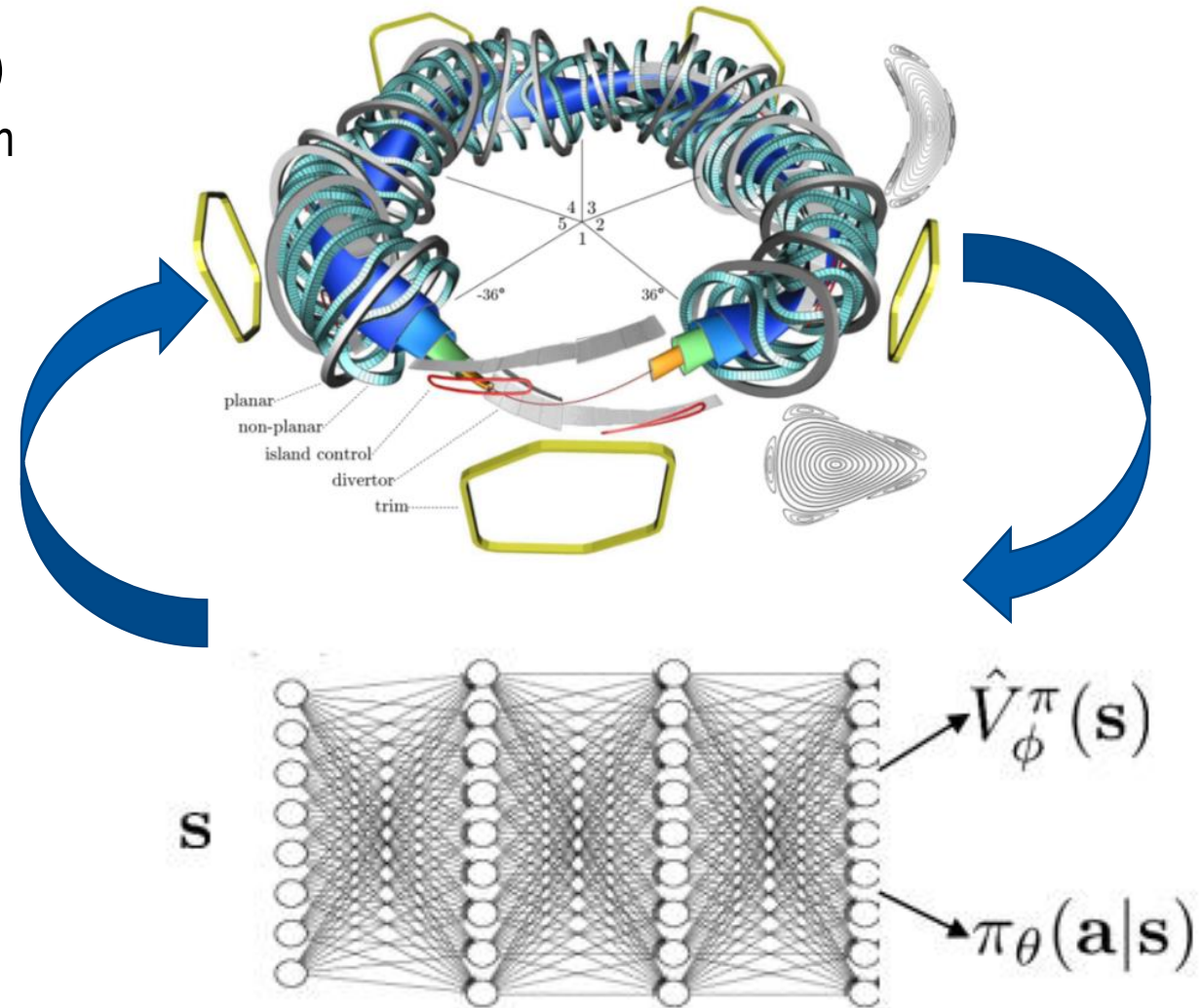
typeeventinfo	
EventName	varchar(255)

Common software framework based on ThermaVIP (CEA)
 Common thermal event data structure and database

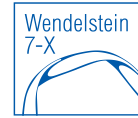
ppoinfo	
NamePPO	varchar(255)

Roadmap for W7-X OP2

- **W7-X OP 2.1** (High-heat-flux divertor and water-cooled PFCs)
 - **Machine protection:** thermal overload → interlock alarm
- **W7-X OP2.x** (Steady-state, 30 min, 18 GJ)
 - **Avoid plasma interruptions**
 - **Deep models for advanced feedback control:**
 - ECRH, NBI, ICRH → hot-spot control
 - Control coils → strike-line position and shape
 - Gas puffing → detachment control
 - Build **larger annotated datasets**

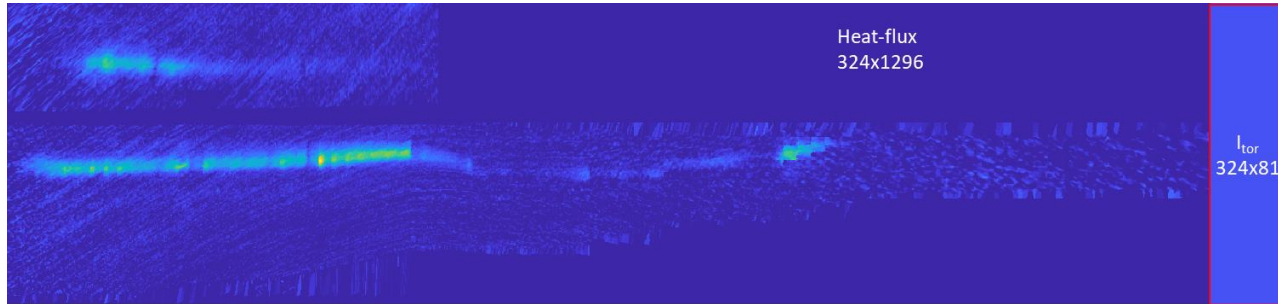


W7-X strike-line control



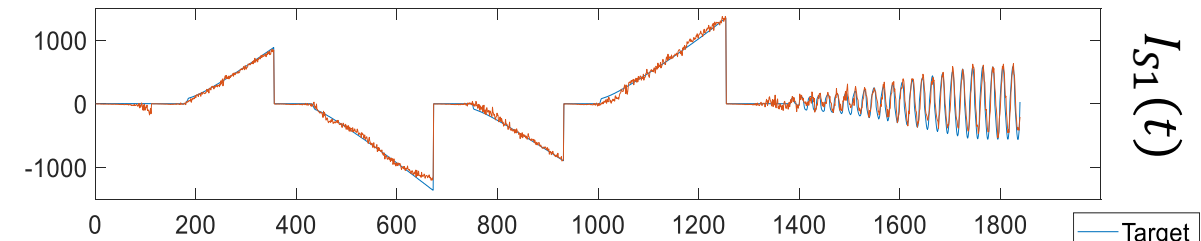
Heat flux data

Toroidal Current

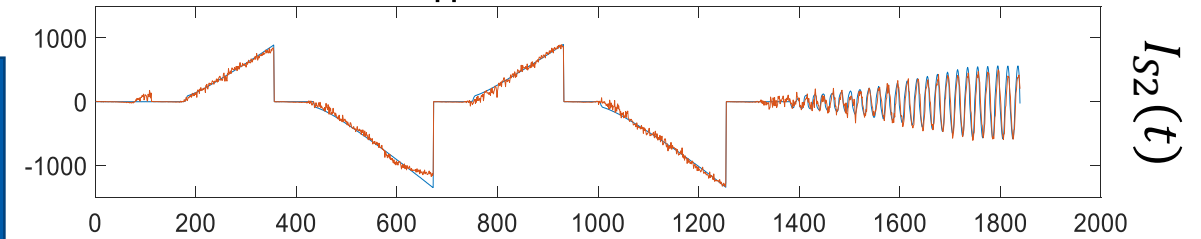


Shots: 20180815.#

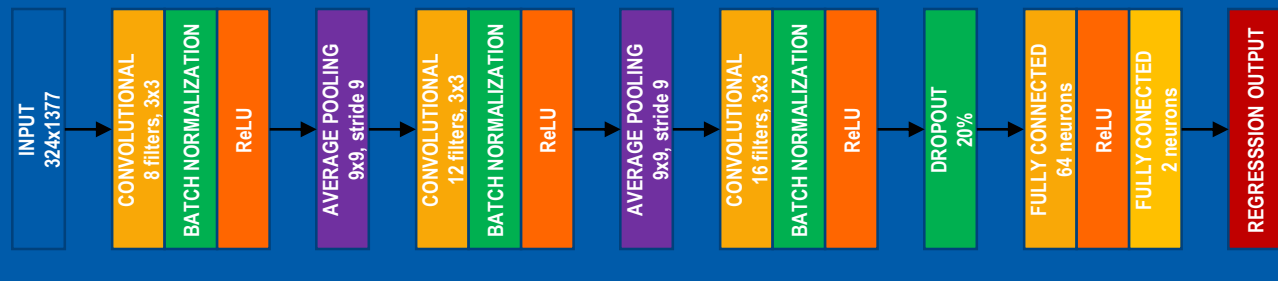
Lower Divertor - Control Coil



Upper Divertor - Control Coil



Convolutional Neural Network (CNN)



Lower Divertor
Control Coil

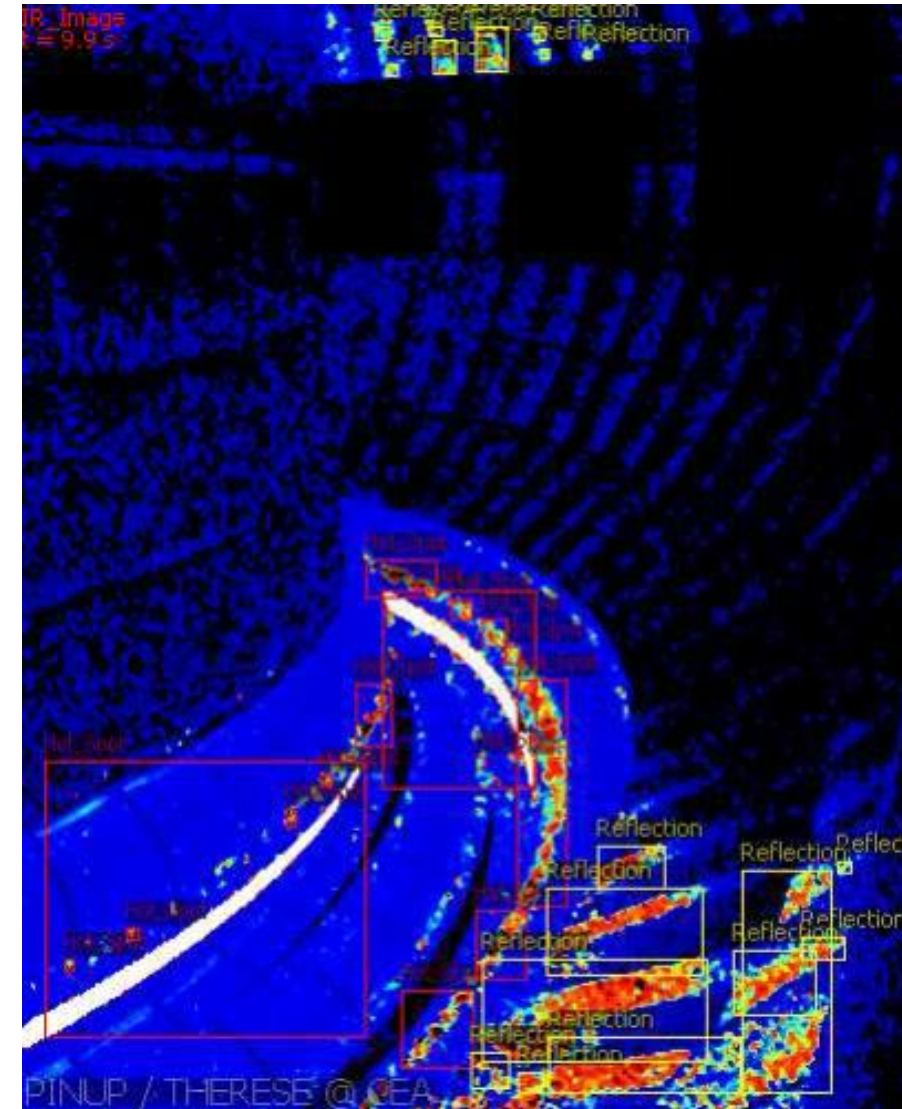
Upper Divertor
Control Coil

Conclusions

- **High-performance steady-state operation** poses new challenges for PFC IR protection systems (W7-X and ITER):
 - **Thermal loads protection** → NIR
 - **Thermal loads control** → MWIR
- MWIR in **metallic walls** → Real-time (AI-based) **reflection models**
- **Full field of view** monitoring → Scene models (extension of ROI concept)
- **Predictive** → **Real-time AI-based 3D heat flux** estimation
- **High-level** scene understanding → **Deep Learning**
- Deep learning → **large datasets** → **transfer learning**
- **Common thermal event database** and software **framework**



Intelligent agents for advanced **control of thermal loads**
for ITER



ITER simulated hot spot detection (CEA)₁₄