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WPAC –DTE 2026-2027

IMPACT : an integrated suite for Advanced Thermal Protection of Tokamaks

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DSO meeting 24th August 2026

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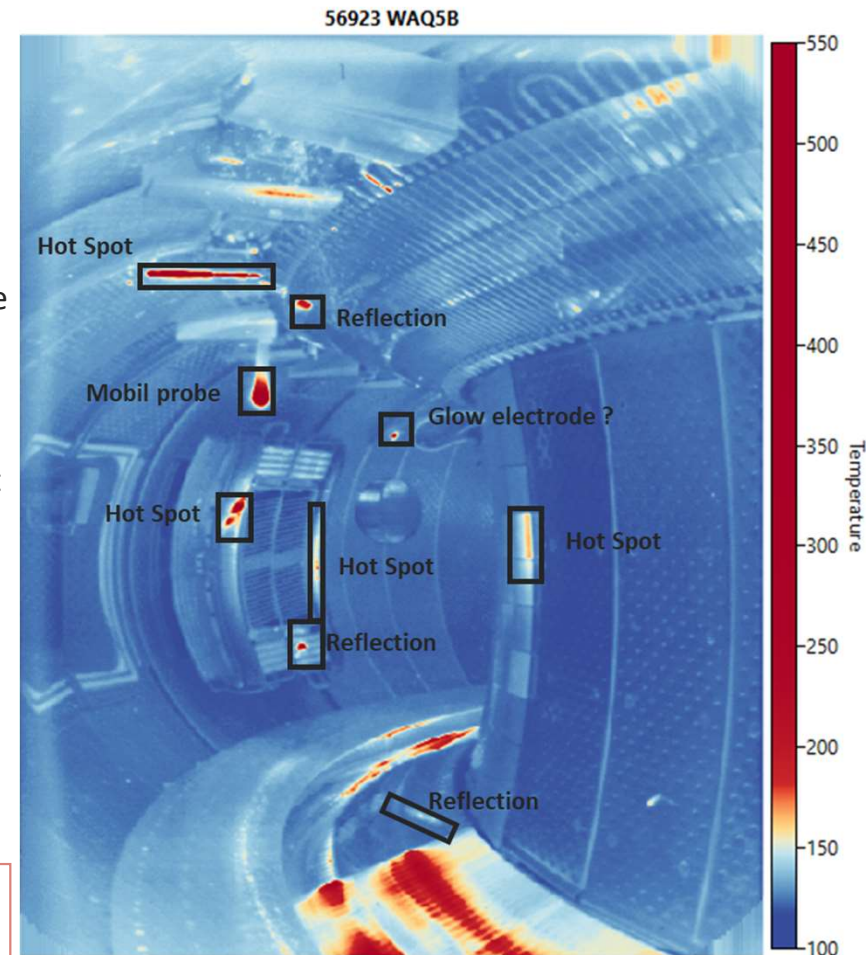


Context: First Wall protection challenges



- ❑ First Wall Protection is **challenging in metallic environment, especially the surface T° measurement** as surface state evolve as the plasma operation progress [1]
- ❑ This has consequences
 - ✓ on **machine protection** : with risk of component damage due to underestimation of surface temperature
 - ✓ on **operations**: limiting operational domain in cases of surface temperature over-estimation (e.g. due to reflections)
 - ✓ on **plasma-wall interaction understanding** with an incorrect estimation of surface temperature
- ❑ Our approach : **a simulation-assisted IR measurement tool** designed to support the **design phase** and **InfraRed analysis during the operations for advanced control of Plasma facing Components**
- ❑ The tool aims to:
 - ✓ **Predict** surface temperature behavior in extreme environment (hot and highly reflective)
 - ✓ **Quantify accurately** the impact of **surface state changes** (e.g., roughness, reflectivity)
 - ✓ **Integrate** these predictions into **inversion methods** for accurate thermal

➔ **Requires a high-fidelity, end-to-end simulation capable of modeling all physical phenomena involved in the measurement chain: IMPACT**



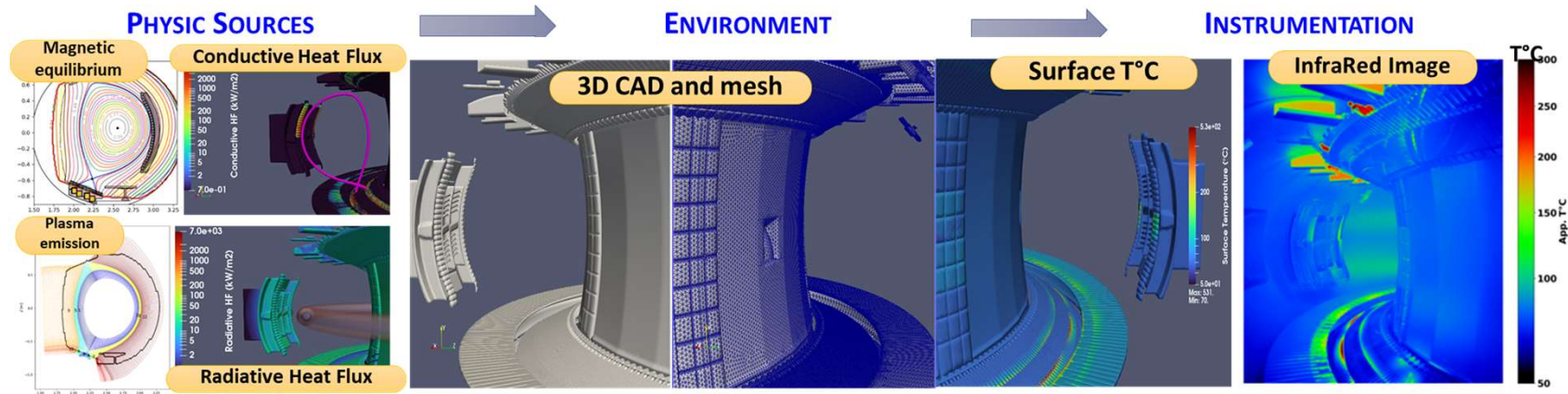
WEST Wide Angle View

2026-08-24

IMPACT: an InfraRed digital twin for Wall Thermal Protection and Analysis

IMPACT[1] is a **multi-physics software suite** designed to integrate and couple physical and engineering simulations involved in the observed thermal scene up to its measurement process

- ✓ **Heat Loads:** Derived from **plasma scenarios** (using **PFCFLUX** [2] + **RADIATIX** [3]).
- ✓ **Thermal Models:** Simulates **materials and cooling systems** (using **THERMIX**).
- ✓ **Photonic and Optics Models:** Accounts for **environment and camera specifications** (using **RAYMOND** [4]).



[1] M.-H. Aumeunier *et al* , 2026 *SOFT conference*

[2] J. Gerardin *et al*, 2019, *Nucl. Mat. & Ener.*, **20**, 100568

[3] D.Barrettepiana *et al*, 2026, *FED*, under submission

[4] A.Juven *et al*, 2024, *Nucl. Mat. & Ener.*, **38**, 101562

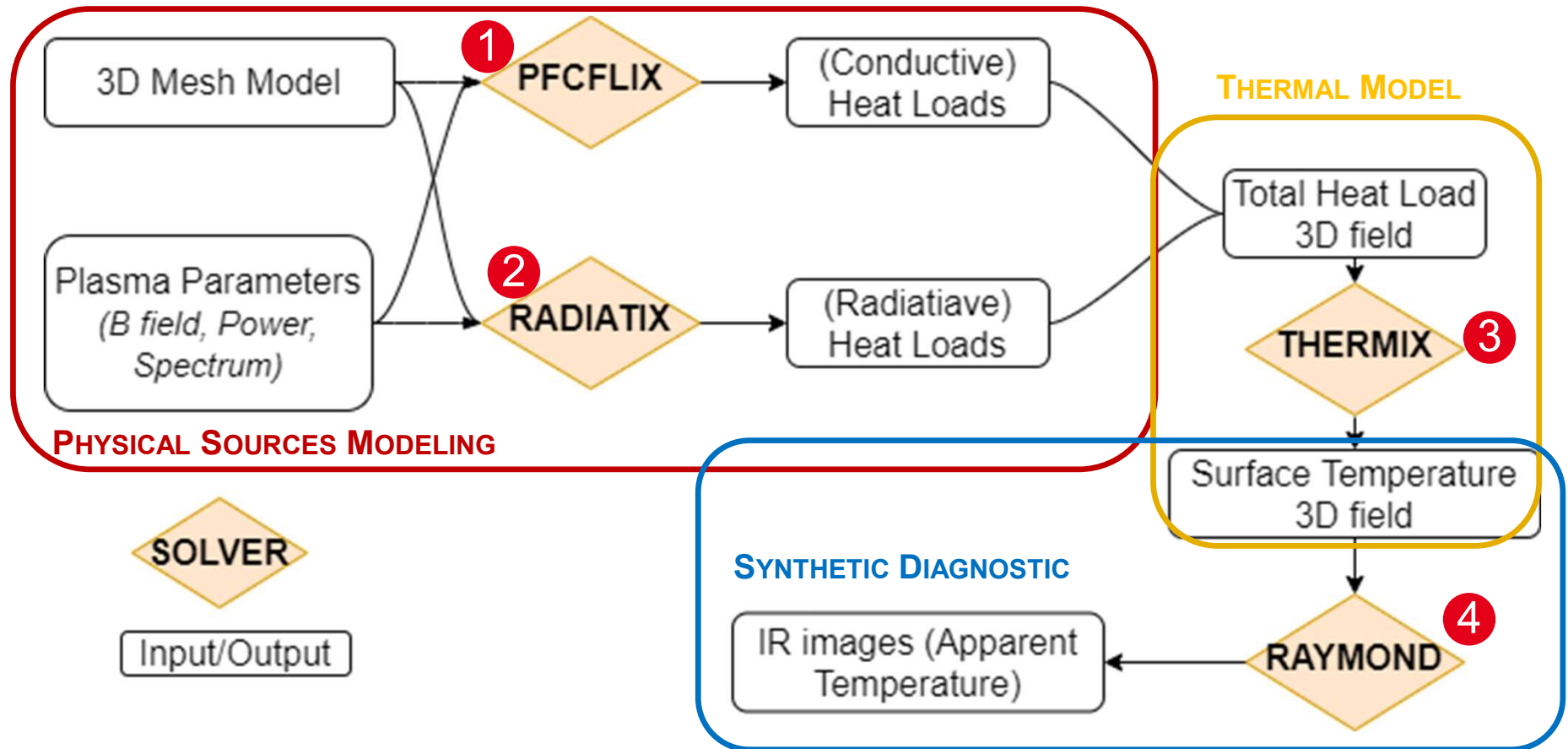


Key features of IMPACT suite: Accelerated Ray Tracing and Multi-Physics Coupling

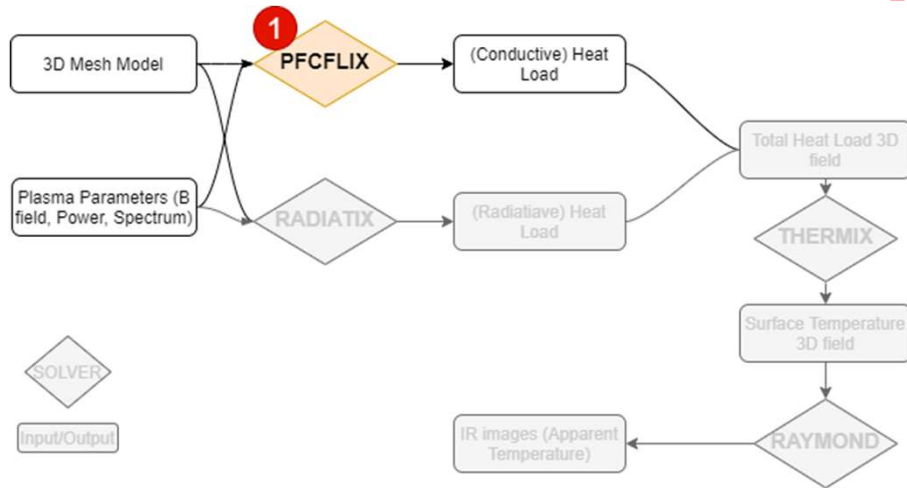
- **Statistical approach (*Monte Carlo ray tracing*)** widely adopted as the primary method for solvers in our simulations, **highly effective for multi-scale and multi-parametric** problems.
- **Accelerated Ray-Intersection:** Significant efforts have been invested to **optimize ray-intersection algorithms** – the computational core of the solvers [1]
- **Hardware Compatibility:** Implemented on both **GPU and CPU architectures** for maximum flexibility.
- **Unique Integrated Platform:** **3D data processing, execution and visualization** achieved using the SALOME solution
- **Code coupling, code parallelization, HPC/ACH compatibility** is ensured by **MUSCLE 3** (Multi-Scale Coupling Library & Environment)
- **Standardized Data:** Input and output data formats are standardized to ensure full compatibility with **IMAS**.

[1] H.Bec *et al.*, Advancements in Accelerated Monte Carlo Ray Tracing for Infrared Image Simulation: Application to Wall Monitoring in Fusion Devices, *18th Quantitative InfraRed Thermography Conference*, 2026

IMPACT suite description | Workflow to simulate IR images from given plasma scenario



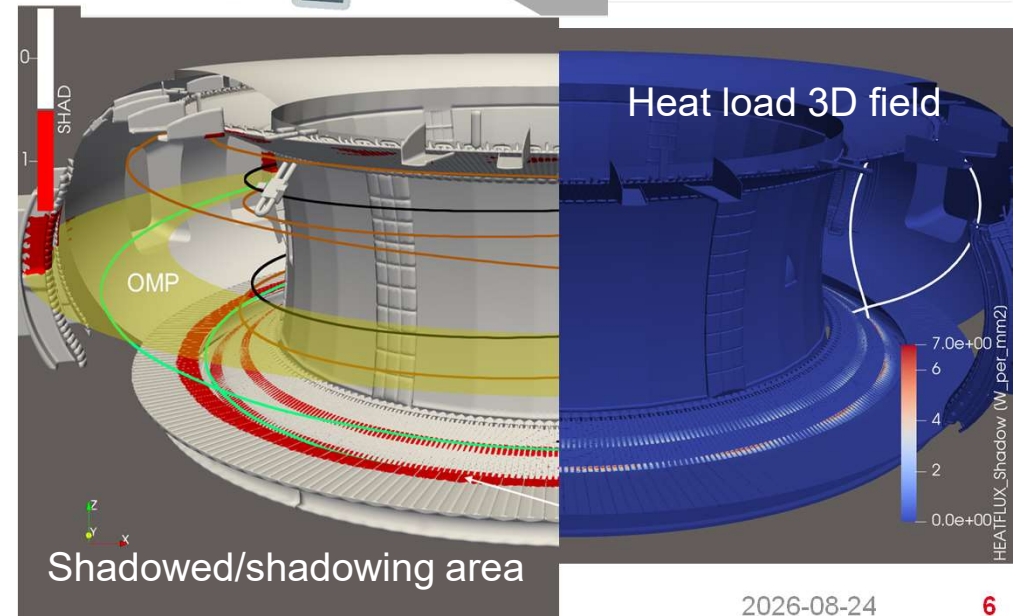
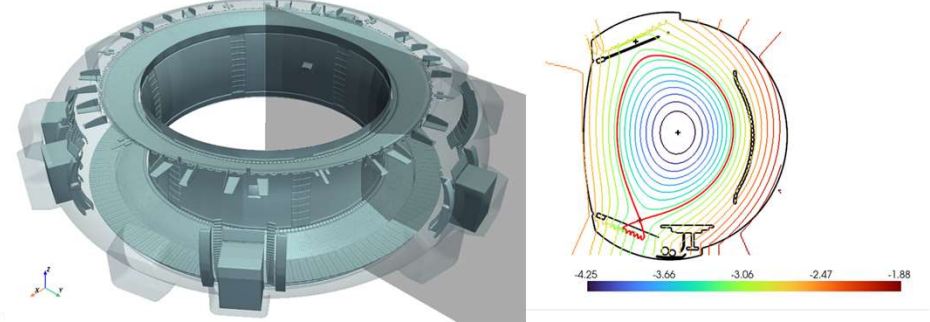
IMPACT suite description | Key Modules



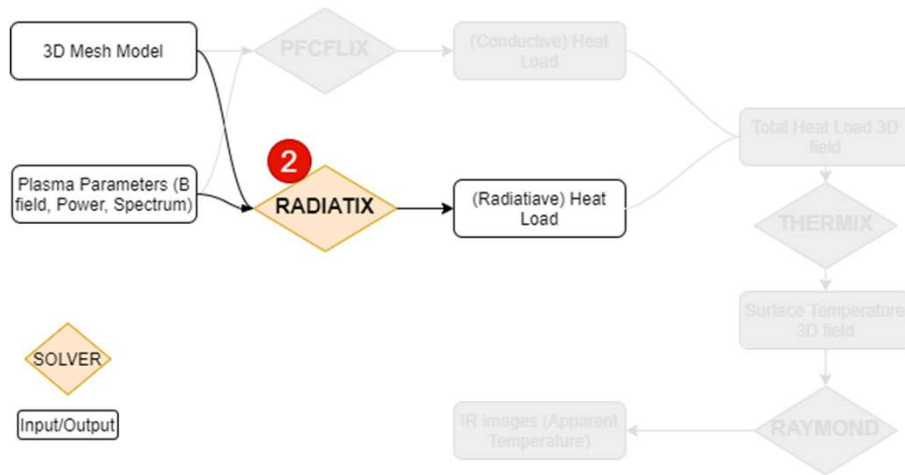
❑ PFCFLIX : GPU-Accelerated Field Line Tracing code (particles exhaust)

- Upgraded version of PFCFLUX with GPU acceleration for high-performance ray intersection computations
- Input:**
 - ✓ Plasma equilibrium
 - ✓ Plasma parameters (λ_q, P_{SOL} , inner – outer ratio)
- Output:** Conductive heat load 3D field

Geometrical calibration of field lines

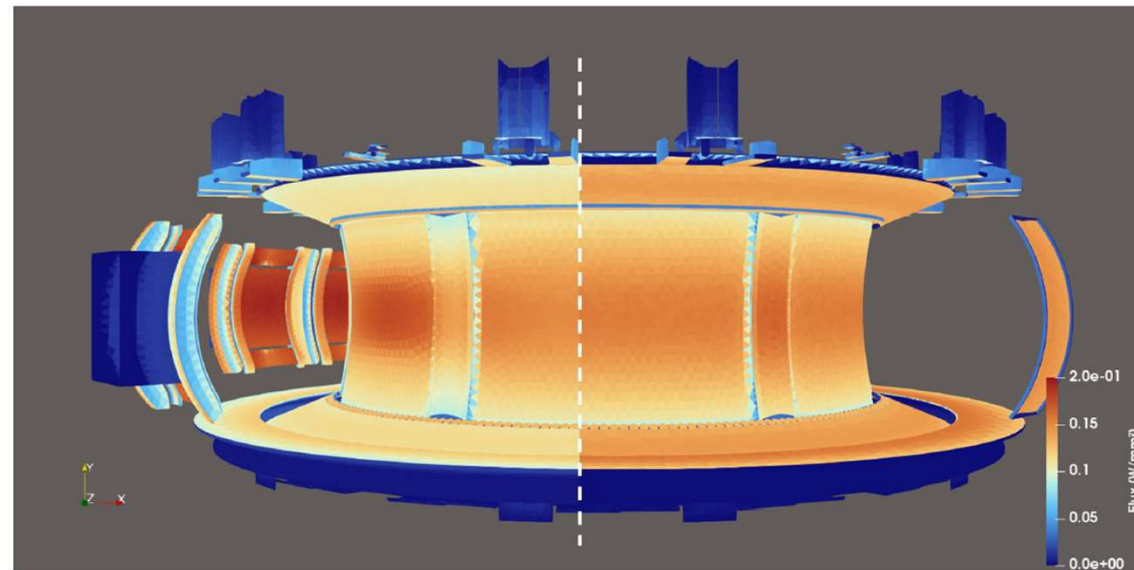


IMPACT suite description | Key Modules



FULL METALLIC MACHINE ($E=0.5$)

FULL ABSORBING MACHINE ($E=1$)

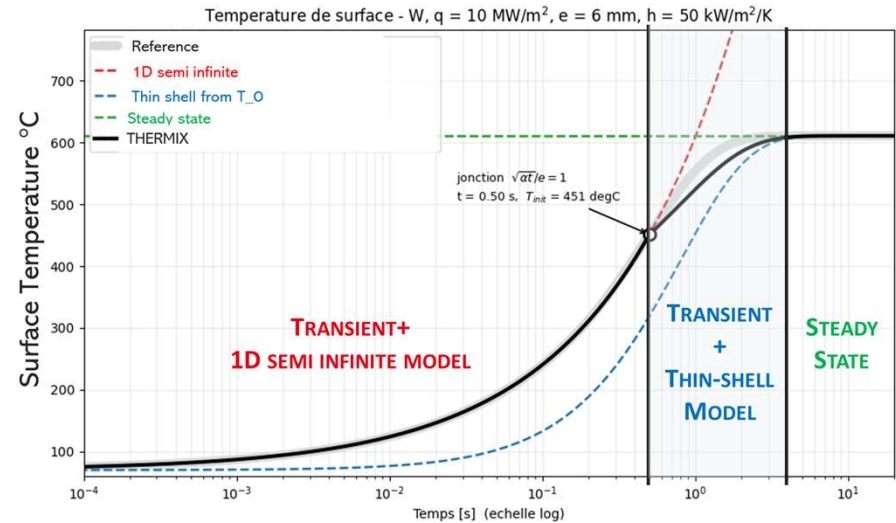
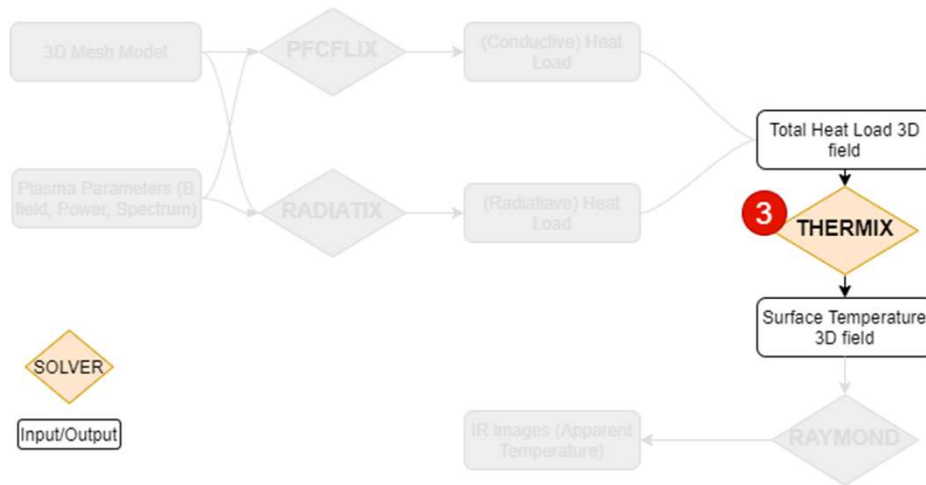


D.Barrettepiana et al., *RADIATIX: A GPU Monte Carlo Ray-Tracing Tool for Radiative Power Deposition in Metallic Environments*, 2026, FED, under submission

RADIATIX - Radiative power computation on in-vessel components

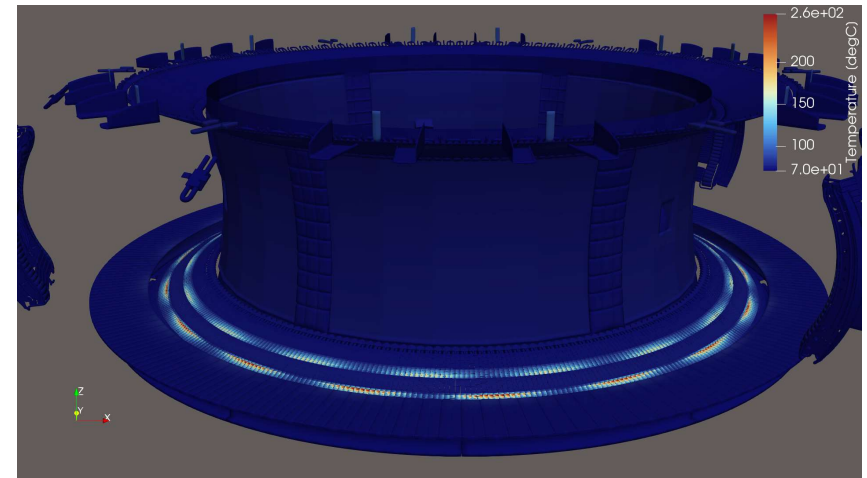
- New module including **multiple reflections** (non-uniform HF distributions) and plasma emission
- **Input:**
 - ✓ Plasma power
 - ✓ plasma shape and position
- **Output:** Radiative heat load 3D field

IMPACT suite description | Key Modules

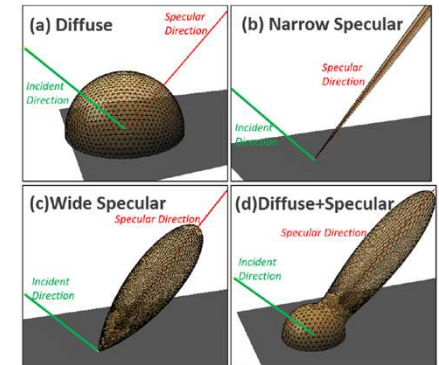
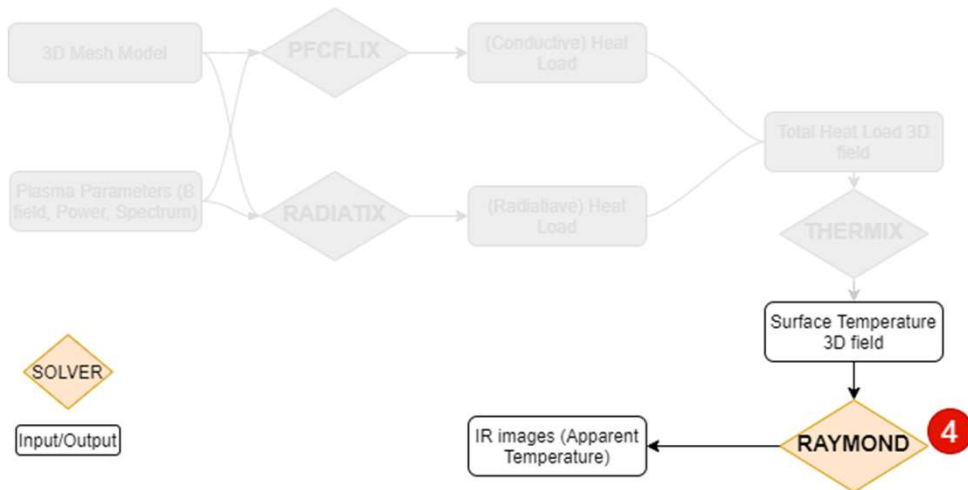


THERMIX - Simplified analytical model for temperature computation

- **Analytical thermal model** for transient and steady-state (screened poisson model)
- Simulates **inertial and cooling materials** using the **thin-shell approximation & semi-infinite model**
- Includes **lateral diffusion** for enhanced accuracy
- **Input:**
 - ✓ Heat load 3D field + boundary conditions
 - ✓ Material thermal properties
- **Output:** Surface temperature 3D field



IMPACT suite description | Key Modules



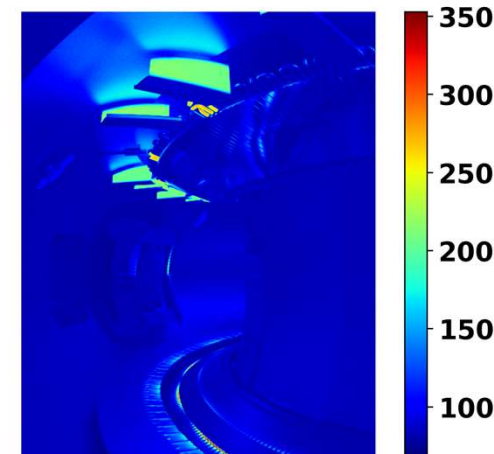
RAYMOND - Photon transport model for IR synthetic images

- ✓ Monte Carlo Ray Tracing (MCRT) for 3D ray propagation in complex geometries
- ✓ Incorporates advanced optical properties:
 - ✓ **Angular-dependent emissivity**
 - ✓ **BRDF** (Bidirectional Reflectance Distribution Function).
- ✓ Reproduces **camera views**, including **lens optical deformations**
- **Input:**
 - ✓ Surface temperature 3D field
 - ✓ Optical materials properties
 - ✓ Camera parameters
- **Output:** IR camera images (free-reflections and with reflections)

Perfect simulated image



With distortions

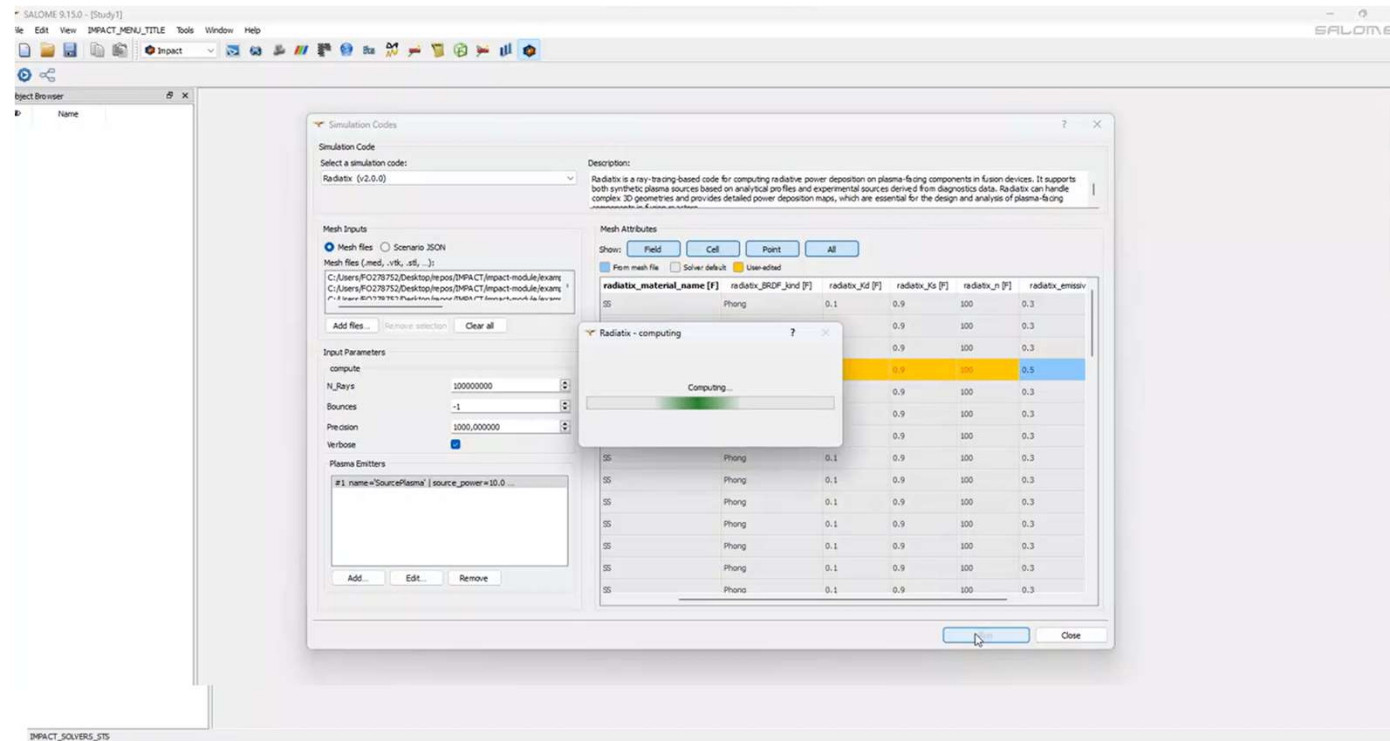


A.Juven *et al*, 2024, *Nucl. Mat. & Ener.*, 38, 101562

IMPACT demonstration in its usage



- ❑ **Input data definition:** define 3D geometry, materials properties
 - ✓ Folder including all 3D geometry (VTK/VTP, MED)
 - ✓ Connected to materials library providing default values of materials properties
 - ✓ Possible to add new materials (custom)
- ❑ **Code chaining:** set up the **sequence of codes** to be executed in the workflow
 - ✓ User friendly interface to set up the code chaining
- ❑ **Code Input Configuration :** define the **inputs for each code** in the chain
 - ✓ Numbers of samples, pulse parameters, reflections-numbers...
 - ✓ Default parameters (or custom)
- ❑ **Code execution:** run the workflow to perform simulations or calculations
 - ✓ Detect automatically if GPU or CPU (under progress)
- ❑ **Visualization:** visualize and **export** the results for analysis and interpretation
 - ✓ Visualisation in SALOME/Paraview
 - ✓ Export HDF5, IMAS format (under progress)



IMPACT demonstration on WEST pulse & performances



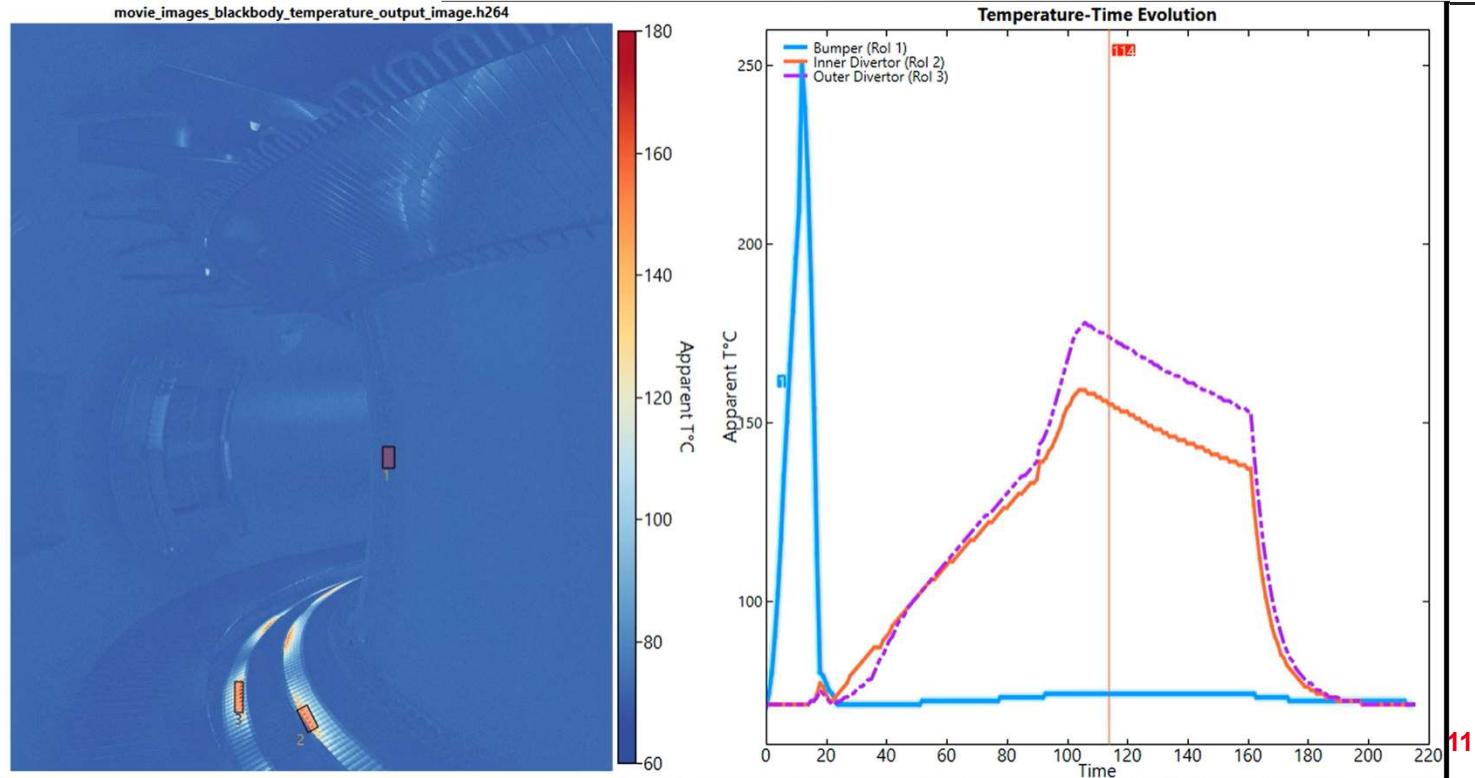
Performance in sequential mode: end-to-end simulation time ~ 1 mn on an A40 NVIDIA GPU for one image !!!

Scene configuration: >5 Millions elements, 50 M rays for radiatix, 512 rays/pixels, 640x512 px for Raymond

For given plasma scenario/one image	PFCFLIX	RADIATIX	THERMIX	RAYMOND	TOTAL
PC (12 cores 2.8 Ghz, Nvidia A500 4Go, 32 Go RAM)	~ 30s	~ 10s	~ 200s	~ 30s	<5 mn
Alnair server (48 cores, Nvidia A40 46Go, 96Go RAM)	~ 10s	~ 2,5s	~ 50s	~ 10s	1mn12s

Thanks to solver optimization, GPU acceleration, and code coupling on a unified integration platform, **we can now simulate entire IR movies of WEST pulses** in just minutes to hours

Simulation of WEST pulse #57757
(216 images)





VVUQ process

□ Verification

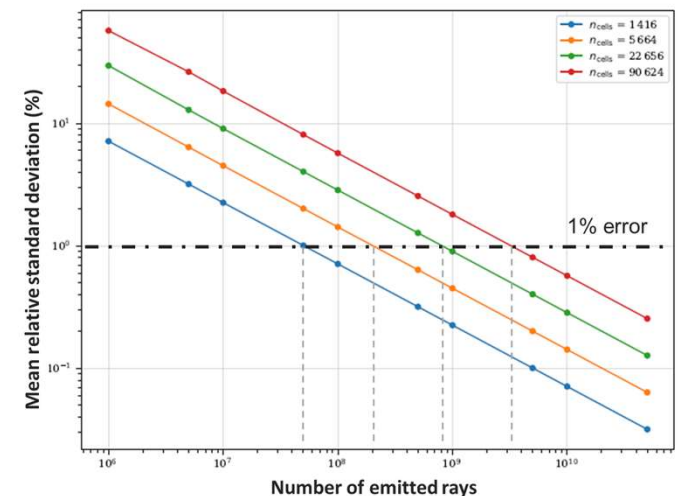
- ✓ Implementation of **dedicated tests (unit tests)** to ensure **absence of bugs** and **reproducibility/convergence of calculations for all platform** (CPU/GPU, Windows/Linux) as developments progress
- ✓ Validation pipeline ready to use, unit tests under progress: 92% code coverage for 3D data manager library, to be done for solvers

□ Validation: comparison of simulation with experimental data

- ✓ **Laboratory (Controlled Environment)**: Validation using **MAGRYT** experiments.
- ✓ **In-Situ (Real-World Conditions)**: Validation on **WEST** with comparison to **embedded diagnostics**

□ Uncertainties quantification

- ✓ **Statistical Errors**: Evaluation of **Monte Carlo uncertainties errors** due to sampling rate to assess reliability



D.Barrettepiana *et al.*, *RADIATIX: A GPU Monte Carlo Ray-Tracing Tool for Radiative Power Deposition in Metallic Environments*, 2026, FED, under submission

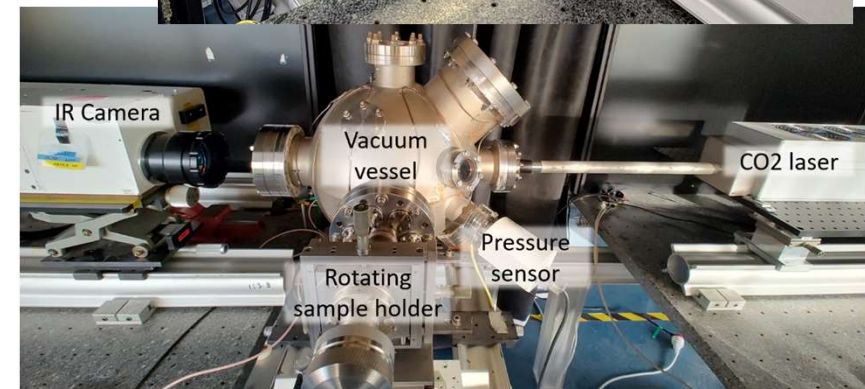
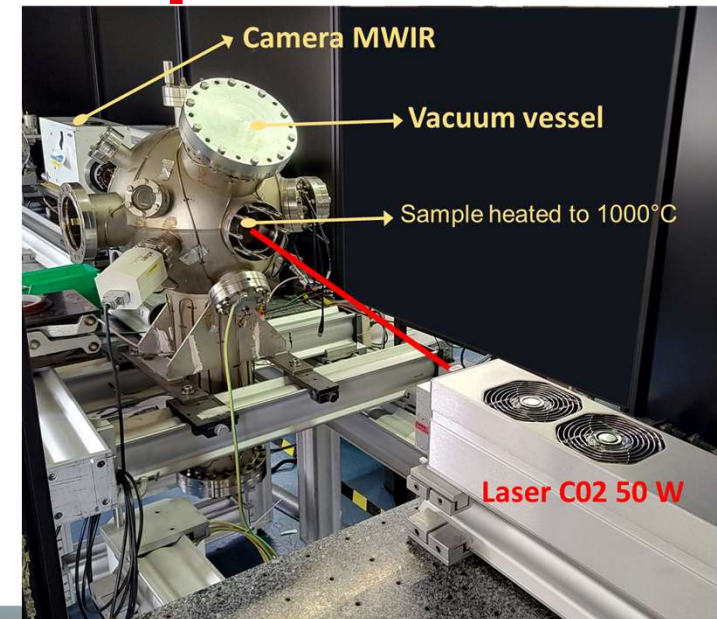
Validation of IMPACT using MAGRYT experiment

MAGRYT objectives

- ❑ **Complete characterization of material properties** (emissivity & reflectance) across the visible to IR range, considering temperature and incident/viewing angle dependencies
 - ➔ Essential step to improve the realism of simulations and constrain variation ranges of input parameters
- ❑ **Validate IR digital twins** in controlled environment replicating the tokamak conditions (fully surrounding hot wall & reflective surfaces)
 - ➔ A part of VVUQ process of IR digital twin

Ongoing Updates to the MAGRYT Test Bed

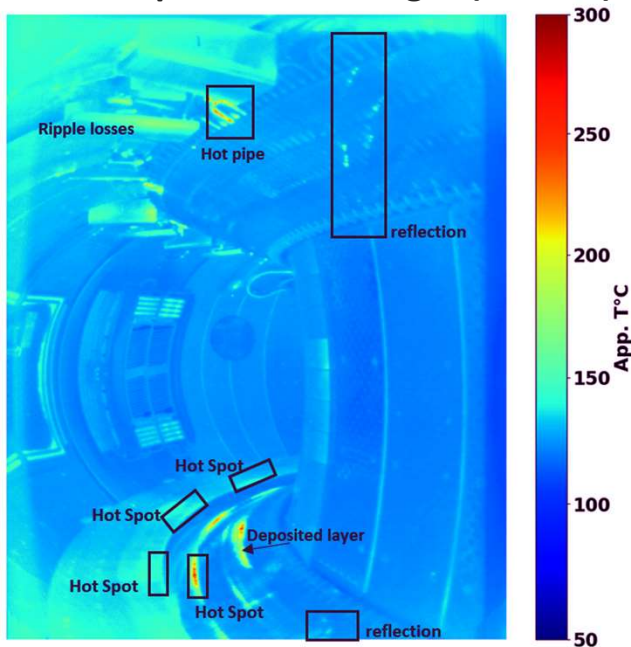
- Implementation of a new control method featuring laser power control
- Upgrade of the environmental heating system
- Optimization of baffles to minimize parasitic light



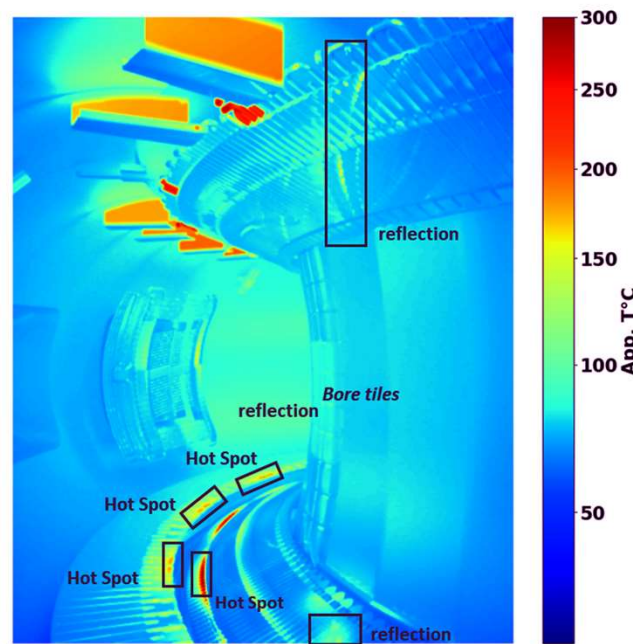
Validation of IMPACT platform using WEST



WEST Experimental images (#57757)



Simulated images



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, **B field accuracy**, **3D thermal model**, etc)

→ contribution/expertise: joint work under discussion with **IPP-Garching** for using & benchmarking volumic heating model + RE simulation (**TSVV M Hoeltz**)

- Here manual adjustment of wall properties

→ on going activities on inverse models to automate and improve the process (**EEG2025 A. Juven**)



Summary and outlooks of IMPACT

IMPACT is an **integrated software suite** that combines **accelerated ray tracing** and **multi-physics coupling** to enable **Advanced Thermal Protection for Tokamaks**

❑ **IMPACT development has well progressed**

- New accelerated version of field line tracing code PFCFLIX implemented
- New solver to compute plasma radiative heat load (needed for XPR scenario)
- New analytical thermal solver capable of handling both transient and steady state, inertial & cooled
- **VVUQ framework** is implemented
- **GPU optimisation** achieved ~1 mn of computing (on GPU A40) from given plasma scenario to IR image (including 4 solvers)
 - **Integration with MUSCLE 3** will further improve performances through code parallelisation

➔ First version of IMPACT is expected to be operational on Linux and GPU by **December 2026**.

❑ **Experimental validation of IMPACT**

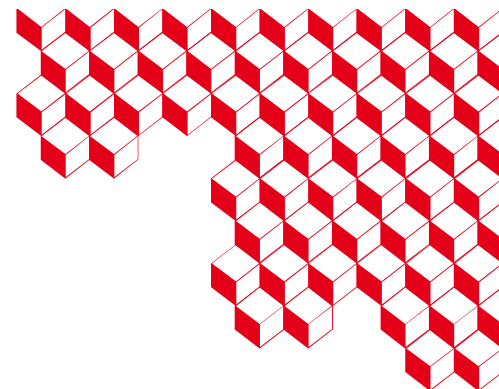
- **Ongoing improvements** to the **MAGRYT test bed** to enhance **control of the heating system**
- **First comparison** between MAGRYT experimental data and simulation results is expected by the **end of 2026**
- IMPACT V1 will be deployed on WEST and **tested by WEST operators** starting in **2027**

❑ **IMPACT and its application**

- Use and test under the TSSV framework in collaboration with M. Hoeltz
- Planned for DTT and DIII-D tokamaks, where IRFM is involved in IR endoscope design
- Under discussion with IO (Diagnostic & Science Division) for potential use in the FWHL (FW Heat Load Control)



Merci



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