IMPACT: a Comprehensive Numerical Platform for Advanced Thermal Protection of Tokamaks

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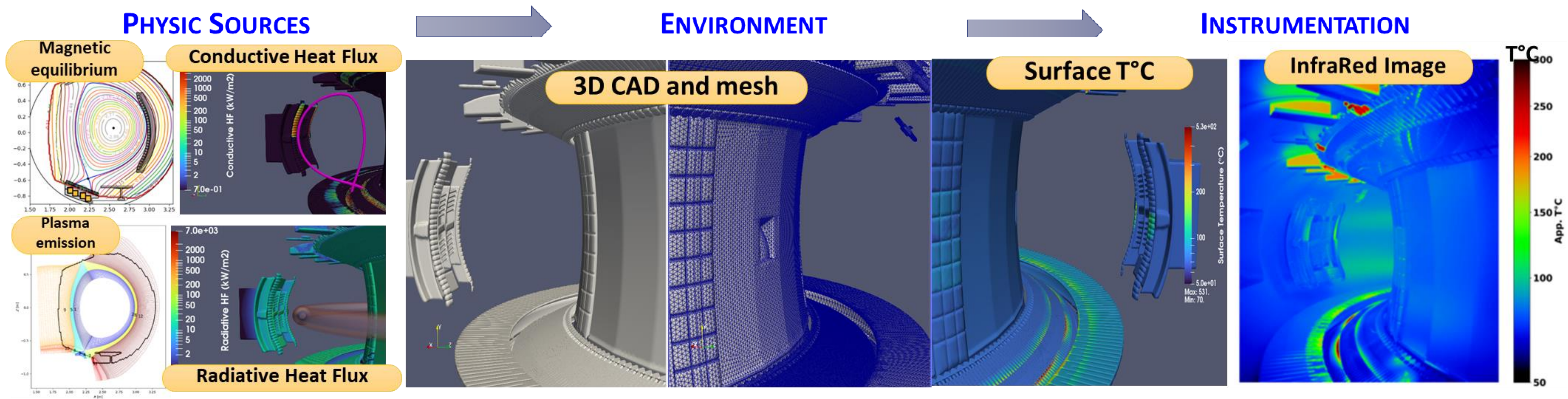
An InfraRed digital twin for Wall Thermal Protection and Analysis

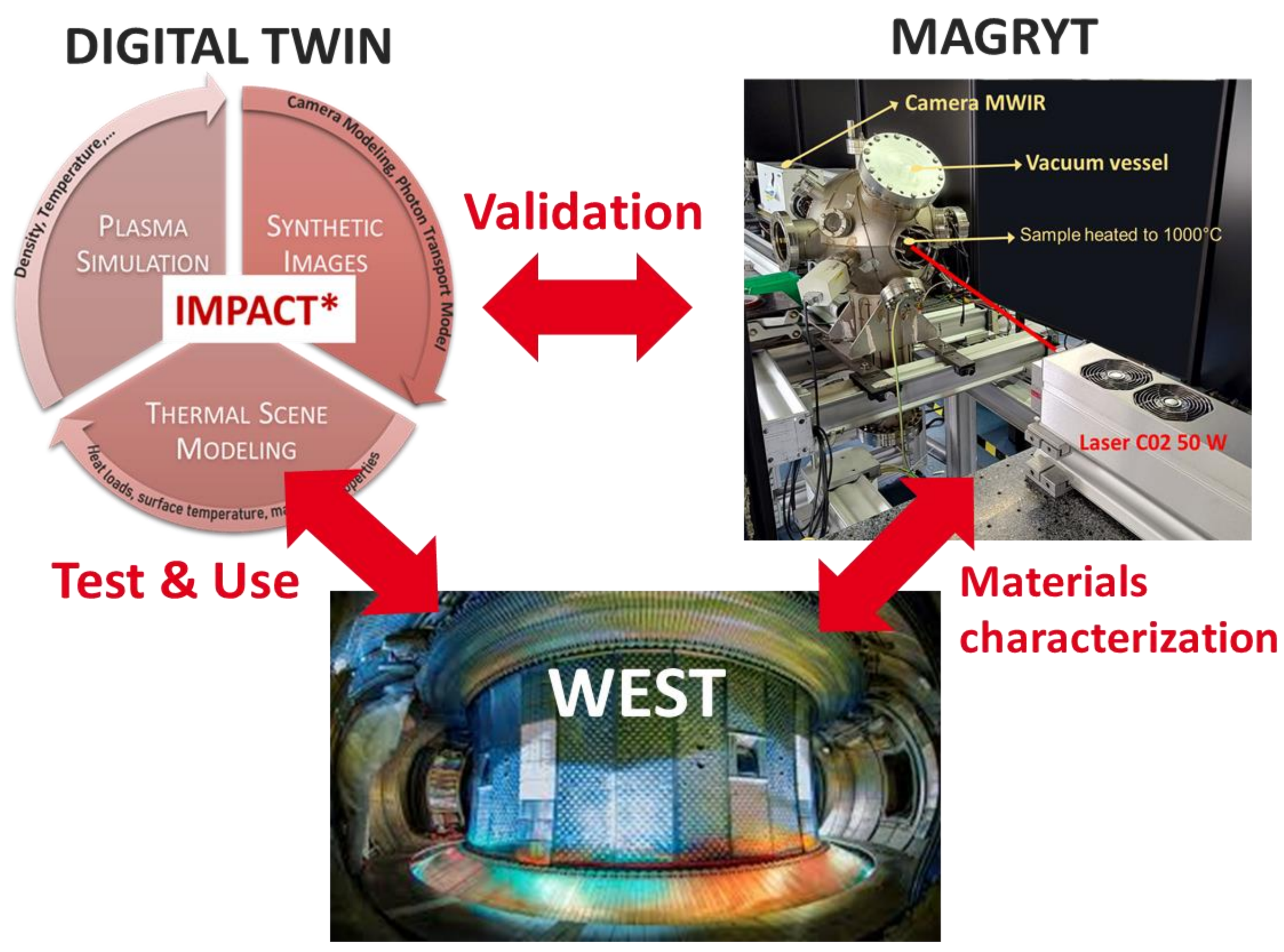
- **Context**: First Wall Protection **is challenging in metallic environment** with changing surface state as the plasma operation progress [1]
- A simulation-assisted IR measurement tool designed to support the **design phase** and **InfraRed analysis during the operations** of Plasma facing Components
- Based on 3D models, an unique multi-physics platform capable of integrating and coupling physical and engineering simulations involved in the observed thermal scene up to its measurement process
  - ✓ **Heat loads** : Derived from given plasma scenarios (PFCFLUX [2] +RADIATIX)
  - ✓ **Thermal models:** For given materials & cooling systems
  - ✓ **Photonic and optics models**: For given environment & camera specifications (SPECULOS/RAYMOND) [3]

Specifications

- **3D Model Continuity Management**: Capable of managing and ensuring the continuity of 3D models, from CAD to mesh models, while processing detailed and large 3D geometries.
- **Modular framework:** Facilitates the integration of updated and advanced versions of various physical codes, as well as new codes
- **Real-time application suitability** (between pulses) using *optimized codes (*via GPU, hardware acceleration and/or CPU parallelization)
- **Intuitive interface for** engineers, scientists and simulation specialists
- **Open source code** base for encouraging community contributions and collaborative development
- **Comprehensive Benchmarking**: Includes laboratory and in-situ benchmarking with uncertainty propagation and estimation.



IMPACT development and benchmarking

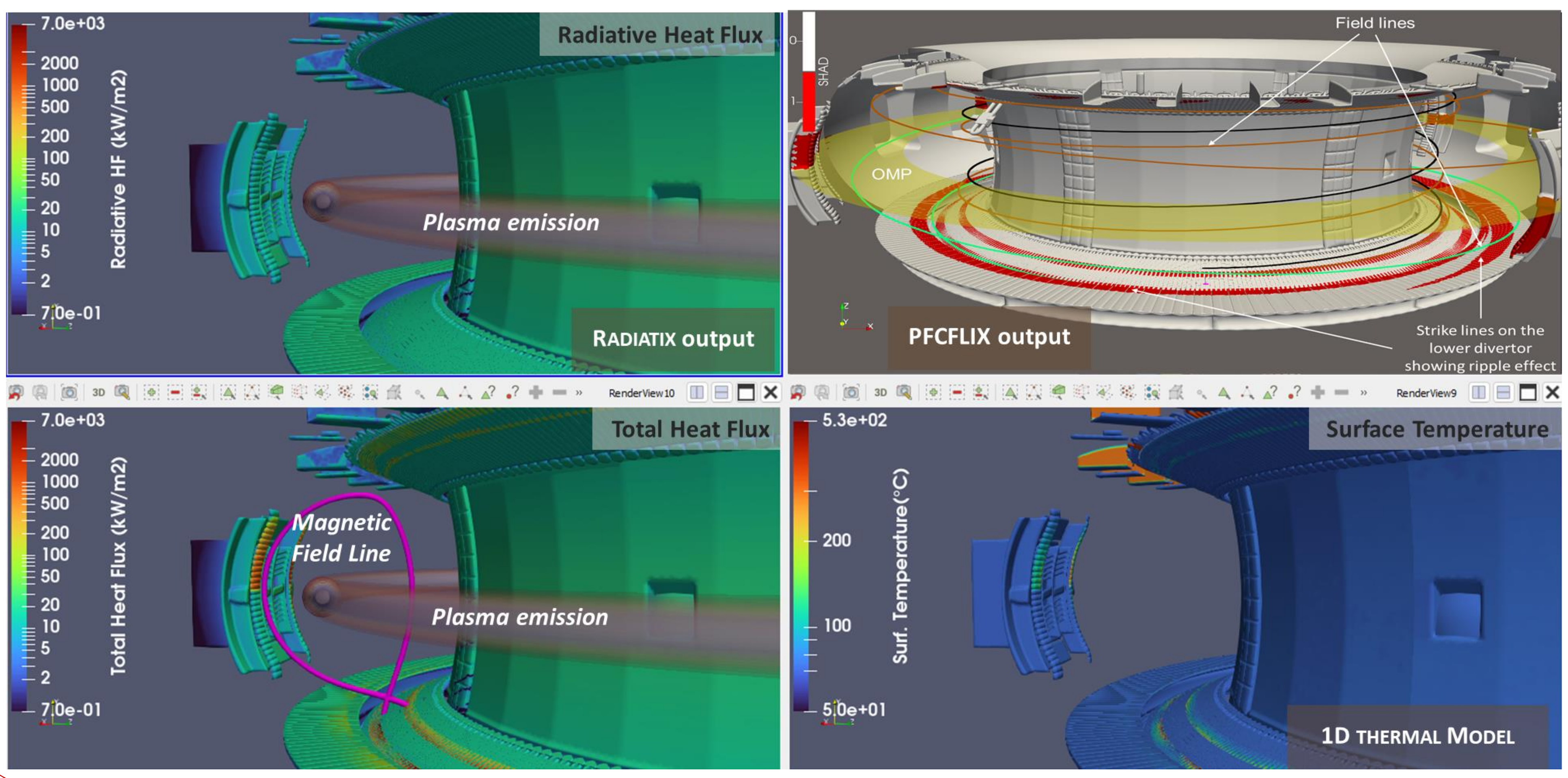


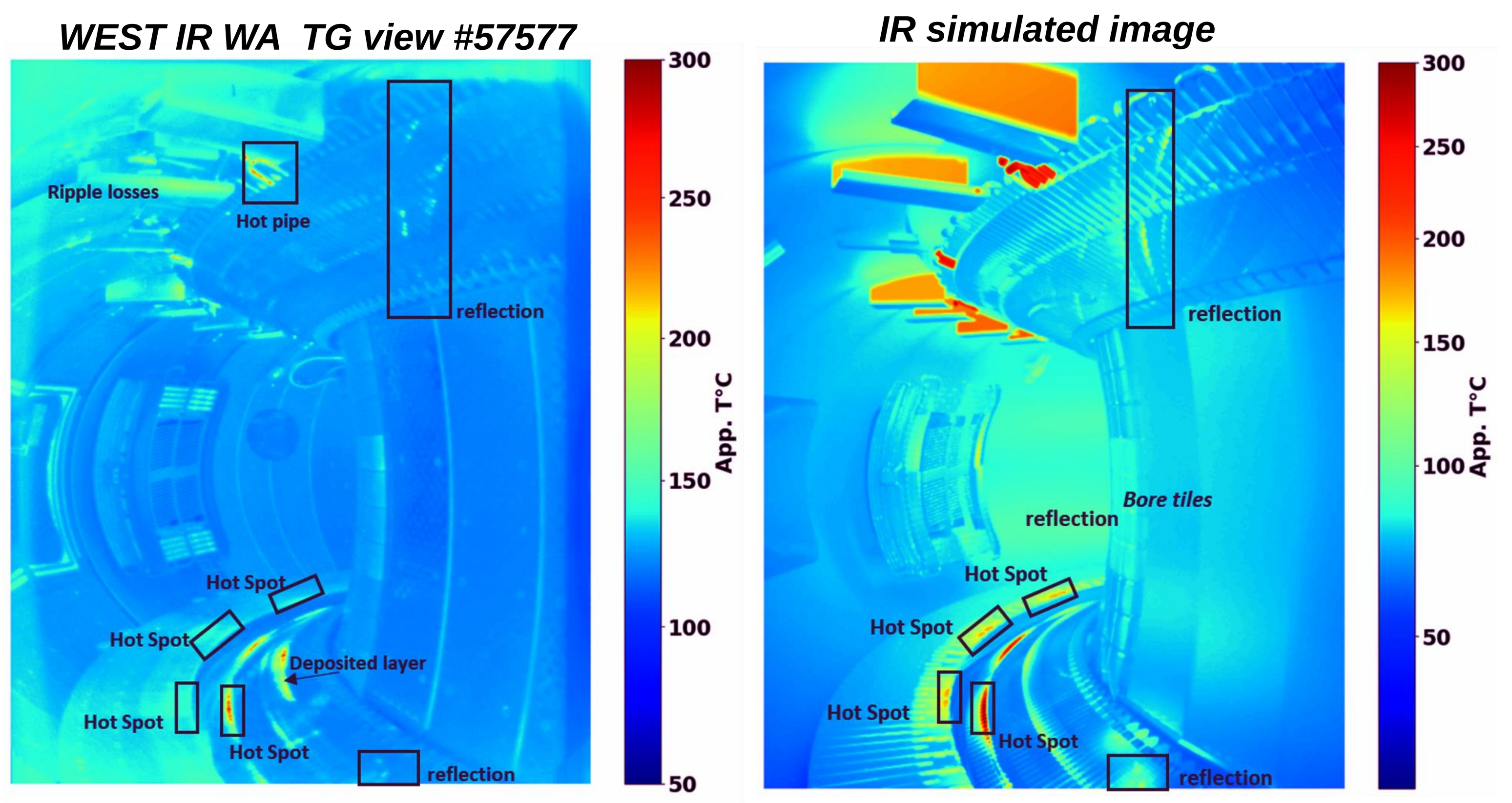
- **Digital Twin development (IMPACT)**
  - ✓ All primary codes for integration into IMPACT are available, with varying degrees of optimization (developed at CEA).
  - ✓ Standardized input and output data, ensuring compatibility with IMAS.
  - ✓ Automatic code coupling for seamless integration.
  - ✓ **Dedicated tools for experimental comparison** (camera alignment, 2D-3D mapping, post-processing, iso-curves, plotting)
- **MAGRYT benchmarking**
  - ✓ An experimental test bed that provides precise and controlled laboratory conditions to evaluate the thermal models and IR measurements predicted by IMPACT, within a vacuum chamber and at high temperatures up to 1000°C [4].
  - ✓ Utilized for comprehensive characterization of material properties -reflectance and emissivity wrt (λ T, angles, roughness), complemented by equipment at Basel University (such as goniometer, AFM, and confocal microscopy [5]
- **WEST benchmarking**
  - ✓ Utilizes local temperature measurements (thermocouples, Bragg fibers).
  - ✓ Employs special scenarios, such as baking-like scenarios with spatially uniform temperature.
  - ✓ Coupled with inverse models (using machine learning or matrix inversion) for estimating thermal scene parameters [6,7] (2025 EEG of A. Juven)

First Demonstration on WEST

- **First codes coupling for simulating realistic IR images and benchmarking with WEST IR images**

  - ✓ Simulation of WEST pulse #57577 - P_{TOT}=3 MW - (P_{SOL}=1.4 MW & P_{RAD}=1.6 MW)
  - ✓ **Significant improvement in computing time**, reduced from 10 hours to 2 minutes on an NVIDIA A40 GPU for heat flux computations and a few seconds for simulating IR images (with 5 millions nodes, 2 millions magnetic field lines and 2 billion photons rays)





Multiphysics codes coupling improves the consistency of simulated images

But **the simulation fidelity will depend on the quality of the the input data**

- Some physics data and models remains missing or inaccurate (antenna heat loads, e- losses, 3D thermal model, etc)
  - ➔ *contribution/expertise are welcome*
- Here manual adjustment of wall properties
  - ➔ *on going activities on inverse models to automate and improve the process*

[1] M.-H. Aumeunier *et al* , 2021, *Nucl. Mat. & Ener.*, **26**, 100879
[2] J. Gerardin *et al*, 2019, *Nucl. Mat. & Ener.*, **20**, 100568
[3] A.Juven *et al*, 2024, *Nucl. Mat. & Ener.*, **38**, 101562
[4] F. Retailleau *et al*, Measuring the directional emissivity of Plasma facing Components at hight temperature, Journal of Quantitative Spectroscopy and Radiative Transfer, under review
[5] F. Retailleau *et al*, *Optik - International Journal for Light and Electron Optics (2025)*, **338** (2025) 172476
[6] M.-H. Aumeunier *et al* ,, 2022, *Nucl. Mat. & Ener.*, **33**, 101231
[7] A.Juven *et al*, 2024, *IEEE International Workshop on Machine Learning for Signal Processing.*

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