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Digital twin applications for the JET divertor

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ABSTRACT

Digital twin techniques enhance traditional engineering analysis workflows of existing systems when a realistic evaluation of a component under complex operating conditions is required. During preparation, commissioning and operating phases, components can be virtually tested by using validated numerical models, operational expertise, and experimental databases.

Three complementary applications have been developed under this approach. The numerical models used for the divertor tiles are based on continuum mechanics formulations. Their loading conditions are defined using the current physics and engineering understanding of a combination of experimental measurements. The aim of these tools is to increase operational range, reliability, and predictability of the JET divertor.

1. Introduction and requirements

JET is being enhanced for a second D-T operations campaign, which will push the limits of ITER-like Wall (ILW) 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, as shown in Fig. 1, 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 the responsibility of different experts who do not necessarily have numerical analysis experience.

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.

The formulation used for this first implementation is based on the thermal equilibrium using the Principle of Virtual Power. The contributions to the power virtual variation, $\delta\dot{\Pi}$, are calculated from the numerical integration of the following residual equation:

$$\delta\dot{\Pi} = \delta\dot{\Pi}_{\text{capacitance}} - \delta\dot{\Pi}_{\text{external}} - \delta\dot{\Pi}_{\text{conduction}} = 0 \tag{1}$$

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

$$\delta\dot{\Pi}_{\text{capacitance}} = \int_{\mathscr{B}} \rho c_p \frac{\text{dT}}{\text{dt}} \delta T \ \text{dV} \tag{2}$$

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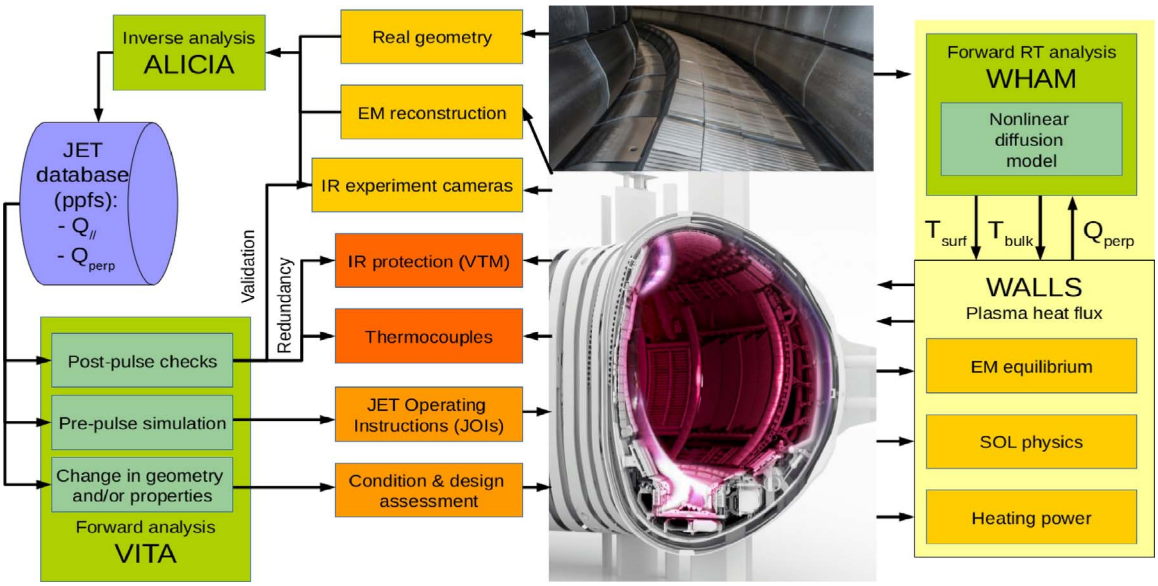

Fig. 1. Overall workflow scheme.

$$\delta\dot{\Pi}_{\text{external}} = \int_{\partial\mathscr{B}} \boldsymbol{q}\delta T\cdot\boldsymbol{n}\ \text{dS} \tag{3}$$

$$\delta\dot{\Pi}_{\text{conduction}} = \int_{\mathscr{B}} (\boldsymbol{\kappa}\nabla T)\cdot\nabla\delta T\ \text{dV} \tag{4}$$

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

Fully nonlinear finite element (FE) approximations are used for all analyses, with some Galerkin meshfree enhancements [3] when applicable. Several de-featuring levels are applied when speed is a concern. Initial implementation uses 2D models shown in Fig. 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 to 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 uses the measured IR temperatures of the divertor tiles to compute the incoming heat flux density over time. Execution parameters correspond

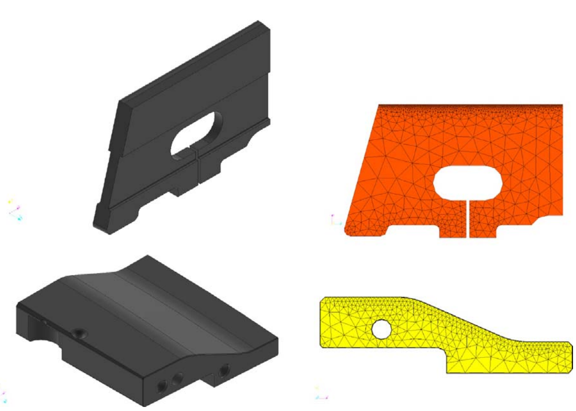

Fig. 2. 3D CAD (left) and 2D numerical discretization (right) of divertor components: tile 5 (top) and tile 6 (bottom).

to the component's physical properties, and IR system characteristics (typically 9 kHz and 1.7 mm pixel width).

The IR temperature measurements in Tungsten surfaces [4] are applied to the numerical model as a constrained Dirichlet boundary condition. In general, this is accomplished by adding a new term to Eq. (1). Existing inverse codes used for Fusion devices such as THEODOR [5], TACO [6], and QFLUX_2D [7] add a constraint equation in the form of $q_s = \alpha\Delta T$, which is interpreted as a deposited layer without any thermal capacity [8]. This term is not needed for the ILW and if considered would be in fact equivalent to a penalty method, which stores energy proportional to a numerical temperature 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 it is very small, $\Delta T < \epsilon$. This imposes the constraint without modifying the power balance, therefore increasing the accuracy.

The use of explicit integration schemes is also common in these types of analysis codes, as they usually need to be run between machine pulses. This scheme speeds up the solution at least by an order of magnitude. The faster explicit procedure has though two compromising features: the nonlinear properties can only be estimated as a parabolic function [5], and the size of the grid or mesh used for the geometrical model is limited by the CFL condition [9]. The use of an implicit scheme is not as fast but eliminates these limits, allowing the use of complex functions for the temperature dependent material properties, usually defined by experimental tables. More importantly, extremely fine meshes can be used at the surface improving the measurement of the intense gradients produced by fast transients. The extra computation effort is achieved in ALICIA through parallel multi-threaded execution.

The resulting output shows a much better capture of extremely fast events, such as filaments and ELMs. Fig. 3 compares the present version of THEODOR [10] used at JET-ILW (using a very high value for $\alpha = 1.44 \times 10^{15}$ W/m^2 K) with the new code ALICIA specifically designed for the ILW. The test is carried out using a synthetic IR signal; generated by forward analysis using ANSYS modelling a bulk Tungsten tile with an extremely fine mesh. This difference has been consistently found using experimental IR measurements. In the case of W-coated CFC targets, the exact modelling of the coating layers—with thickness of 10–20 µm—improves the ELM peak heat flux measurement even more. Fig. 4 compares the two codes developed for JET divertor for tile 6, showing peak value differences of up to 100% for which only ALICIA gives ELM heat fluxes similar to those calculated for bulk-W tiles. The