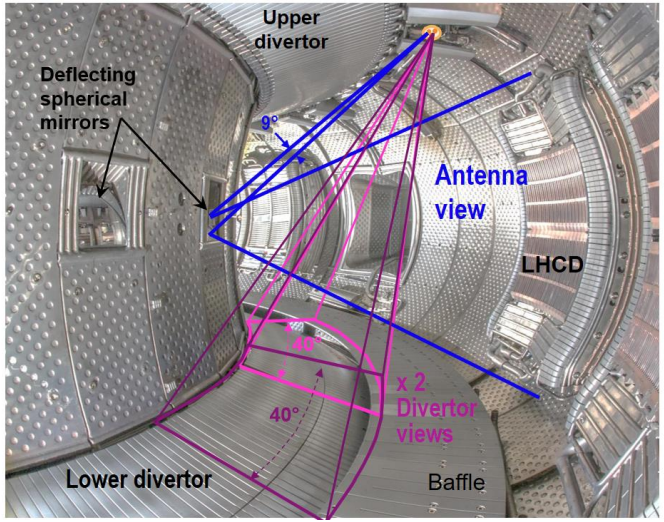
Toward Automatic Wall Protection of Magnetic Fusion Reactors based on Infrared Monitoring

R. Mitteau, E. Grelier, V. Moncada, M. Houry

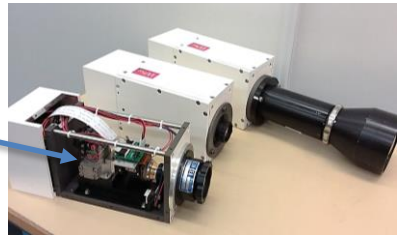
4th IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis

December 1th, 2021



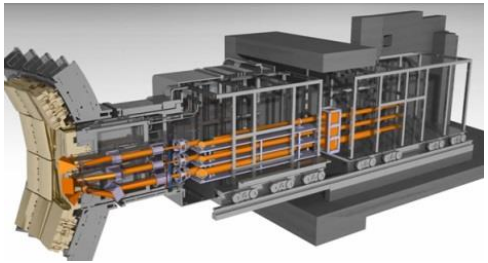
WEST vessel with Field of Views (FoV)

InSb detector

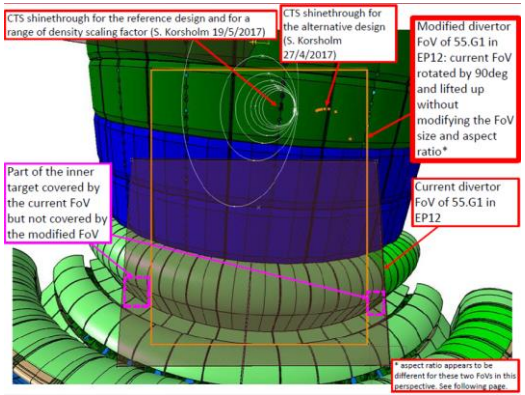


WEST IR cameras

WEST InfraRed (IR) endoscopes

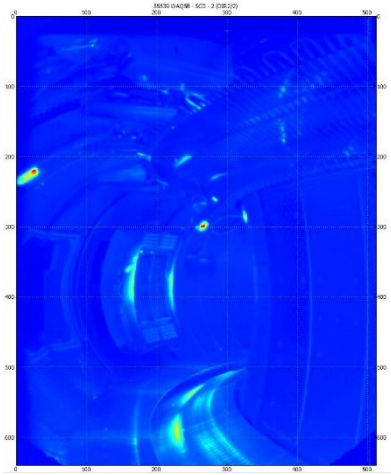


ITER Wide Angle Viewing system

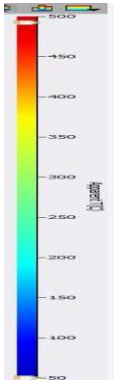


ITER In vessel FoVs

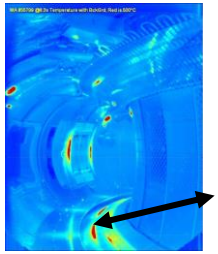
Temperature maps, hot spots and thermal events (ThEv)



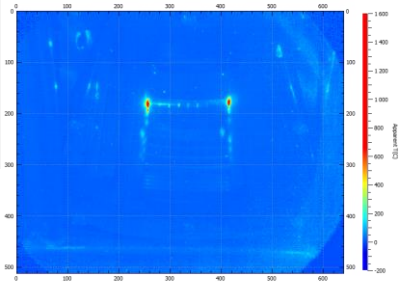
500°C



50°C



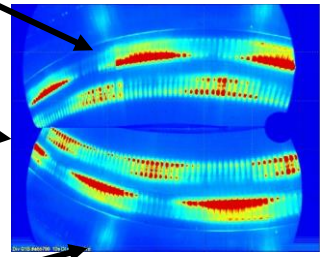
Hot spot overlap



Textured pattern : the event is the large contour, the smaller hot spots are less relevant

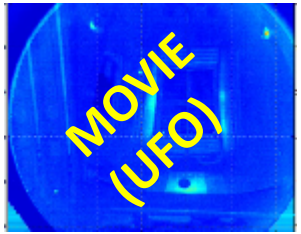
Many thermal event in the image

Some ThEv close to image maximum intensity, while other important hot spots are just above background level



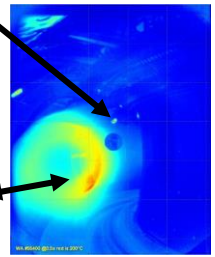
View of WEST wide angle tangential viewing system

An outstanding diversity of thermal events

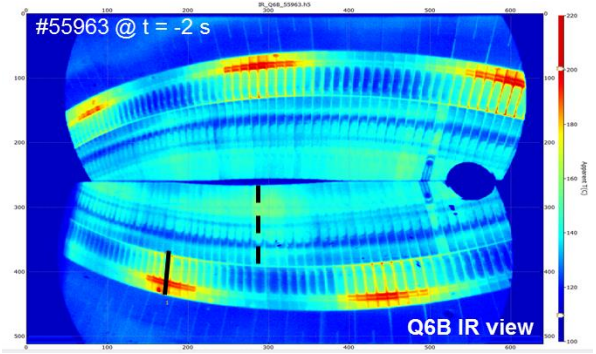


Moving spots : reciprocating probe, UFOs (dust, flakes)

Some hot spots are some very small (pixels)

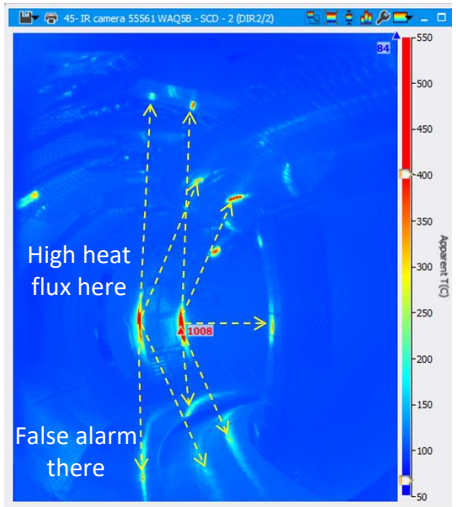


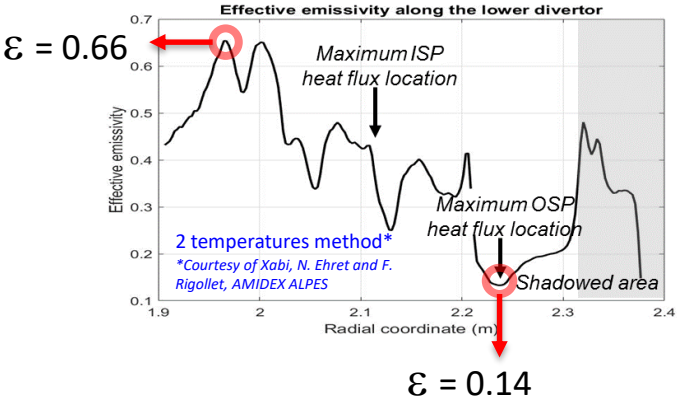
Very large hot spot (linear size 1/3 of image ~200 pixels)



Spatially and time changing emissivity

Hot spot reflection within the vessel (metallic armour)





X6

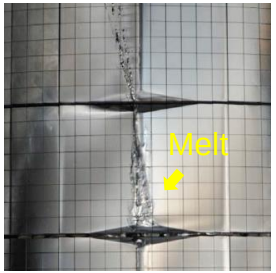
Challenges being addressed by science community toward obtaining broadly recognised analysis techniques

[J. Gaspar et al., Fusion Engineering and Design Volume 149, December 2019, 111328]

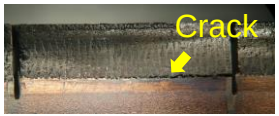
[M.H. Aumeunier et Al., Nuclear Materials and Energy Volume 12, August 2017, Pages 1265-1269]

Wall components typical damage times

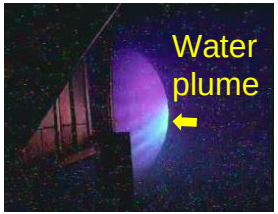
JET melted tiles (Beryllium)



Delaminated tile in carbon era Tore Supra

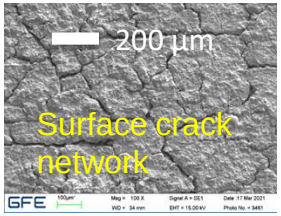


Tore Supra in-vessel water leak during operation



Boiling crisis

Component wear



Surface effects (Cracking, melting)

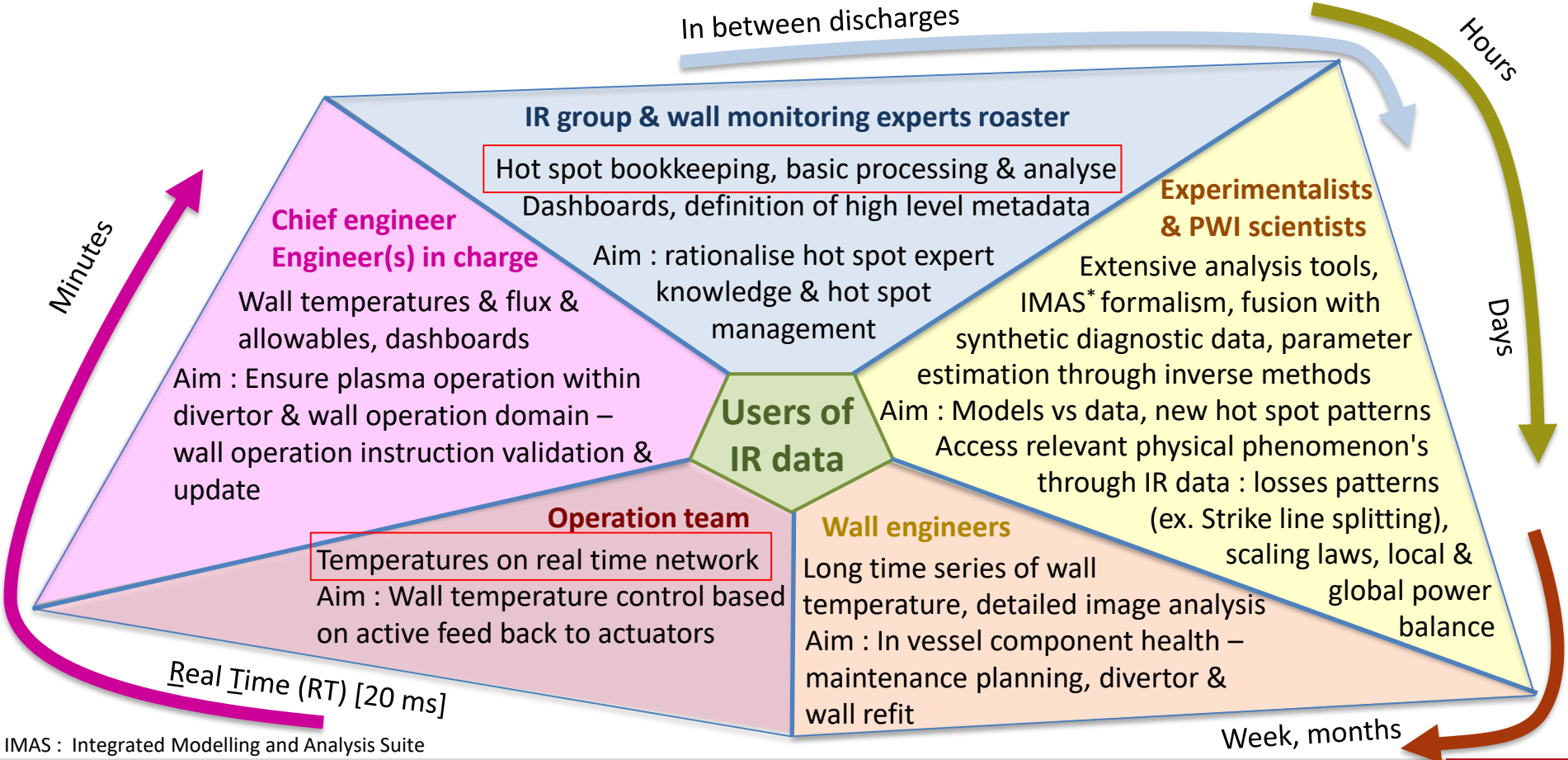
Heat sink damage (Water leak)

Fatigue, wear

Milliseconds | Seconds | Hours | Days

Scope of IR-based machine protection @50 Hz

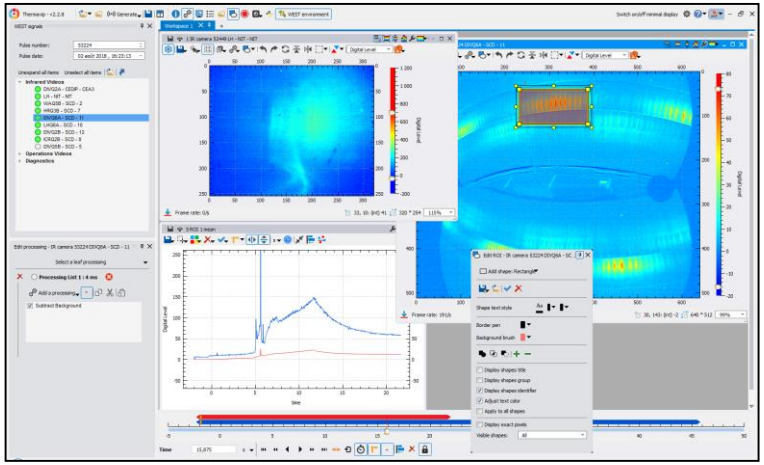
Infrared viewing diagnostic users



IMAS : Integrated Modelling and Analysis Suite

Human expertise in between plasma discharges – wall monitoring roster at WEST

WEST control room



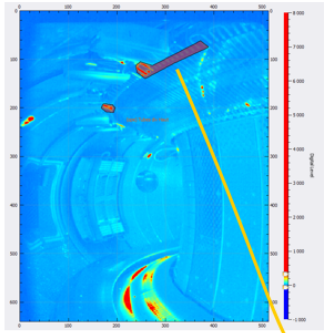
In between discharge analysis tool - ThermaVIP

- Detect & acknowledge hot spot → Identify, record, store
- Get more information about hot spot → Already happened y/n, where, which component
- Explain hot spot → Heat source, overheat y/n, normal y/n
- Grading : severity, urgency → Issue y/n, immediate vs delayed management
- Determine action course → Accept and do nothing, issue warning to op. team ?

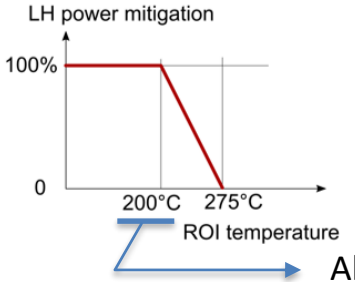
WEST real time feed back control on IR live data

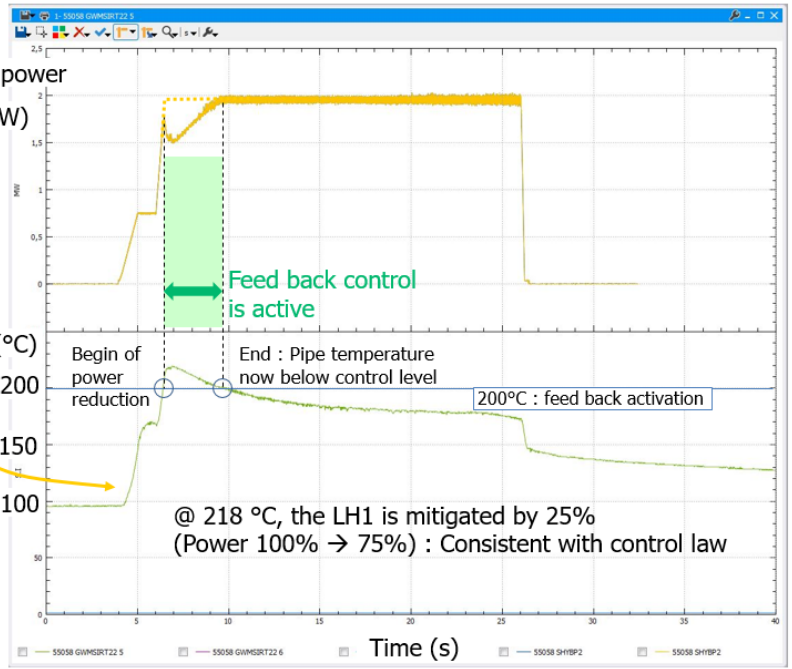
Test on a cooled component : power reduction triggers obtention of new equilibrium point

ROI : upper divertor pipe temperature



Action : LH2 → Electron ripples losses → Upper divertor pipe temperature





Alarm threshold : activates feedback control

ROIs

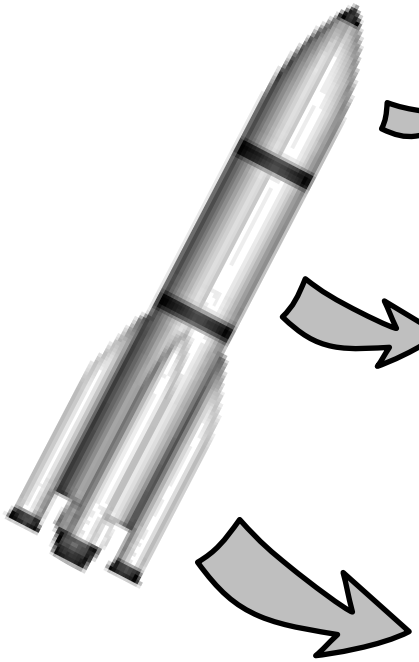
Basic actuators : heating systems

ROI	Lim	Max	LH1	LH2	IC1	IC2	IC3
LH1-Grill	220	270	X				
LH1-Grill eq. Plane	550	600	X				
LH2-Grill	220	270		X			
LH2-Grill eq. Plane	550	600		X			
WA-Udiv Pipes	235	275	X	X			
LH1-Side Limiter	650	700	X	X	X	X	X
LH2-Side Limiter	650	700	X	X	X	X	X
IC-Q2-Side Limiter	650	700	X	X	X	X	X
IC-Q4-Side Limiter	650	700	X	X	X	X	X
IC-Q1-Side Limiter	650	700	X	X	X	X	X

Control matrix

*ROI : Region of Interest

Use case → 3 stages : Hot spot detection – Expertise - Action



Stage 3 : what do next ?
Determine best actuator toward temperature control
Solutions, grading

- Control may be multiple / complex
- Attempt to control within op. envelope (→ PCS*)
- Or escalate the issue toward fast shutdown (CIS*)

Stage 2 : expertise, analyse
increase knowledge
Classification

- Fast (coarse) classification for RT
- Allow to change class later at refined classification stage
- Expertise time ranges from RT, but can last weeks for 'new events'

Stage 1 : Detection
De-noising / Thresholding …
Tracking
Or … pattern based

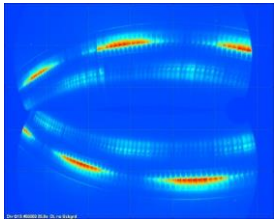
- Anomaly detection
- UFO detection
- Possible several detectors in //

All tasks have unique needs & constraints

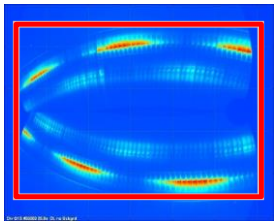
Standard imaging solutions (thresholding, expert rules) not convenient - Need bring in some "intelligence"

*PCS : Plasma Control System / *CIS : Central Interlock System

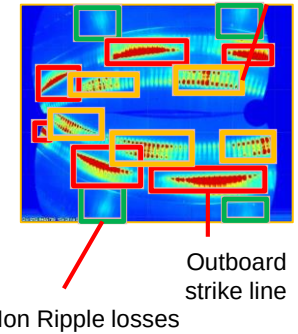
Basic actions of AI* based image processing

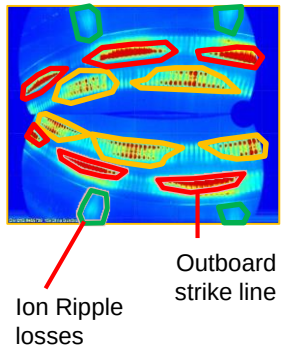


Regular plasma contact (strike line)



Regular plasma contact (strike line)

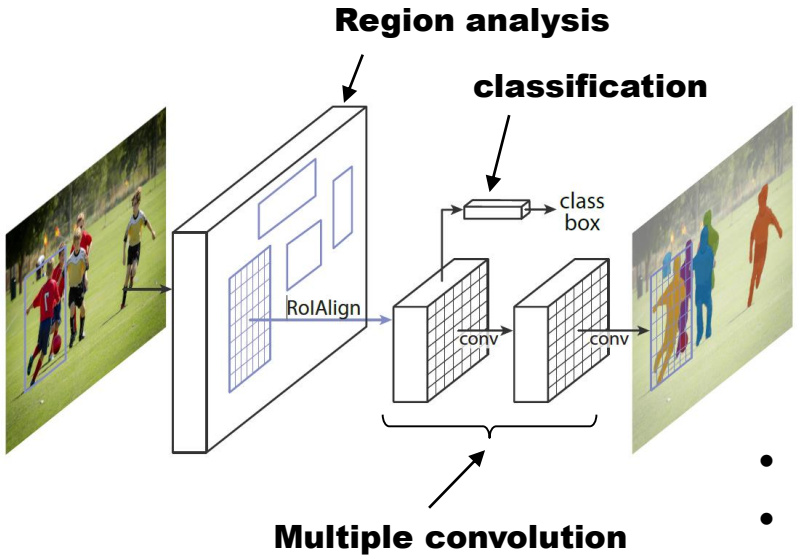


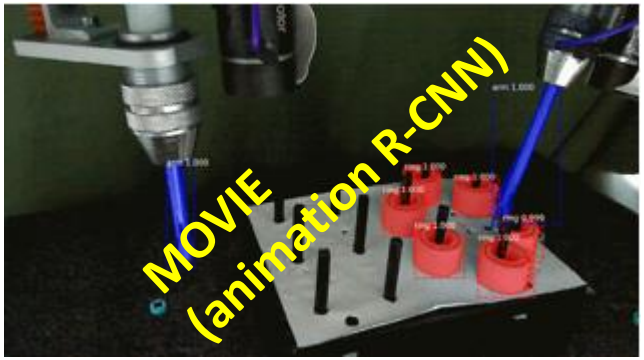


- Classification:
  Assign only one class label based on the dominant object inside it.
- Classification and localization:
  Assign only one class label to the object in the image and draw a bounding box around it.
- Object detection:
  Assign multi bounding box per object instance and classify it.
- Instance segmentation:
  Assign a class label and an instance for each pixel.

*AI : Artificial Intelligence

R-CNN : region based pattern recognition





56 10^6 parameters (Weights)

Cf E. Grelier presentation (next talk)

- Meet requirements (multiple object detection)
- Lively family of algorithms
- Recognised as performant
- Available Github
- Potential for real time operation (@ 50Hz)

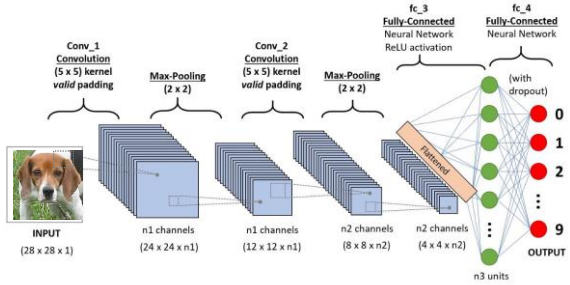
Ren, S., He, K., Girshick, R., & Sun, J. (2016). Faster r-cnn : Towards real-time object detection with region proposal networks. *arXiv:1506.01497 [cs]*.

Stage 1

Creation / definition of annotated dataset

Stage 2

2.a Select / adapt process with learning capability



2.b Train the process

Machine learning

Learning set → Calculation → Trained model

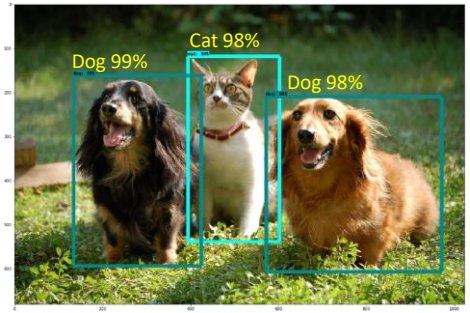
-Training result : weights -

Stage 3

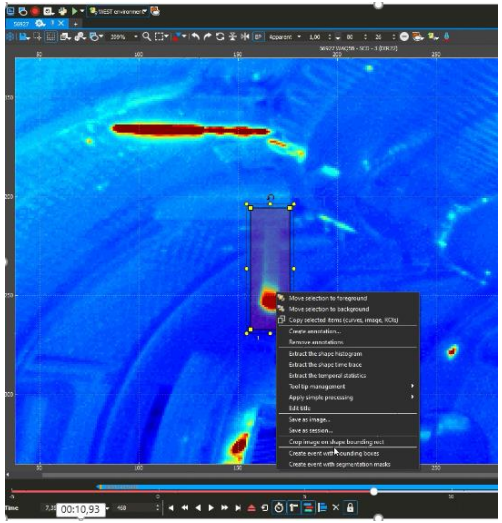
Test the process, qualification, usage

Trained model : inference

New set → Calculation → Results



Get an dataset of *annotated* wall hot spots

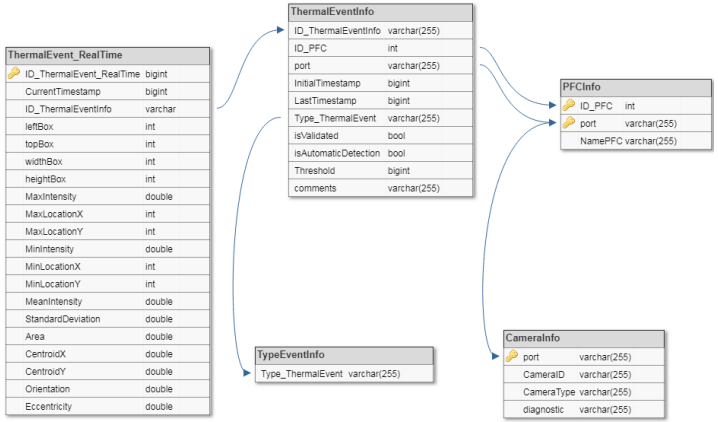


- Annotation recognised as being a time-intensive work
- Unified dataset across views for maximising dataset size
- List of label (or classes) needed (“ontology”)

WEST Annotated data set
~ 8000 events - Ground truth

Work toward creating better + faster annotation tool

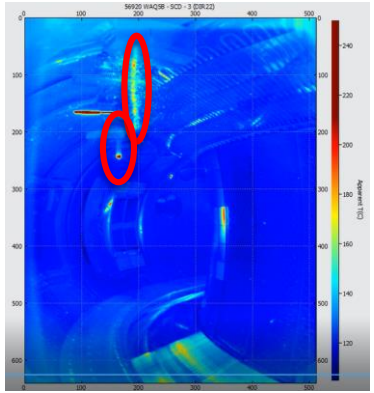
- User friendly
- Faster annotation
- Make annotations less dependant on annotator
- Harmonise annotations → annotation guidelines



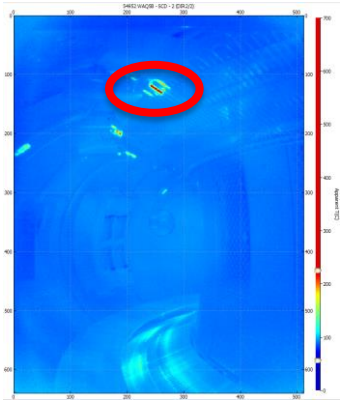
Challenges and WEST approach to defining classes (Ontology)

Key properties

- Consistent
- Complete & stable
- Fit to the need



Class according to <u>physical component</u> :
Langmuir probe, powder dropper



Class according to <u>heat source</u> :
LH* electron ripple losses

Current classes

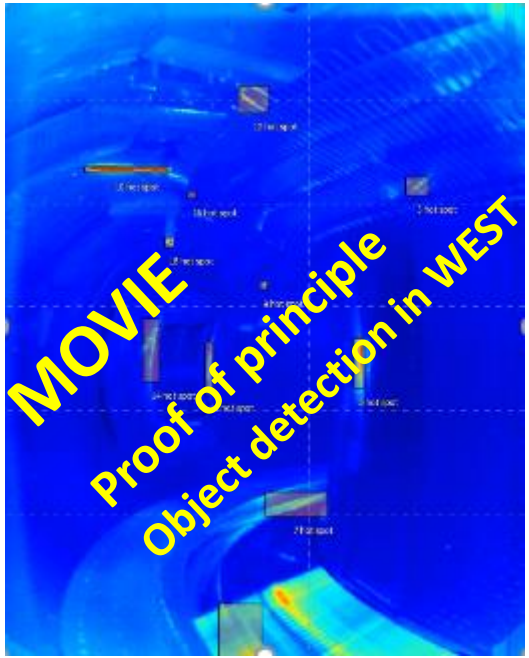
- Inboard strike point
- Outboard strike point
- LH Electron losses
- Reflection
- Radiated heat flux
- UFO
- Hot spot – catch all class

Current hot spot ontology

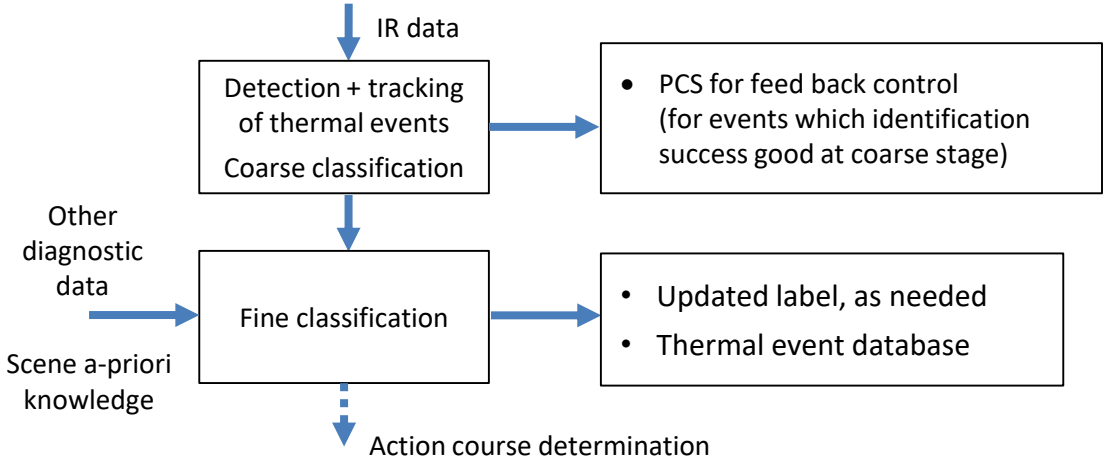
Consistent → to be improved, through the use of a multiple entry ontology
Complete & stable → accept inevitable new classes (experimental science)
Fit to the need → multiple lists of labels according to the usage

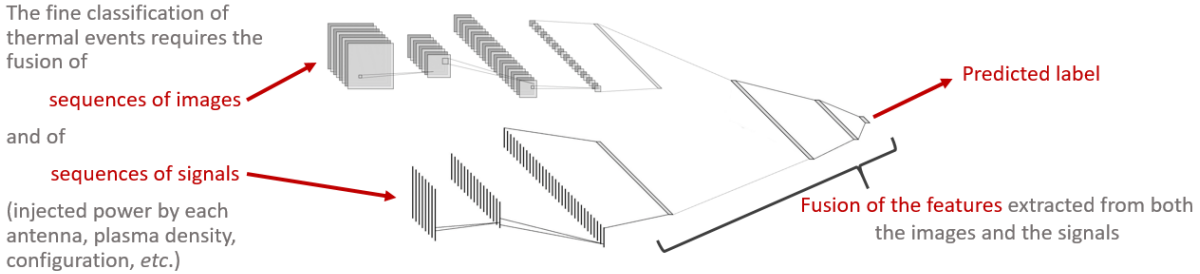
*LH : Lower Hybrid (heating system)

Illustration of WEST automatized hot spot process



Object detection on WEST tangential view

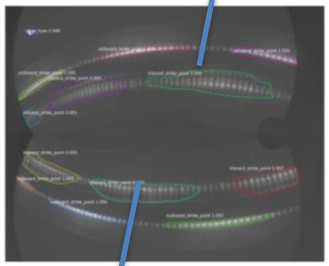




Success metrics / Key performance indicator

Strike line confidence level

99%

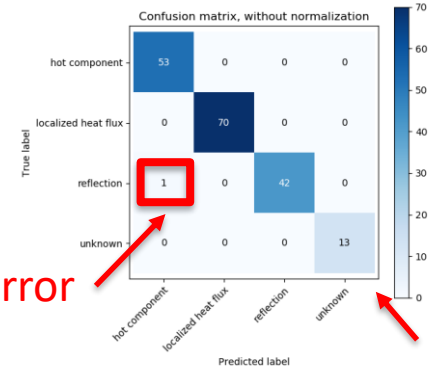


98%

High detection & classification accuracy for typical events

Formal AI metric : complete & formal

- Mean average precision
- Incorporates count of false positive / negative, labelling error



Error

ok

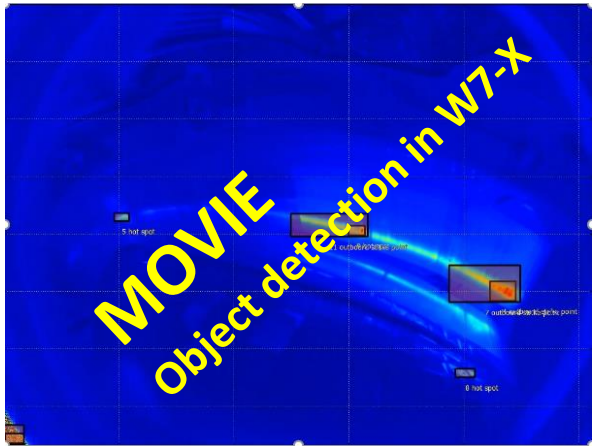
- Use cases dedicated metric → metric depends on client
- Incorporate client specific requirement into the metric
- Example : Increased penalization for false alarms

To be developed though further formalisation work with the various clients

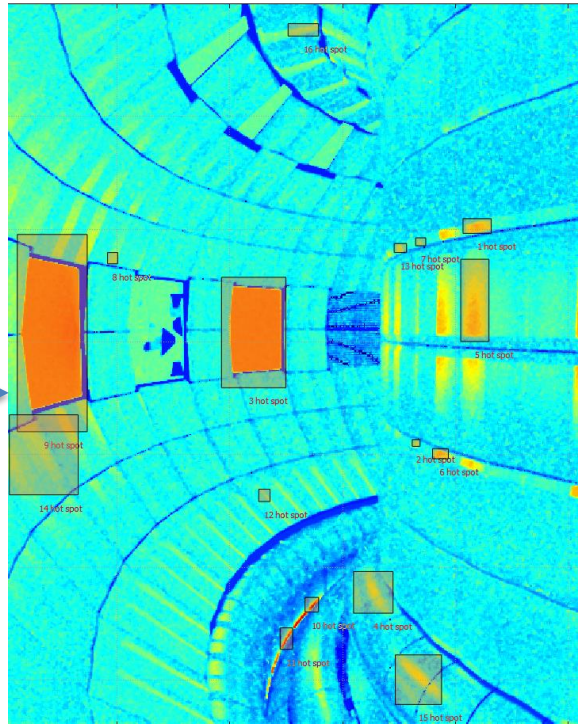
- Note : the metric affects the process

Transfer learning to other machines : W7X and ITER

Hot spot tracking for W7-X (20181017.038_AEF10)



Hot spot detection on an ITER synthetic infrared image of the wall, using a hot spot detection network trained on WEST experimental hot spots



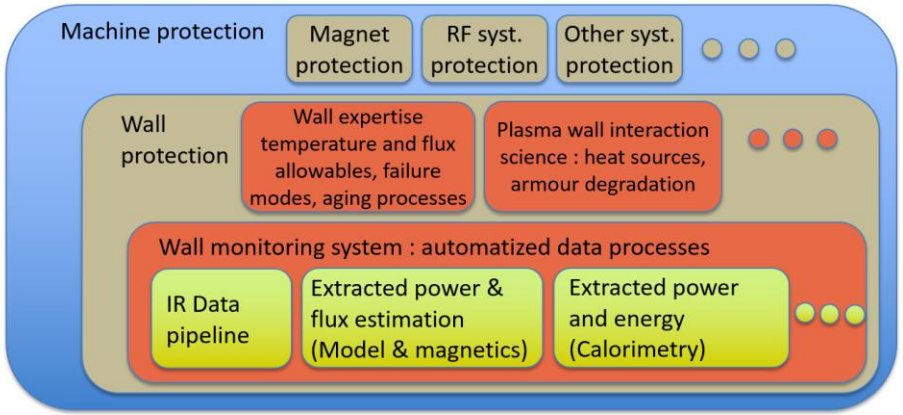
- Proof of principle transfer learning WEST → W7-X
- Next goal : WEST + W7-X* common wall hot spot dataset, toward IR data pipeline transferable to ITER, functional from day 1

* Open to other contributors

[Aumeunier, M.-H., Kočan, M., Reichle, R., & Gauthier, E. (2017). Impact of reflections on the divertor and first wall temperature measurements from the ITER infrared imaging system. *Nuclear Materials and Energy*, *12*, 1265-1269. https://doi.org/10.1016/j.nme.2017.02.014]

Conclusion

- A prototypical computerized image process for detecting and classifying relevant wall hot spots is being operated at WEST for wall protection
- Based on region convolutional neural network (R-CNN) – Machine learning
- Next steps :
  - Operate it during the next experimental campaign (March 2022)
  - Transfer to on-line functionality
  - Develop an advanced network for fine classification of hot spots, including time series from other diagnostics



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- EUROfusion WP-W7X & WP-PrIO