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Virtual Prototyping Tools for the JET Divertor

D. Iglesias[a], I. Balboa[a], P. Bunting[a], S. Equembri[b], J. Hollocombe[a], A. Huber[c], G Matthews[a], V. Riccardo[a], F. Rimini[a], S. Silburn[a], D. Valcarcel[a]

[a] *UKAEA-CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
[b] *UPM-I2A2, Technical University of Madrid, 28031 Madrid, Spain*
[c] *Institute of Energy and Climate Research – Plasma Physics, Forschungszentrum Jülich, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany*

Abstract

Virtual prototyping enhances traditional engineering analysis workflow when a quick evaluation of complex load cases is required. During design, commissioning or operating phases, components can be virtually tested in realistic conditions by using previously validated numerical models and experimental databases

Three complementary applications have been developed under this approach for the JET divertor. Their aim is increasing its operational range, reliability, and understanding. At the same time, they are designed to be extensible to any plasma facing component.

1. Introduction and requirements

JET is being enhanced for a second D-T operations campaign, which will push the limits of ITER-like Wall components [1], and will also pose a challenge for diagnostic systems. A set of tools are in development with the objective of mitigating risks related to the unavailability or unreliability of protection IR cameras. In addition, increased accuracy will be provided to the understanding and the interpretation of these experiments.

The basic requirements for the new codes are grouped depending on the operating phase:

- Pulse preparation: The use of virtual modelling in this stage is to have a better estimate of the effect of the pulse in order to comply to the JET Operating Instructions (JOIs).

- Pulse monitoring: Real-time temperature estimation need reliable 2D nonlinear diffusion models.

- Post-pulse processing: Virtual Thermal Map (VTM) uses protection IR cameras. A backup for recreating the surface and bulk temperatures shall be provided through quick analysis.

- Condition and design assessment: any change on divertor components needs to be checked to actual experimental conditions, in order to evaluate the impact of any deviation from nominal geometry and properties, or even to assess new designs.

All of the previous simulation scenarios are responsibility of different experts who do not necessarily have numerical analysis experience.

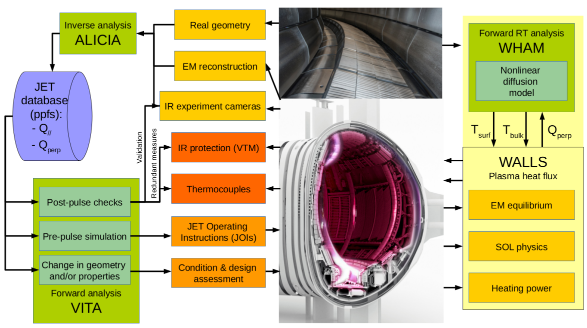

Figure 1: Overall workflow scheme

2. Objectives, formulation and models

In order to provide the functionality needed, each of the tools tackles one specific phase. As opposed to a typical analysis workflow, the main objective is maximizing the final user's productivity. Their design therefore hides any numerical complexity, and allows their operation using machine and experimental parameters. Several models are provided as a black-box, which is previously validated by analyst experts, but its source code can be inspected, audited, and extended at any time.

Formulation used for this first implementation is based on the thermal equilibrium using the Principle of Virtual Power. Each of the terms of the assembled system of equations are calculated from the numerical integration of the following residual equation:

$$\delta\dot{\Pi} = \delta\dot{\Pi}_{capacitance} - \delta\dot{\Pi}_{external} - \delta\dot{\Pi}_{conduction} = 0 \quad (1)$$

Each of the previous contribution terms can be expressed in the reference configuration [2] as:

$$\delta\dot{\Pi}_{capacitance} = \int_{\mathcal{B}} \rho C_p \frac{d\Theta}{dt} \delta\Theta \, dV \quad (2)$$

$$\delta\dot{\Pi}_{external} = \int_{\partial B} \boldsymbol{q} \delta\Theta \cdot \boldsymbol{n} \, dS \quad (3)$$

$$\delta\dot{\Pi}_{conduction} = \int_{\mathcal{B}} (\boldsymbol{\kappa}\nabla\Theta) \cdot \nabla\delta\Theta \, dV \quad (4)$$

where the conductivity tensor $\boldsymbol{\kappa}$ and the specific heat capacity c_p, are temperature dependent, $f(\Theta)$, properties of the material, and the density ρ is considered constant.

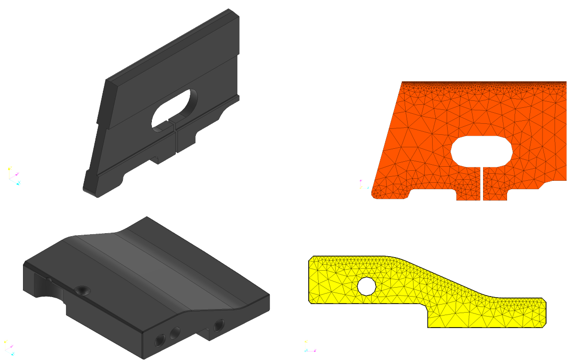

Figure 2: 3D CAD (left) and 2D numerical discretization (right) of divertor components: Tile 5 (top) and tile 6 (bottom).

Fully nonlinear finite Element (FE) approximations are used for all analyses, with some Galerkin meshfree enhancements [3] when applicable. Several defeaturing levels are applied when speed is a concern. Initial implementation uses 2D models shown in Figure 2, but design is extensible to 3D in the future. Orthotropic effects, as well as Planck radiation or convection cooling are also foreseen.

Coatings and deposits can be modelled with exact properties, by means of a proper layer formulation which is available for all the applications. Usual parameters for the JET divertor tiles range from 10–20 µm thickness for the W coating on CFC tiles, to 50 µm node separation in direction normal to the surface for modelling ELMs accurately in bulk W tiles.

3. ALICIA

The *Augmented Lagrangian Implicit Constrained Inverse Analysis* tool improves the existing heat flux calculation capabilities provided by other codes in the following aspects:

- Implicit integration augmented Lagrangian ensures temperature controlled smooth convergence.
- Very fine node distribution allows precise capture of transient events.
- Multiple materials, irregular geometries, and proper layer modelling are available if required.
- Execution parameters correspond to the component's physical properties, and IR system characteristics (typically 9 kHz and 1.7mm pixel width).

The IR temperature measurements over time [4] are applied as a constrained Dirichlet boundary condition. In general, this is accomplished by adding a new term to equation 1. Existing inverse codes used for Fusion devices [5] use an approach which tries to simulate a deposited layer by a heat flux in the form of $q_s = \alpha\Delta T$. The interpretation of that flux lacks to consider the thermal capacity of the assumed deposited material. This term is in fact equivalent to a Penalty method, which stores energy proportional to a numerical temperature

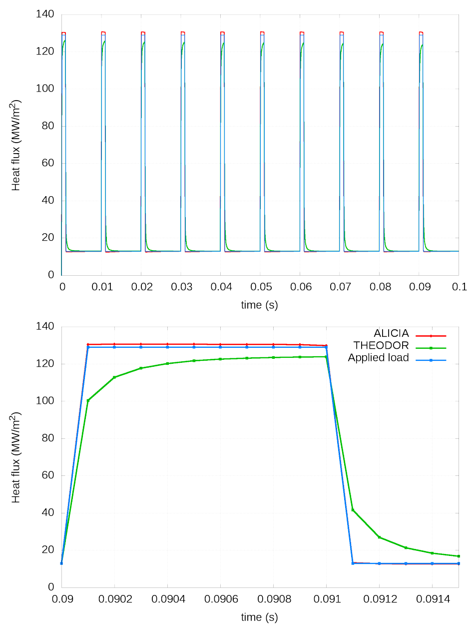

Figure 3: Fast transient benchmark: Comparison between THEODOR and ALICIA.

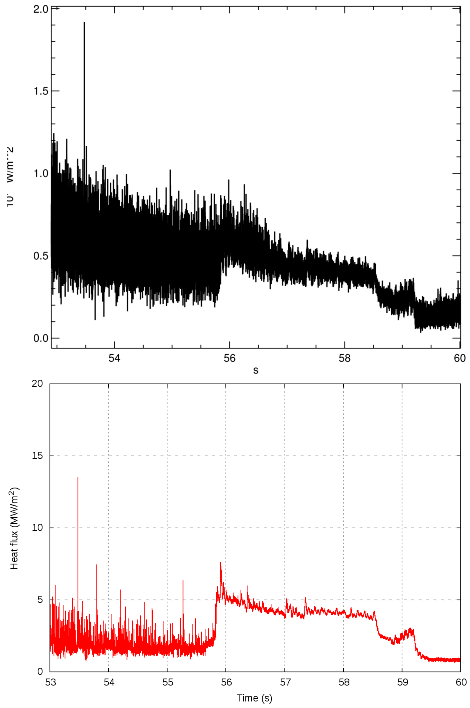

Figure 4: Calculated maximum heat flux for an L-mode shot (JPN 89162): THEODOR (top), and ALICIA (bottom).

difference, ΔT, in a similar way to a spring. The Augmented Lagrangian scheme detailed in [2] adds a loop to the numerical procedure reducing the temperature difference until is very small, $\Delta T < \epsilon$. This fixes the constraint without modifying the power balance, therefore increasing the accuracy.

The resulting output shows to a much better capture of extremely fast events, such as filaments and ELMs. Figure 3 compares the present code used at JET with the new code ALICIA. The test is carried out using a synthetic IR signal; generated by forward analysis using ANSYS with an extremely fine mesh. The Augmented Lagrangian scheme along with the refined mesh towards the plasma facing surface allows an almost perfect match of the varying load, while at the same time reduces the numerical noise, as shown in Figure 4 for L-mode reconstruction comparison using real JET data.

4. VITA

Virtual Thermal Analysis is a forward simulation code featuring a GUI—shown in Figure 5—for ease of use. Its main goal is to allow both quick and accurate analysis of components to users by setting global machine parameters, recreating previous stored pulses, or a mix of both. The time varying boundary conditions and integration parameters are automatically set, therefore not requiring the user to deal with numerical details.

It is designed for pulse preparation activities, post-pulse checks, and integrity assessments of damaged components. It might as well be used to test alternative divertor configurations under experimental conditions. It includes the following capabilities:

- Automatic readout of experimental conditions, as stored in JET database.
- Manual input of machine parameters, with automatic setting of boundary conditions.
- Selection of In-vessel component and accuracy of the approximation.
- Direct output of diagnostic synthetic signals.

Input power from NBI and RF, along with the radiated and toroidal wetted fractions define the total power for the model. The footprint of the plasma is then characterized by three available functions: triangular, skewed Gaussian, or exponential convoluted with a Gaussian. The power profile is combined with the strike point time evolution, defining the power at each boundary point. The use of analytical functions for the heat flux profile allows calculating the exact power density at every surface node in an energy consistent manner (i.e. eliminating interpolation errors). In addition, the application of meshfree C^∞ shape functions greatly increases the accuracy of surface temperature simulation.

5. WHAM

WALLS Heat Analysis Module is the first nonlinear thermal finite element solver designed to work in a tokamak real time machine protection system. It is included as a module for the Wall Load Limitation System (WALLS), simulating the transient 2D thermal response of plasma facing components. It must output the synthetic tile surface temperatures within a strict cycle time limit of 8.5 ms, and should operate continuously for months without any external intervention. Successful tests have been performed to comply with the stability requirements, as shown in Figure 6.

The module is initialized by the definition of the model geometry and properties, and the boundary interface nodes. The WALLS system directly computes the value for the total power at each node, which is an input to WHAM at each time step. There is also a function for resetting the model's temperatures to a value (e.g. thermocouples measurement) right before the beginning of each pulse.

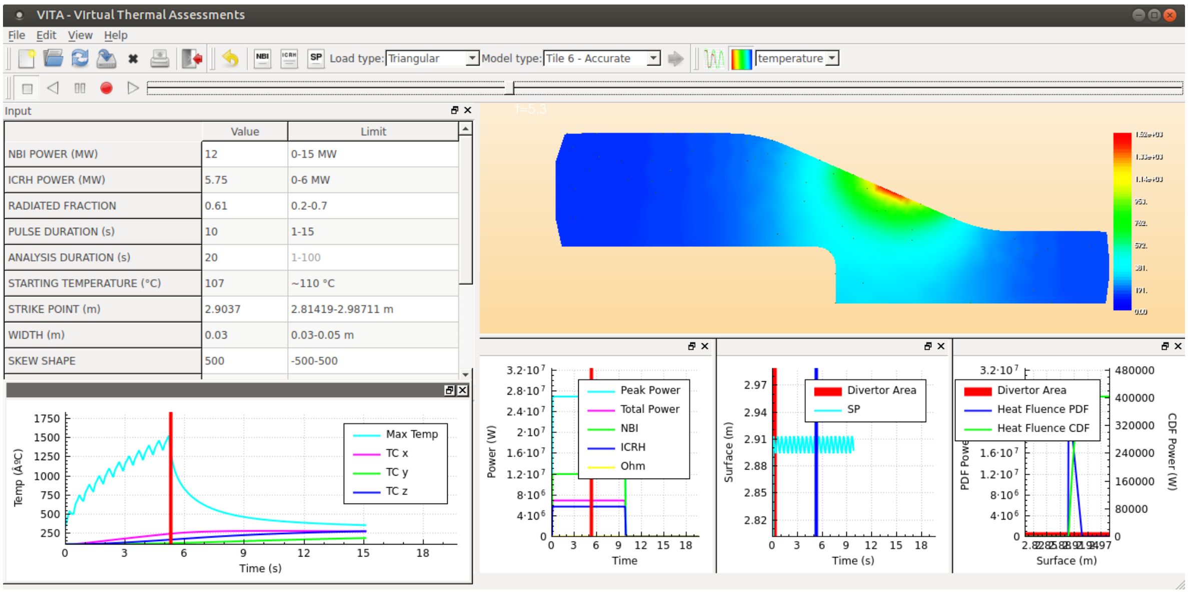

Figure 5: VITA user's interface during tile 6 sweeping simulation.

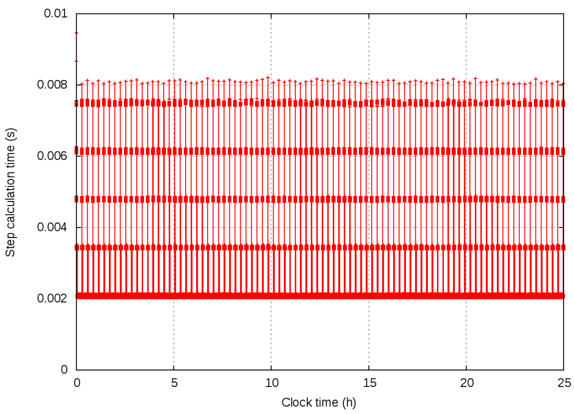

Figure 6: Stability analysis results for WHAM

6. Conclusions and further work

Three complimentary applications have been introduced for enhancing JET divertor operations using a Virtual Prototyping approach. All of them have been verified using commercial codes (Abaqus, Ansys), extensively validated to experimental data, and can be executed using exclusively machine parameters, diagnostics characteristics, and material properties. The use of modern C++11 language with a minimum set of functionality in each class maximizes execution speed and maintainability of the codes.

The final goal is increasing the JET reliability, operational limits, and accuracy of experimental results. Pulse preparation, IR diagnostics fallback, and real-time protection systems have been enhanced by this first implementation. This work will be continued using user and final customer's feedback, and application to other in-vessel components and machines will follow.

Acknowledgements

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