JINTRAC: A System of Codes for Integrated Simulation of Tokamak Scenarios*)

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Operation and exploitation of present and future Tokamak reactors require advanced scenario modeling in order to optimize engineering parameters in the design phase as well as physics performance during the exploitation phase. The simulation of Tokamak scenarios involves simultaneous modeling of different regions of the reactor, characterized by different physics and symmetries, in order to predict quantities such as particle and energy confinement, fusion yield, power deposited on wall, wall load from fast particles. JINTRAC is a system of 25 interfaced Tokamak-physics codes for the integrated simulation of all phases of a Tokamak scenario. JINTRAC predictions reflect the physics and assumptions implemented in each module and extensive comparison with experimental data is needed to allow validation of the models and improvement of Tokamak-physics understanding.

Keywords: Tokamak, scenario modelling, integrated modelling, transport, scrape-off layer, fuelling and heating

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1. Introduction

JINTRAC is a system of 25 different physics-modules for the integrated modeling of complex Tokamak [1] scenarios. A Tokamak reactor consists of a toroidally symmetric vacuum-vessel in which an intense toroidal magnetic field (of the order of 5 - 8 Tesla) helps confining energy and particles of a strongly inhomogeneous plasma. The plasma is created in the vacuum vessel ionising a mixture of deuterium and tritium gases by driving a large toroidal current (of the order of 10 - 20 MA). Self generated poloidal magnetic field coupled with the toroidal current provides the force which balances the pressure gradient needed to achieve a hot plasma core (of the order of tens of keV) while keeping the outer layer at a temperature compatible with the vessel wall (of the order of few eV). The complex equilibrium magnetic field in the Tokamak-vessel is therefore the composition of an externally imposed field and that generated/modified by the plasma (both toroidally symmetric). A magnetic field equilibrium code is therefore needed in any scenario modelling suite. The magnetic equilibrium codes adopted interchangeably in JINTRAC are EFIT [2], CREATE-NL [3] and ESCO, a simplified fix boundary solver. In order for the deuterium-tritium plasma to preserve its purity and avoid cooling by impurity radiation and dilution, it is necessary to "isolate" it from the wall. This is achieved by limiting the contact with the wall, using a so-called limiter or by introducing a magnetic X-point and a magnetic separatrix-line. In both cases two toroidally symmetric regions appear in the vacuum vessel: one characterized by strong toroidal plasma current, closed toroidal magnetic-surfaces (flux-surfaces) and higher plasma purity; the second characterized by open

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Table 1 JINTRAC integrates 25 independent modules. Here is a summary of the size and speed of the main components. Sizes include interfaces to the external modules for core and edge modeling. JETTO size includes SANCO and the smaller core modules. The values of the execution time and time-step are for a typical JET simulation.

Module	Language	Lines	Exec. time/step	Run
JETTO	Fortran	270 k	~ 10^{-2} s / 10^{-3} s	Serial
TGLF	Fortran	18 k	~1 s (per grid point on 20 proc.)	Parallel
ASCOT	Fortran	100 k	~ 120 s (10^4 part. on 8 proc.)	Parallel
EDGE2D	Fortran	152 k	~ 1 s / 10^{-5} s	Serial
EIRENE	Fortran	121 k	~120 s (10^4 part. on single proc.)	Parallel

magnetic field lines, neutral fuel gas and impurities originating from the wall. These two coupled regions have very different dynamics and require different physics descriptions. The dynamics in the core plasma region can be reduced to that of one-dimensional multi-species plasma by exploiting the intrinsic toroidal symmetry and taking averages of the fields over the magnetic surfaces. In first approximation and in the absence of strongly asymmetric sources or strong rotation, the kinetic fields (species densities and temperatures) are independent of the poloidal angle. Transport equations for the flux-surface averaged fields of two fluid plasmas are solved in JINTRAC using the transport code JETTO [4] coupled to an impurity transport code SANCO [5]. The coupling between the equilibrium code, JETTO and SANCO is discussed in the next section along with the available transport models. External auxiliary heating and current drive are needed in order to ignite fusion reaction and to sustain the toroidal current. There are two forms of auxiliary heating modeled in JINTRAC, neutral beam injection (NBI) through the ASCOT [6] code and radio frequency (RF) heating through the codes PION and LHCD. The coupling between JETTO and the heating codes is presented in section 2. The dynamics in the open-field-line region is more complex and has to be described by the 2D fluid code EDGE2D [7] coupled to a kinetic Monte Carlo code which calculates the trajectories of the neutral particles, EIRENE [8], and takes into account atomic and molecular physics processes. The complex grids of EDGE2D/EIRENE are bounded by the divertor plates and by the vessel wall which act as a source and sink for heat and particles. Table 1 reports the characteristics of the main components of JINTRAC.

2. Coupling of Core Codes

Core codes in JINTRAC are one dimensional transport solvers, solving: Faraday's equation for the time-evolution of the plasma current, electron and total-ion energy equations, individual ion mass-continuity and total ion toroidal momentum equations. The equations for electron and main fuel ions (hydrogenic species) are solved on a regular grid that allows resolving finer gradient structures (approximately hundred points are used for JET simulations). The radial variable represents the toroidal magnetic flux and it is a dynamical variable which evolves according to the evolution of the equilibrium magnetic field. The solution of the finite difference electron and main ion equations is performed by the JETTO solver by tridiagonal matrix inversion using an implicit scheme on a typical time step shorter than one tenth of the confinement time ($\Delta t = 10^{-3}$ s for a Tokamak of $B = 2$ T, $I = 2$ MA, $R = 3.0$ m, $a = 1$ m). The equilibrium solver is called within JETTO on a frequency selected by the user. The inputs for the equilibrium solver are: the plasma pressure-profile and the plasma current-profile (q-profile) along with the plasma boundary for the fix boundary solver (ESCO). The above variables are passed from JETTO to the equilibrium solver. ESCO equilibrium code solves the Grad-Shafranov equation and provide a matrix with the values of the poloidal flux at given R, Z positions along with surface averaged geometric quantities required by JETTO. For other equilibrium options the equilibrium matrix is processed by a package (FLUSH) that calculates the same geometric quantities (e.g. metric coefficients) that are then returned to JETTO. Along with the solution of the electron and hydrogenic ion equations, the system solves for up to three impurities and their ionization states. Mass continuity equations for the impurities are solved by SANCO which is called within JETTO at each time step before the JETTO matrix inversion to update the impurity radiation terms in the equations and to provide impurity densities and gradients for the transport models to be used in the next time step. SANCO uses the metric coefficients from JETTO but solves its equations on an irregular grid. This is to account for the fact that higher resolution is required towards the plasma boundary where atomic processes are important. SANCO calculates the evolution of each ionization state of the impurity species by taking into account ionization, recombination, charge exchange and other atomic processes. Relevant cross sections are taken from the ADAS data base [9]. The time step used by SANCO is the same as JETTO. Transport models to close the dynamical equations are provided in different forms: analytical models such as the Bohm-gyro-Bohm model [10], neoclassical transport models such as NCLASS [11] and drift wave models such as Weiland, GLF23 and TGLF [12–14]. In order to calculate the effective transport coefficients the above models need as input the densities, temperatures, momentum and gradients of the electrons and all the ion species along with the magnetic shear and q profile. The drift wave transport models are called within JETTO at each time step before the matrix inversion via an interface, TCI (Transport Code Interface) [15]. TCI uses the variables passed by JETTO to construct the correct input to each model. Moreover TCI collects the output from the models and constructs the effective diffusivities as required by JETTO. The most advanced gyro-kinetic drift-wave models are amongst the most computationally demanding codes for core modeling. These are typically parallelized and can be run as independent codes on supercomputers. However, in JINTRAC (and in most transport solvers) reduced fluid transport models are applied for their computational efficiency. Typical execution time of TGLF in JINTRAC is on 20 processors and shows 90 % parallel efficiency. Heat and particle sources for JETTO are calculated by Monte Carlo codes. EIRENE provides thermal neutrals while ASCOT calculates the power and particle deposition from the NBI. Both codes are called by JETTO before the matrix inversion to update the source terms in the equations. Both EIRENE and ASCOT are three dimensional codes and use internal grids for solving the Monte Carlo problem (built on the same equilibrium used by JETTO). The interface between the source codes and JETTO provides flux surface averaged quantities (averaged power per cubic meter or particles per cubic meter) as required by the core solver. Typical execution time of ASCOT with 10^4 particles is 2 minutes on 8 processors. Typical EIRENE run time with 10^4 particles is 2 minutes per EDGE2D time step on single processor. A pellet module is also available in JETTO. Simplified modules for NBI, LH and particle sources also exist (PENCIL [16], FRTC, and FRANTIC [17]) which are used for faster simulations. Analytical models are incorporated in JETTO to take into account sawteeth instabilities (based on the Porcelli trigger model [18] and Kadomtsev model), NTMs and ELMs. These latter models are based on the rapid increase of the transport coefficients (up to 50 times above their initial value) in a prescribed region of plasma for all the fields solved (densities, temperatures, momentum). The transport coefficients are then kept at the higher value for a fixed duration and finally reduced back to their initial values.

3. Coupling Edge/SOL/Neutral Codes

The solvers adopted in JINTRAC to model the egde/SOL are EDGE2D and EIRENE. EDGE2D solves the equations for electron and total ion thermal energy, ions mass-continuity and momentum for all charge states in a two dimensional grid as constructed by GRID2D from the equilibrium calculated with EFIT or CREATE-NL. Typical grid for JET simulations is 80 poloidal points and 25 radial points. The 2D equations are solved by tridiagonal matrix inversion using a SLOR (line relaxation) method or a GMRES (minimal residual) method on a time step of up to 10^{-5} s to account for the fast parallel dynamics. Perpendicular drifts are taken into account and perpendicular transport is modeled with analytically prescribed diffusion coefficients. An example of EDGE2D grid is shown in Fig. 1a. EIRENE solves for the dynamics of neutrals and provides EDGE2D with sources and sinks for the plasma equations while EDGE2D provides EIRENE with the electron-ions fluxes towards the wall [8]. EIRENE is called by EDGE2D typically every 10 to 30 time steps (for linearized source description) and the interface allows for mapping of plasma fields from EDGE2D grid onto the overlapping EIRENE grid (Fig. 1b) and vice versa.

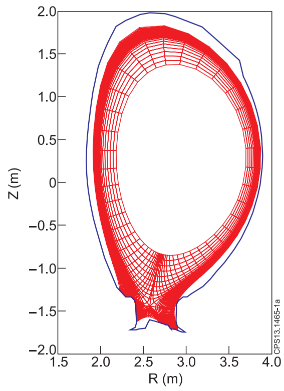

Fig. 1a Example of EDGE2D grid for JET.

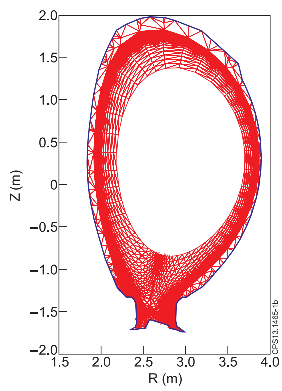

Fig. 1b Example of EIRENE grid for JET.

EIRENE grid extends EDGE2D grid to cover the "vacuum" region where plasma densities and temperatures are set to vacuum-like values to avoid plasma neutral interaction. The charged particles leaving the EDGE2D grid become the recycled source of neutrals EIRENE. Puffs and pumps can be modeled by additional neutrals sources and sinks. The triangular grid of EIRENE allows covering complex wall surface structures for interaction with neutrals.

4. Coupling of Core and Edge

The coupling between the core codes orchestrated by JETTO and the edge/SOL codes orchestrated by EDGE2D is achieved in a static way by building a single executable. A coupled version of EDGE2D contains calls to JETTO and drives the entire simulation process. EDGE2D calls JETTO as a subroutine with arguments: the densities and temperature of the plasma species evolved by EDGE2D and averaged over the last closed magnetic surface of the EDGE2D grid which coincides with the boundary of the JETTO radial grid. The flux of neutrals crossing the separatrix computed by EIRENE is also passed to JETTO. Also, EDGE2D provides JETTO with the value of the time step to allow JETTO to advance in synchrony. Once JETTO step is completed it returns to EDGE2D the values of the particle and energy fluxes at the boundary of the radial grid. These are mapped onto the 2D grid of EDGE2D over the last closed magnetic surface. Different poloidal dependencies for the fluxes can be adopted (the simplest being uniform fluxes all over the surface). To initialize the simulation JETTO is advanced alone (within EDGE2D, but with user provided boundary conditions) to define a stable core plasma state. This provides an initial boundary condition for EDGE2D to be advanced "alone" (fixed

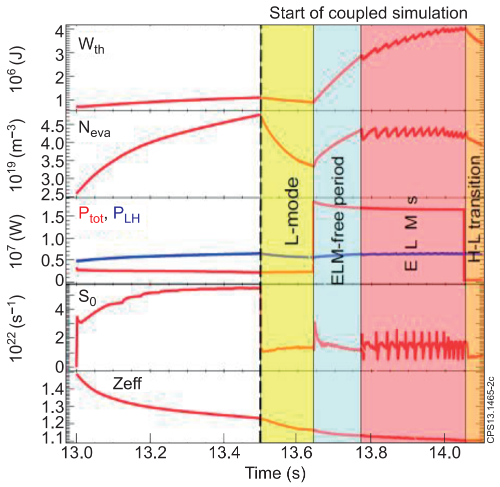

Fig. 2 JINTRAC simulation of a JET-type discharge.

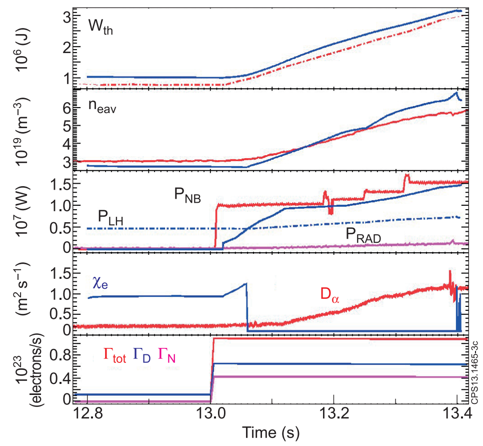

Fig. 3 Comparison of JINTRAC simulation of JET #83359 (blue) and experimental measurements (red, purple). Last panel shows the rate of injection of D and N (simulation).

boundary conditions provided through JETTO) to allow the SOL to relax to a compatible starting condition (about 30 ms for JET conditions) after which both codes are advanced with the same time step with EDGE2D now providing all boundary conditions to JETTO and vice versa.

5. Example of Integrated Simulations

Recent results of JINTRAC integrated modeling have been discussed in details in [19–21]. Figure 2 illustrates the various phases of a typical integrated simulation of a JET-type discharge where the time traces of the total energy content, the line average density, the total injected power, the L-H threshold power, the neutral deuterium source at the boundary of JETTO grid and Z_{eff} are plotted. JETTO with "user defined" boundary conditions is run between 13.0 s and 13.5 s when the coupling with the edge is switched on. The drop of the neutral source at the plasma boundary corresponds to the change in JETTO boundary conditions from "user prescribed" to EDGE2D. This brings about the observed relaxation of the line average density during the L-mode phase of the simulation. The L-H transition is triggered at $t = 13.65$ s when the total power exceeds the P_{LH} threshold power. The transition accompanied by the edge barrier formation (not shown) leads to a steady increase of the core density and energy content. ELMs are triggered just before $t = 13.8$ s when the pressure gradient at the edge barrier region reaches the prescribed critical value. The H-L transition follows the switch off of the neutral beam at $t = 14.5$ s. Comparison between a JINTRAC simulation (blue traces) and JET experimental data is shown in Fig. 3 for JET pulse #83359. The measured P_{NB} is used in the simulation to calculate the deposited power (blue). The thermal conductivity χ_e at the plasma boundary drops at the L-H transition (increase of D_α). JINTRAC predictions reflect the physics and assumptions implemented in each of its modules and extensive comparison with experimental data is needed to allow validation of the models and improvement of Tokamak-physics understanding. This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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