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The European Integrated Tokamak Modelling (ITM) Effort: Achievements and First Physics Results

The European Integrated Tokamak Modelling (ITM) Effort: Achievements and First Physics Results

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ABSTRACT.
The achievements and first physics results are presented of the European Integrated Tokamak Modelling Task Force (EFDA ITM-TF) effort, aiming at providing a standardized platform and an integrated modelling suite of validated numerical codes, for the simulation and prediction of a complete plasma discharge in arbitrary tokamaks. The framework developed by the ITM-TF, based on a generic data structure enclosing both simulated and experimental data, allowed for the development of sophisticated integrated simulations (workflows) for physics application. The equilibrium reconstruction and linear MHD stability simulation chain was applied, in particular, to the analysis of the edge MHD stability of ASDEX Upgrade type-I ELMy H-mode discharges and ITER hybrid scenario, demonstrating the stabilizing effect of an increased Shafranov shift on edge modes. A successful benchmark among five EC beam/ray-tracing codes was performed in the ITM framework for an ITER inductive scenario for different launching conditions from the Equatorial and Upper Launcher, showing good agreement of the computed absorbed power and driven current. Finally, the progress status of simulations performed within the ITM infrastructure with the electromagnetic turbulence gyrofluid code GEM for a JET hybrid discharge is presented.

1. INTRODUCTION

The European Integrated Tokamak Modelling Task Force (ITM-TF) [1,2], was established in 2004 with the aim of providing a standardized platform and an integrated modelling suite of validated numerical codes, for the simulation and prediction of a complete plasma discharge in arbitrary tokamaks. Over the last few years, the main effort of the ITM-TF was dedicated to building the modelling infrastructure, focusing on the development of a data and communication ontology, i.e., standardizing the data exchange between different codes, through a generic data structure incorporating both simulated and experimental data. The elements of this data structure are identified as "Consistent Physical Objects", or CPO [3]. Physics modules of various complexities can be easily adapted to the data structure, which is code and language agnostic, and thus coupled and interchanged in an integrated simulation (workflow). The physics modules integrated into ITM workflows are being cross-verified within the ITM framework as well as against existing integrated modelling codes to guarantee on one side their interchangeability and on the other their validation. Moreover, in the ITMTF framework all machine related data are extracted into standardized machine descriptions (MD) so that physics modules, like equilibrium reconstruction tools, also become independent of the specific tokamak experiment. The ITM-TF uses the open-source Kepler [4] scientific workflow manager and orchestrator tool, which allows for a user-friendly graphical construction of the integrated simulation. It has to be noted though that the generic datastructure is totally independent of the used workflow orchestrator tool.

The framework developed by the ITM-TF allowed for the development of sophisticated workflows for physics application since 2009. Those include the European Transport Solver (ETS), a leading ITM tool for both interpretive and predictive transport simulations and scenario modelling, incorporating a sophisticated module for synergy effects between heating schemes, several equilibrium modules, pellets, impurities, neutrals, sawteeth and neoclassical tearing modes (NTM) modules, as well as a variety of neoclassical and turbulence transport modules of different complexity. The ETS workflows have been subject to an extensive verification and validation for a variety of JET discharges against leading tokamak plasma core transport codes [5]. The very good agreement achieved for the simulated quantities (temperatures and current density profile) and applied modules, lays the foundations for the use of ETS for both predictive and interpretative runs on present devices and ITER, in a variety of scenarios. The effect of NTMs on plasma transport and confinement is also incorporated in ETS workflows via a dedicated NTM module that derives the island frequency, width and associated reshaping in transport coefficients [5]. Other ITM-TF workflow capabilities include the coupling of the transport simulator to a first-principle turbulence code [5] as well as direct coupling of the ETS core transport solver to a 2D edge transport code, demonstrated for the particular case of steady state and multiple impurities [6]. More recently, synthetic diagnostics, namely fusion products, 3D reflectometry, Motional Stark Effect (MSE), neutron and Neutral Particle Analyser (NPA) diagnostics have been integrated on the ITM platform and are being validated [7].

2. PHYSICS RESULTS

First physics results produced using the ITM-TF framework are presented in the following subsections.

2.1 EQUILIBRIUM RECONSTRUCTION AND LINEAR MHD STABILITY

The first demonstration of the use of ITM-TF integrated simulation workflows for physics studies on experimental data addressed equilibrium reconstruction, refinement and linear MHD stability calculations [9]. The corresponding Kepler workflow is illustrated in Fig.1, modules (“actors” in Kepler terminology) for free-boundary equilibrium reconstruction (e.g. EQUAL or CLISTE), high resolution fixed-boundary Grad-Shafranov solver (e.g. HELENA or CHEASE), and linear MHD stability (e.g. ILSA) are seamlessly integrated in the workflow environment [8].

In particular, an analysis of the edge MHD stability of ASDEX Upgrade type-I ELMy Hmode discharges was carried out, using the stability chain coupling CLISTE, HELENA and ILSA (used in MISHKA operation mode) [9 references therein]. Figure 2 shows the stability diagram for the variation of the pedestal height for ASDEX Upgrade Pulse No: 23223 at t = 5.33s. The profiles were taken just before the crash of type-I ELMs and modified using the JALPHA module, varying pressure and plasma current in a loop. As expected, the experimental equilibrium is marginally unstable with a toroidal mode number (n = 5) indicating a strong peeling component.

Core and pedestal scans of the normalized plasma beta bN were also been performed using the linear MHD stability chain for the ASDEX Upgrade type-I ELMy Pulse No: 20116 at t = 3.59s as well as an ITER hybrid scenario (Fig.3). It is evident from the computed growth rates in dashed lines that the increased Shafranov shift helps stabilizing edge modes. When scaling the entire pressure profile (solid lines), the destabilizing effect of the larger edge pressure gradient strongly dominates over the stabilizing effect by the Shafranov shift.

The machine independent equilibrium reconstruction code EQUAL has been extensively validated (at a first stage with magnetic data only) both on JET discharges [10] and Tore Supra; production runs with the equilibrium reconstruction and linear MHD stability simulation chain are being performed on several devices.

2.2 BENCHMARKING OF ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE CODES ON AN ITER SCENARIO

A benchmark among five European EC beam/ray-tracing codes (C3PO, GRAY, TORAYFOM, TORBEAM, TRAVIS) [11 and references therein] has been successfully performed within the ITM framework for a standard inductive H-mode ITER scenario (“Scenario 2”) for three different launching conditions both from the Equatorial Launcher (EL) and Upper Launcher (UL), see Table I. The three cases have been selected to cover different geometries and physics: divergent beam absorbed in the core (EL25), interaction dominated by Doppler broadening (EL40), focussed beam (UL). The frequency of the launched beam is 170GHz and the input power is 1MW.

The five EC codes above have been ported to the ITM framework, share the same interface for data input/output, and can be interchanged in the same ITM Kepler workflow, thus minimizing the possible external sources of discrepancy. In all the three cases good agreement is found, with differences in total current $|\delta I_{CD}/ I_{CD}|< 15\%$, and with peak values of power density dP/dV and driven current density typically matching within 10%, and the position of the profiles match within $\delta\rho\sim 0.02$ in normalized radius units (Fig.4). Small discrepancies can be ascribed to the different models used for wave propagation and absorption and current drive. In the EL40 case Doppler broadening dominates the effect of finite beam size in the determination of the profiles width, and all the codes here agree very well. In the UL case, despite the focused beam, the profiles are reasonably well reconstructed also by ray-tracing codes, giving results comparable to those obtained by the codes which account for diffraction effects. The large edge density gradient, and long path from boundary to absorption region, amplifies the impact of edge refraction on beam propagation. However, the influence of the observed discrepancies on computed power and current density profiles is still moderate. Only in case of strongly focused beam, like in the UL case, the uncertainty may approach the profiles width.

2.3 TURBULENCE SIMULATIONS

Conventional direct comparison of a turbulence code’s results to experimental measurements and transport analysis is often discrepant, unless some form of artificial convergence is used. Here turbulence simulations of a JET hybrid discharge were performed with the electromagnetic gyrofluid turbulence code GEM [12], executed in batch on the HPC-FF within an ITM workflow. JET Pulse

No: 77922 data at t = 47.7s were used. First, profiles of electron and ion density and temperature, toroidal current and basic MHD equilibrium geometry were given and an s-alpha model assumed. GEM actor runs in parallel 8 independent fluxtube cases, each at a given reference point on the profile (each with own normalised units including time, since the gyro-Bohm time $\tau_{GB} = c_s/L_\perp$ depends on the local steepest profile gradient length scale), producing particle and heat fluxes profiles for both species. The experimental case was found to be ITG stable for most of the profile except for the edge point at r/a = 0.96, this implying that the gyrofluid model was essentially used outside its validity. This comparison demonstrated the difficulty of interpretative turbulence runs from experimental data profiles, a transport workflow had to be therefore setup.

A fluxtube chain workflow is being used consisting of an independent run of the local delta-f model at each of 8 reference points on the profile, as above, but with the fluxes equalised using a profile modification algorithm designed to adjust the profiles into transport equilibrium. In the simplest case a prescribed power profile with the correct total power at the outermost surface is used. Each workflow step takes the plasma profiles as input, calculates an equilibrium using a simple equilibrium code (at present, a shifted circular model), both are then input to GEM for a run segment of 10 tGB producing fluxes profiles, finally the simple equilibration model is used to adjust the temperature profiles. Saturation occurs on a scale of a few 100 τ_{GB} but a fully relaxed run is much longer; in this case, 2000 loop steps are used, corresponding to 2×10^4 τ_{GB}. The current version of the model uses a relaxation time constant to equalise the profiles; this needs to be calibrated in order to allow for profile relaxation while preventing workflow crash. At the time of this writing the workflow testing together with this calibration is still in progress and a fully relaxed case is not yet available.

3. CORE-EDGE COUPLING

Direct coupling of an edge and a core transport code using the ITM-TF infrastructure was demonstrated for the particular case of steady state and multiple impurities [6].

The edge 2D transport code (SOLPS) [13] was coupled with the 1D core main plasma transport code ETS [14] and a core impurity transport code, developed within the framework of the ITM-TF. In this work a Fortran version of the ETS workflow was used, including the equilibrium code HELENA and simple models for particle and energy sources as well as transport coefficients. ASDEX Upgrade shot #17151 equilibrium at 2.5s was imported into equilibrium and limiter CPOs, and the bounding surface separating the calculation domains between the core and edge codes was evaluated (at 95% of the normalized poloidal flux in the case below). These CPOs enter the HELENA code providing equilibrium to the core transport code and were used to create the SOLPS grid (Fig.6 left). The two codes were then called alternately and individually run until converged, with information about the boundary conditions transferred from one to the other during the process. Values of density and temperature were passed from SOLPS to the ETS, and the ETS returned energy and particle fluxes. For the most complicated test case, SOLPS treated all of the charge states of D, He, C, Ar and Ne (including the neutrals), a total of 42. The ETS treated D+ and He+2 as main ions, and the core impurity code treated the individual charge states of C, Ar and Ne. The core codes did not, in this case, treat the neutrals. SOLPS used a zero-flux boundary condition for neutrals, all of the charge states of C, Ar, Ne and for He+1. The results for the electron temperature and density are shown in Fig.6.

4. SYNTHETIC DIAGNOSTIC INTEGRATION

The ongoing efforts on synthetic diagnostic integration in the ITM-TF platform focus on reflectometry, neutron and NPA diagnostics and spectral MSE.

A full-wave 3D code (ERC3d) valid for both O and X-mode polarizations has been developed, ported and tested on the ITM platform and work is under way to enhance the kernel to cope with high levels of turbulence and high injection angles (Doppler reflectometry operation). A generic framework for neutron synthetic diagnostics has been integrated which is composed of three different modules: calculation of the effective solid angle of the detector from small plasma volumes (LINE21 code); a Directional RElativistic Spectrum Simulator (DRESS) to derive the energy spectra and source rates of particles created in fusion reactions emitted in a specified direction and a diagnostic response function. Integration of JET neutron camera setup is ongoing. The integration of NPA diagnostics in the ITM platform was also carried out using modules of the ASCOT code package [17] and calculating the fraction of the tokamak chamber and born neutrals (with given pitch velocity) that are within the sight of the NPA collimator. A spectral MSE forward model [16] that calculates the emissivity for each MSE channel and the resultant radiance Balmer-alpha MSE spectra as well as the charge exchange of the plasma with the beam has been integrated. Full, half and third beam energy components are considered and a collisional-radiative beam-plasma model is used to determine the coupled densities of charged states along the diagnostic neutral beam path. Preliminary results on the MSE synthetic diagnostic validation on ASDEX Upgrade data (Pulse No: 26323) are presented in Fig.8, showing the simulated and experimental emissivities.

CONCLUSIONS

The ITM-TF standardized, modular and flexible integrated modelling framework allows building sophisticated workflows for physics application and is a valuable environment to benchmark codes describing similar physics processes, interchanging those as modules within the same workflow. The first application of the simulation chain coupling equilibrium reconstruction, refinement and linear MHD stability modules addressed edge stability of ASDEX Upgrade ELMy H-Mode and ITER hybrid scenario The benchmark among EC beam/ray-tracing codes for a standard inductive H-mode ITER scenario for three different launching conditions, showed good agreement of the five codes even in the more demanding test cases, like central ECCD at high temperature, and beam focused close to the resonance region. The interoperability of the local ITM cluster with HPC-FF was proven for gyrofluid turbulence simulations. Gyrofluid turbulence code interpretative runs starting from given experimental profiles near to stability threshold conditions remain challenging, results of the ongoing dedicated transport workflows will be reported in a subsequent paper. Automated direct coupling of a core and edge transport code was demonstrated for the particular case of steady state and multiple impurities. Synthetic diagnostics are being integrated and tested on the ITM-TF platform, namely 3D reflectometry, neutron and NPA diagnostics as well as a spectral MSE forward model, which is being validated on ASDEX Upgrade data.

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Case	R_m (m)	z_m (m)	α (*)	β (*)	w_0 (m)	d (m)
EL25	9.27	0.62	0	25	0.030	0.00
EL40	9.27	0.62	0	40	0.030	0.00
UL	6.90	4.18	48	18	0.021	1.62

Table 1: Launching conditions used in the benchmark. The poloidal and toroidal launching angles are defined as α*=tan-1(*k_0*,z/*$k_{0,R}$ *) and* $\beta = \sin^{-1}(k_{0,\phi} / k_0)$*, where (*$k_{0,R}$*,* $k_{0,\phi}$ *,*$k_{0,z}$*) are the cylindrical wave vector components of the launched wave. The beam has a Gaussian profile, with waist* w_0 *at a distance d from the launching point.*

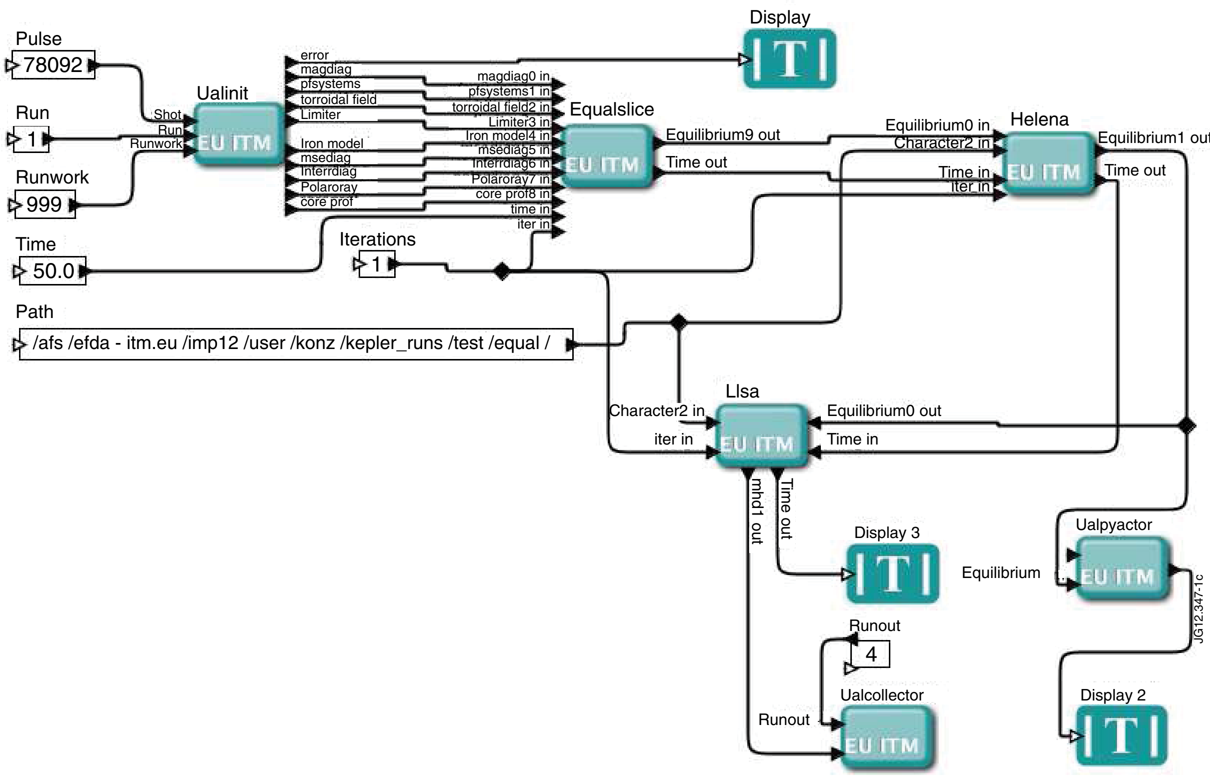

Figure 1: ITM-TF Kepler workflow for MHD linear stability coupling: an initialization module (ualinit) reading experimental data, EQUAL, HELENA and ILSA modules. A python script actor (ualpyactor) provides the visualization of the reconstructed equilibrium. Replacing equalslice with the j-alpha module allows to perform a parameter study by modifying pressure and plasma current.

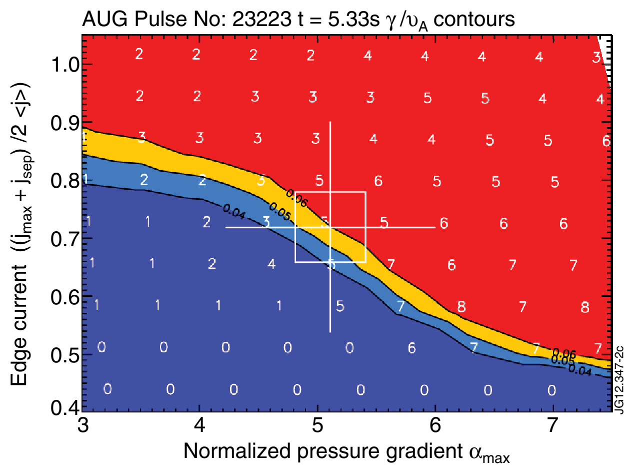

Figure 2: Pedestal height study for ASDEX Upgrade obtained with the J-alpha stability workflow [8]. The plot shows the contours of the linear ideal MHD growthrates γ (normalized to the Alfvén frequency v_A) of the fastest growing edge modes in the plane defined by the maximum normalized edge pressure gradient amax and the normalized edge current density. Contours indicate the level of the diamagnetic drift frequency separating the stable (blue) from the unstable (red) region. The crosshair indicates the experimental equilibrium including error bars.

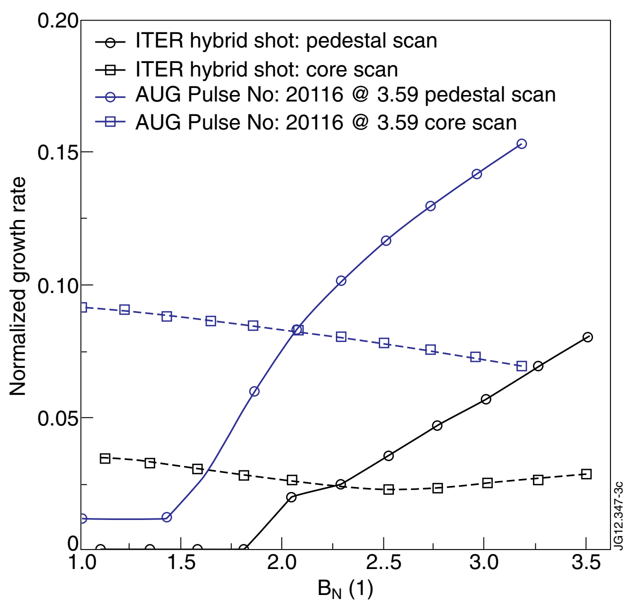

Figure 3: Core and pedestal scans of the normalized plasma beta for ASDEX Upgrade type-I ELMy Pulse No: 20116 (blue) and an ITER hybrid scenario (black) [9]. The dashed lines show modification of the plasma β_N via modification of the core pressure profile while keeping the pedestal pressure unchanged. The solid lines, on the other hand, show modification of the plasmabN via scaling of the entire pressure profile.

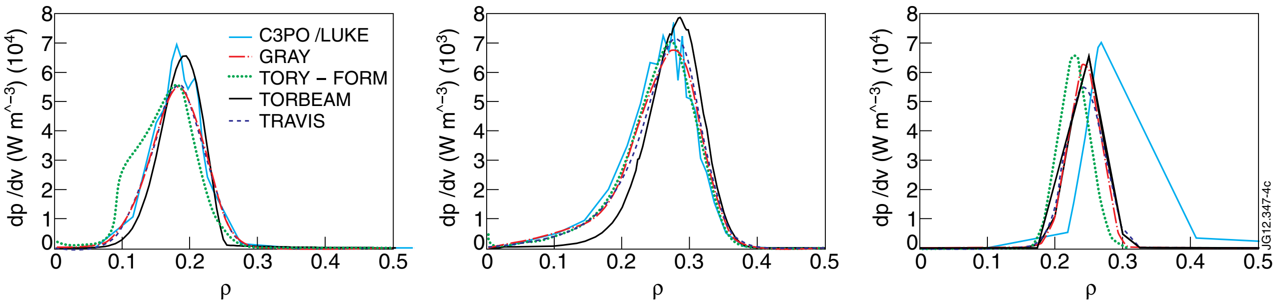

Figure 4: Power density profiles computed for the launching conditions of Table 1: EL25 (left), EL40 (center) and UL (right).

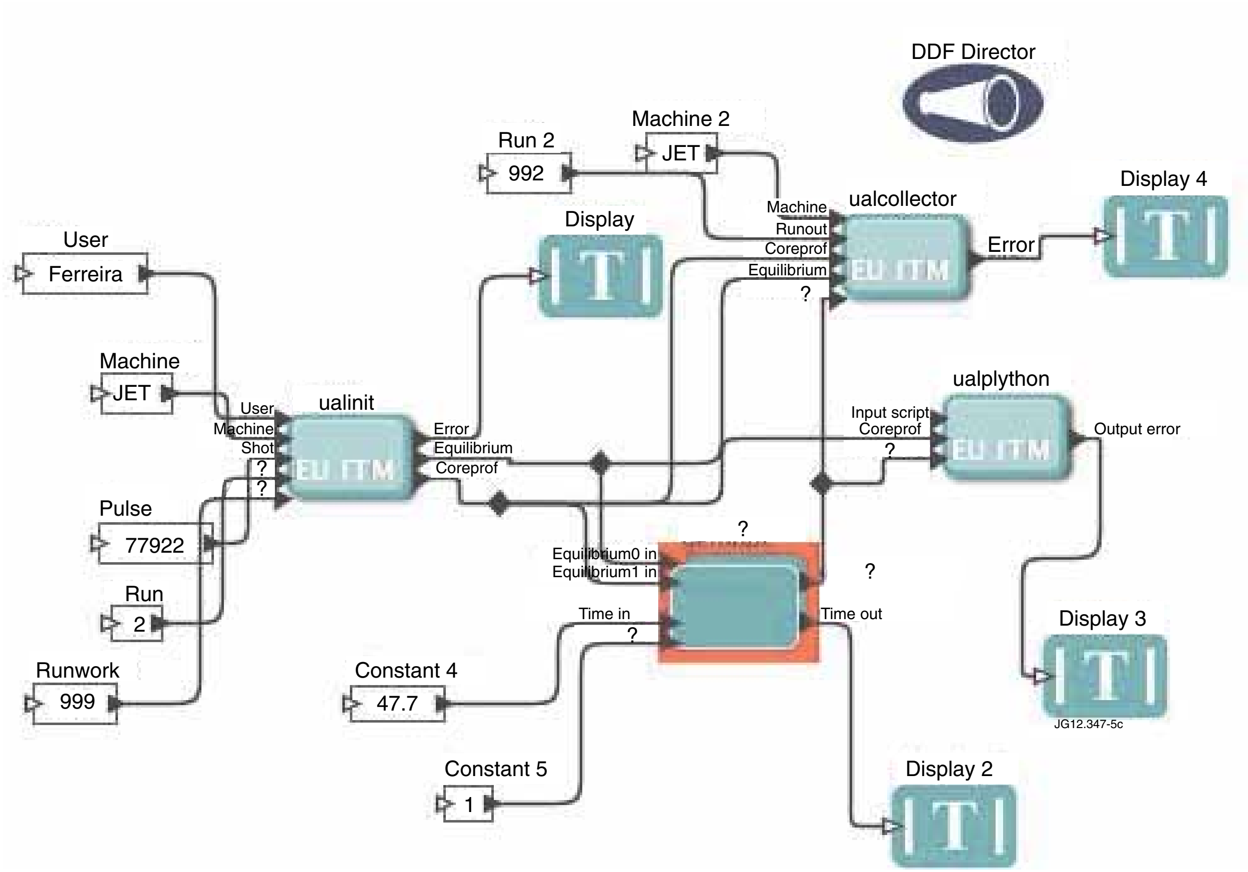

Figure 5: Simple Kepler workflow, accessing JET shot data from the ITM database. GEM code actor (produced via HPC2K ITM tool) is executed in batch on the HPC-FF .

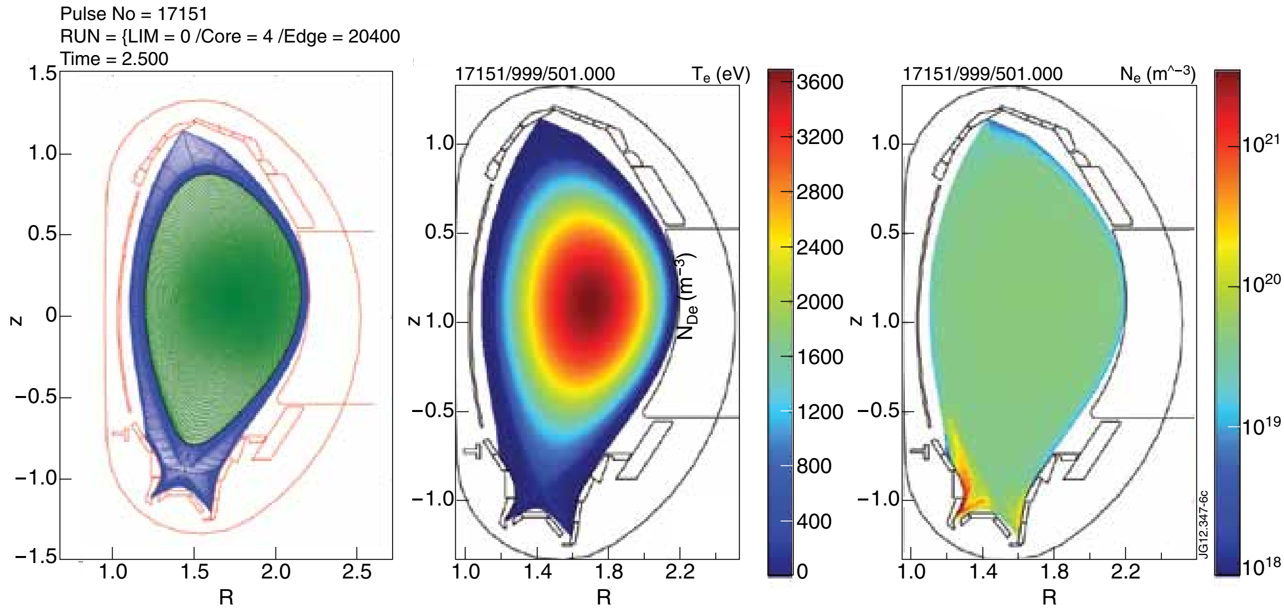

Figure 6: Left, the combined core and edge grids for ASDEX Upgrade shot 17151. All plot data are derived from ITM CPOs. Te (center) and ne (right) for the final state of the D+He+C+Ar+Ne case [6].

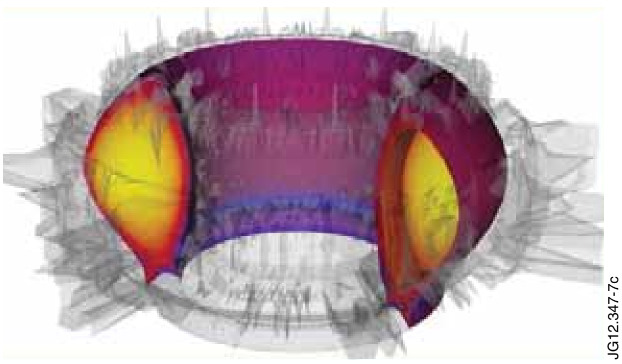

Figure 7: Visualization of the core-edge coupled simulation results: T_e calculated in the core with the ETS, in the edge with SOLPS, within the 3D defeatured first wall of ASDEX Upgrade obtained using a ray tracing rasterization and smoothing [15]. All data is stored in CPOs and plot with VisIT.

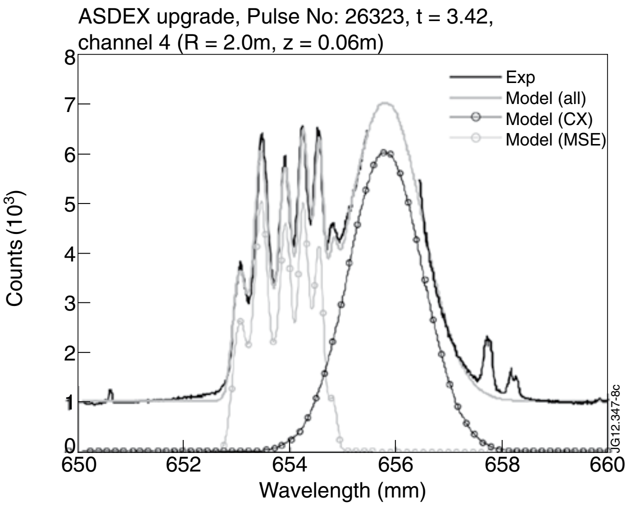

Figure 8: MSE emissivity wavelength spectra for ASDEX Upgrade Pulse No:26323. The contribution from half and third beam energy components, beam divergence and unshifted D_α emission are shown. An offset of ~1000 counts is added to the MSE+CX synthetic counts to account for the characteristic background level of the measured signal by the CCD.