The European Transport Solver: an integrated approach for transport simulations in the plasma core.

D. Kalupin [2,3], V. Basiuk[4], D. Coster[5], Ph. Huynh[4], L. Alves[6],Th. Aniel[4], J. F Artaud[4], J. P.S. Bizarro[6], C. Boulbe[7], R. Coelho[6], . Farina[8], B. Faugeras[7], J. Ferreira[6], A. Figueiredo[6], L. Figini[8], K. Gal[9], L. Garzotti[1], F. Imbeaux[4], I. Ivanova-Stanik[10], T. Jonsson[11], C.J. Konz[5], E. Nardon[4], S. Nowak[8], G. Pereverzev†, O. Sauter[12], B. Scott[5], M. Schneider[4], . Stankiewicz[10], P. Strand[13], I. Voitsekhovitch[1], TM-TF contributors and JET-EFDA Contributors

[1] JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK
[2] EFDA-CSU Garching, Boltzmannstr. 2, D-85748, Garching, Germany
[3] Institute of Energy and Climate Research – Plasma Physics,, Forschungszentrum Jülich, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany, www.fz-juelich.de/iek/iek-4
[4] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.
[5] Max-Planck-Institut für Plasmaphysik, EURATOM-IPP Association, Garching, Germany
[6] Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear – Laboratório Associado, Instituto Superior Técnico, P-1049-001 Lisboa, Portugal
[7] Laboratoire J.A. Dieudonné, UMR 6621, Université de Nice Sophia Antipolis, Parc Valrose, 06108 Nice Cedex 02, France
[8] Istituto di Fisica del Plasma CNR, Euratom-ENEA-CNR Association, 20125 Milano, Italy
[9] KFKI RMKI, EURATOM Association, PO Box 49, H-1525 Budapest-114, Hungary
[10] Institute of Plasma Physics and Laser Microfusion, EURATOM Association,00-908 Warsaw, Poland
[11] Royal Institute of Technology, VR-Euratom Association, Teknikringen 31, 100 44 Stockholm, Sweden
[12] Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland
[13] Euratom-VR, Chalmers University of Technology, Göteborg, Sweden

E-mail contact of main author: denis.kalupin@efda.org

Abstract

The new transport simulator developed by the EU Integrated Tokamak Modelling Task-Force (ITM-TF, https://www.efda-itm.eu/ is a modular package for transport simulations and scenario modelling which couples precompiled physics modules into a workflow, using the user friendly interface of KEPLER workflow manager (http://kepler-project.org).

The main solver for 1-D transport equations is declined over several numerical schemes, which a user can choose to optimize the code performance for a particular physics problem (i.e. stiff transport model)

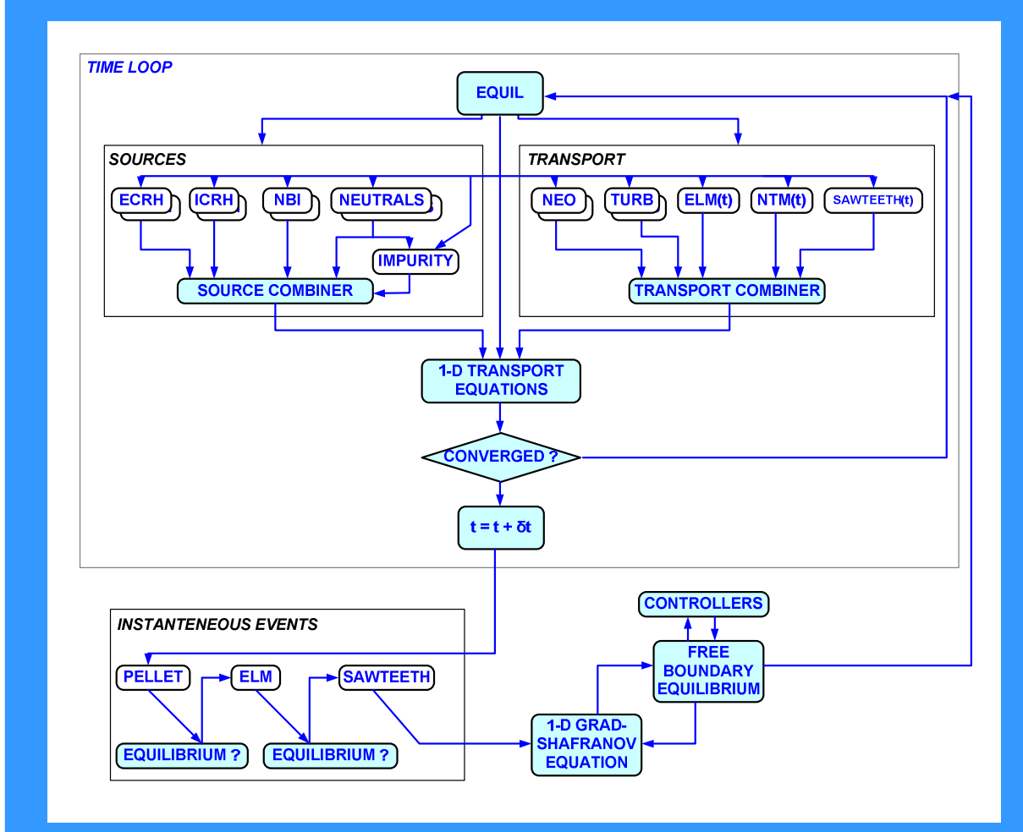
The ETS workflow presently incorporates a large number of sophisticated physics modules for the equilibrium, pellets, impurities, neutrals, sawteeth and NTM, as well as a variety of modules for the auxiliary heating and particle sources, neoclassical and turbulence transport. Integrated modules can be executed on the same node as KEPLER or can be submitted by the workflow as a batch job to the ITM computing cluster or to an external HPC.

The ETS has been subject to an extensive V&V for a variety of JET discharges and ITER conditions against leading tokamak plasma core transport codes. Satisfactory agreement was obtained for temperatures and q-profile simulated by ETS, ASTRA and CRONOS as well as for the computed thermal diffusivities.

Impurity simulations performed for JET conditions allow to infer that the increased radiation during the ICRH phase as compared to the NBI phase can be explained by an increased W source.

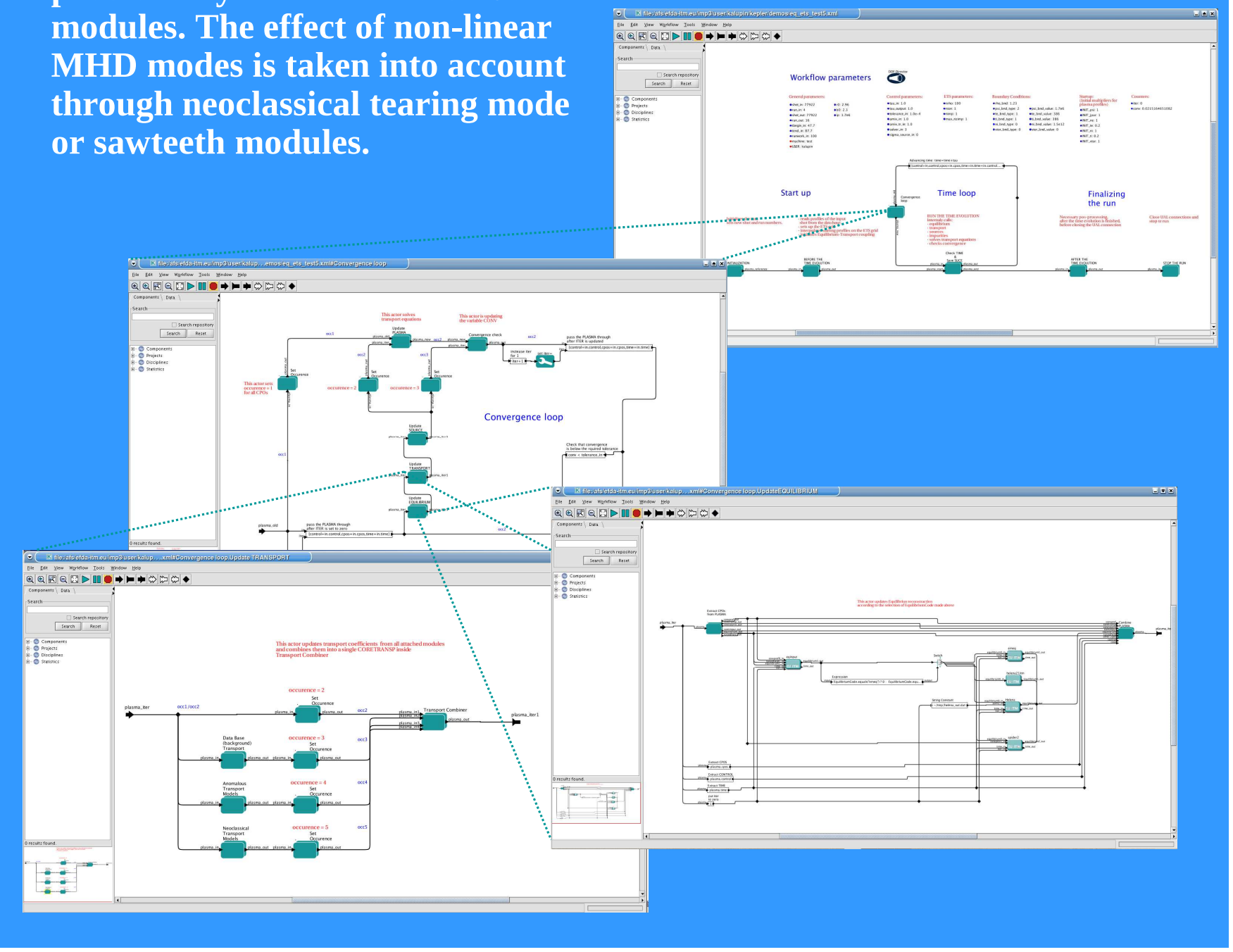
Design & Verification

Workflow design



Physics modules coupled to the ETS:

A large choice of equilibrium solvers is available (BDSEQ, EMEQ, SPIDER, EQUAL, HELENA, CHEASE, EQUIFAST). Transport coefficients can be used, provided by neoclassical transport (NCLASS, NEOWES, NEOS) as well as anomalous transport modules of different complexity, from an analytical description (Bohm-GyroBohm, Coppi-Tang, ETAIGB), to a quasi-linear description (GLF23 or Weiland model), up to first-principle electromagnetic turbulence models (GEM code) run in parallel on the HPC-FF as an integral part of the transport simulations. Sources and sinks include the contribution of electron cyclotron heating (GRAY code), neutral beam injection (NEMO code), radiation from impurities and Bremsstrahlung radiation, gas puffing, pellet injection and Ohmic power. The total transport coefficients or sources for each equation can also be taken from the database or can be derived as linear combination of values provided by different individual modules. The effect of non-linear MHD modes is taken into account through neoclassical tearing mode or sawteeth modules.

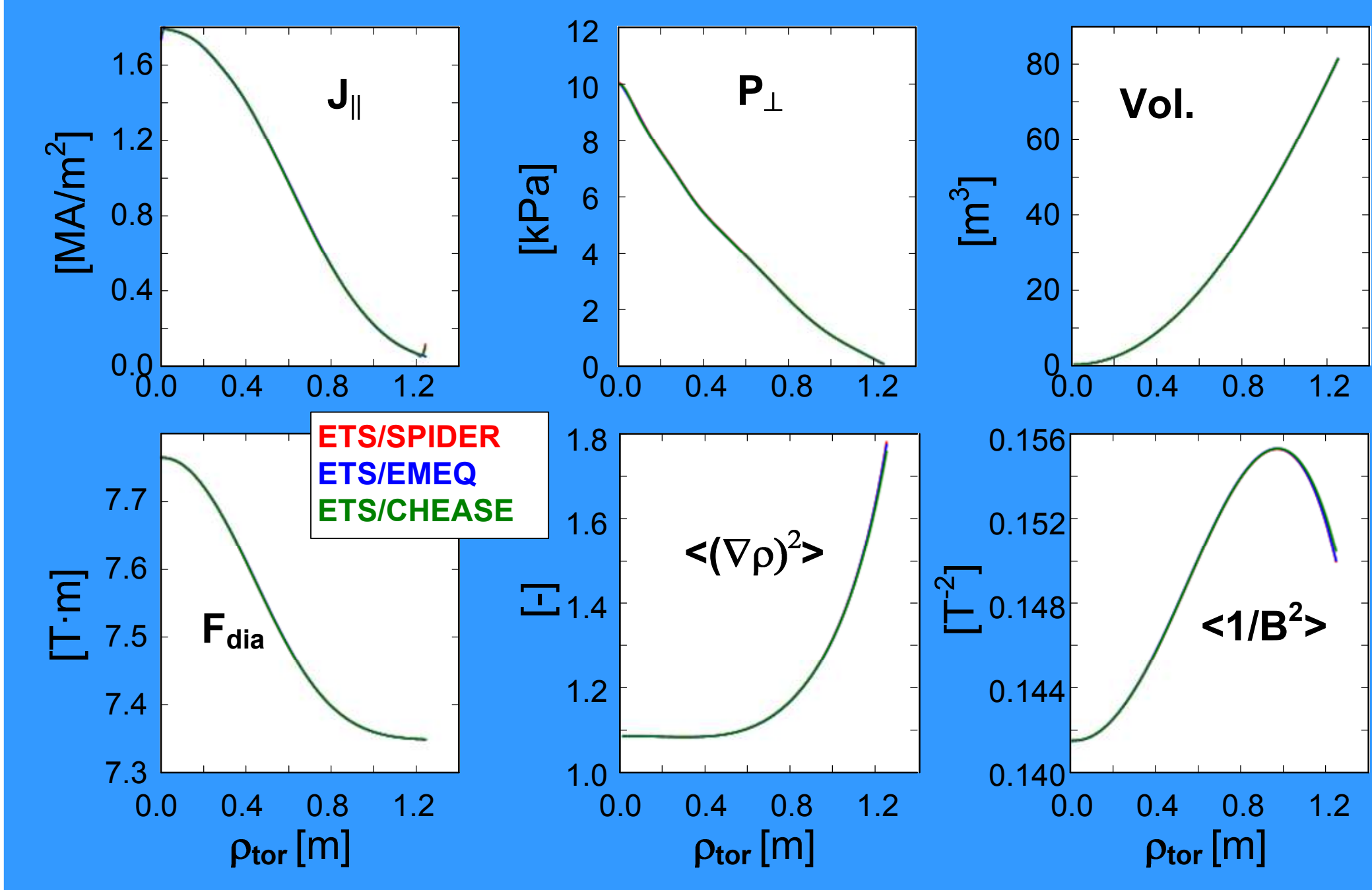


ETS workflow under KEPLER:

- Physicist-friendly graphical interface
- Any physics module can be easily replaced by an equivalent module
- All modules communicate via CPOs
  • Can run on the same node as Kepler
  • In the batch queue of the Gateway
  • Remotely on the HPC-FF

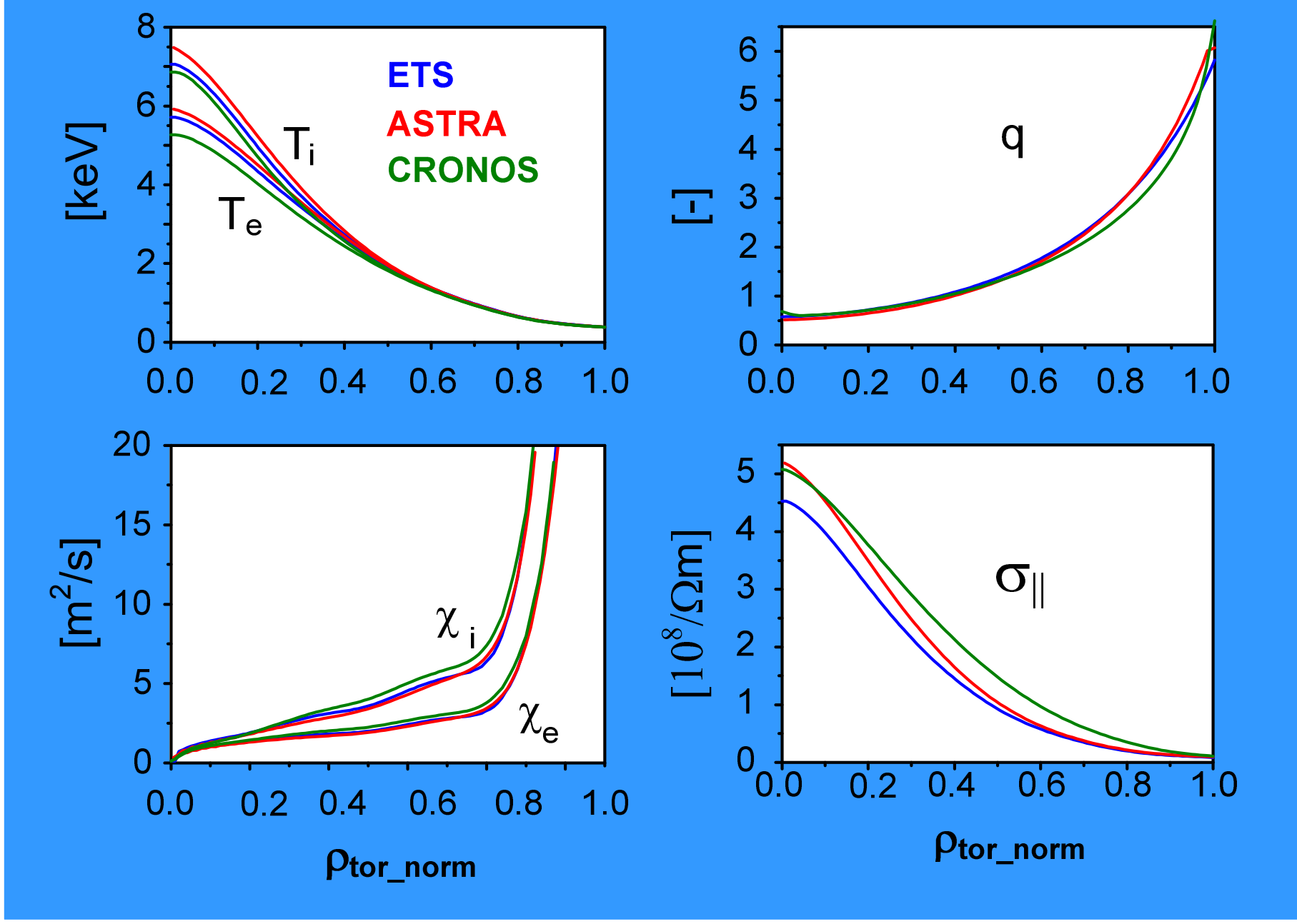
- Allowing for easy benchmarking between codes
- Allows for the trade-off of accuracy and speed
  •Versions that run faster than real-time
  •Versions that might require huge computing resources to try to understand every

Validation and verification



Computations obtained with the ETS using three different equilibrium solvers, SPIDER, EMEQ and CHEASE, for the conditions of JET shot (#71827). Transport equations for poloidal flux, electron and ion temperatures were solved, using Spitzer resistivity for the current and Bohm-GyroBohm heat conductivity for the temperature. The electron density was prescribed from the experiment at a given time. The computations were carried out to simulate 4 s of the time evolution at which a steady state solution is reached.

A rather good agreement is observed among computations using different options for the equilibrium solver.



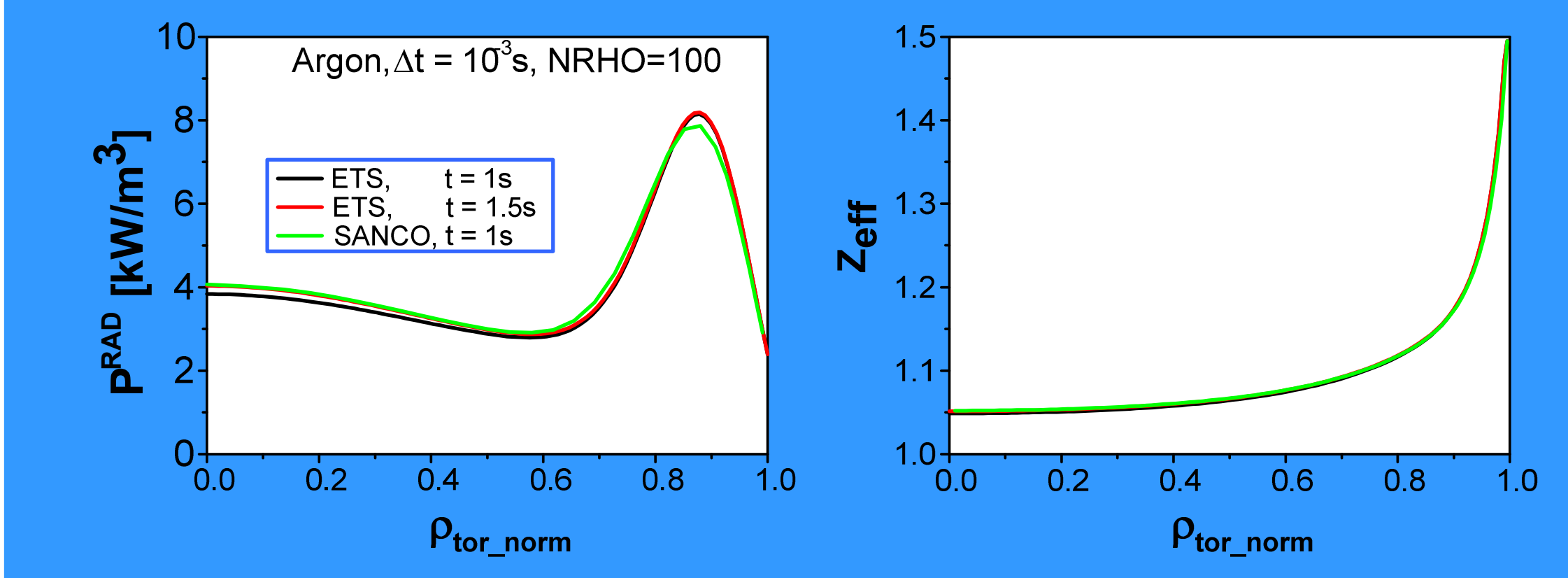
Benchmarking of the ETS against ASTRA and CRONOS transport codes was performed for conditions of hybrid scenario discharge with current overshoot, Btor=2.3 T, Ipl=1.7 MA, high triangularity (0.38), 18MW of NBI, nl=4.8e19 m-3, βN = 2.8. Spitzer resistivity was used for the current transport and heat transport coefficients were obtained from Bohm-gyroBohm model. The Gaussian H&CD profiles (centred at ρ=0, half-width ρΔ=0.3), with the total heating power Ptot=18 MW, distributed 70/30 between ions and electrons, were used with all codes. Total non-inductive current was Ini=0.12 MA, neglecting bootstrap current contribution.

Satisfactory agreement has been obtained. Slight differences in profiles refer to different equilibrium solvers used within compared codes.

Physics Applications

Impurity

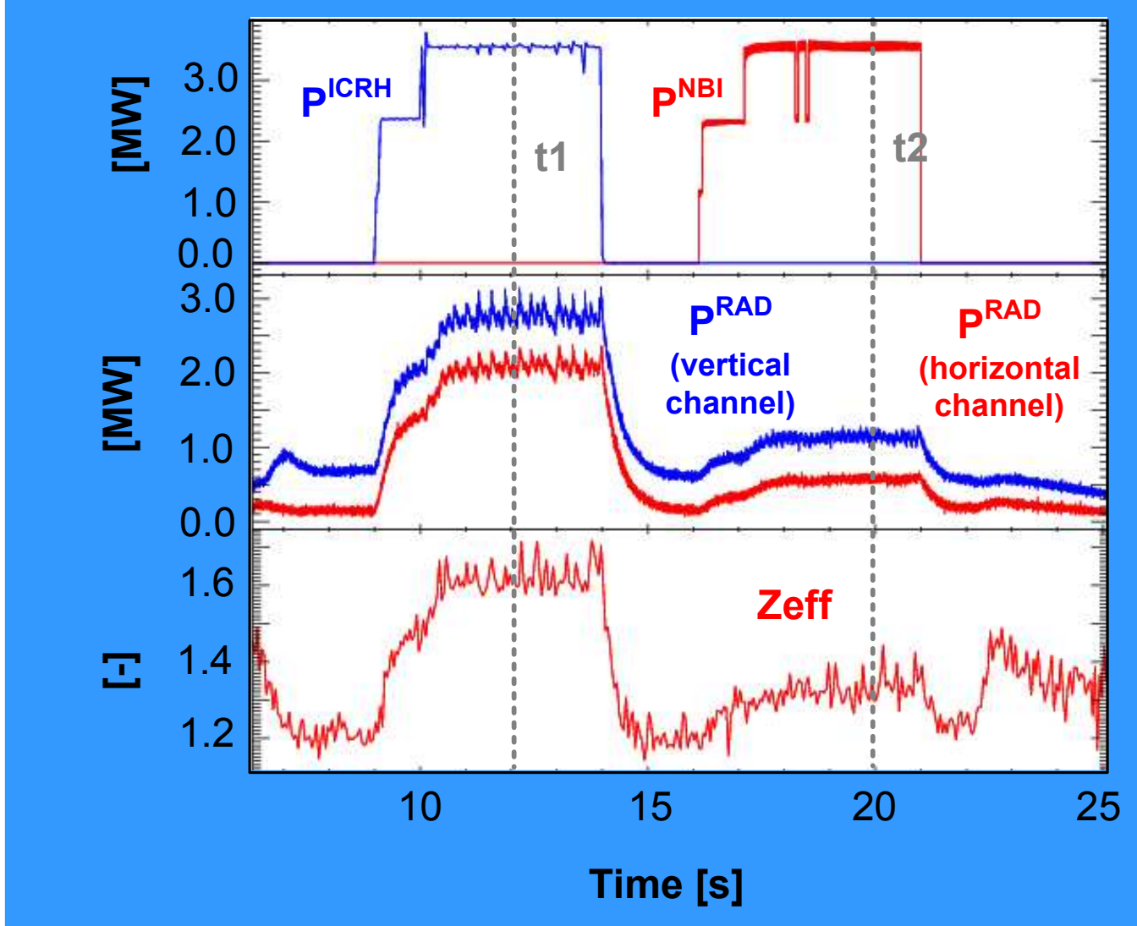
Verification of impurity module



Steady state profiles of radiative power density and ion effective ion charge, obtained after 1s. of time evolution wit ETS and SANCO.

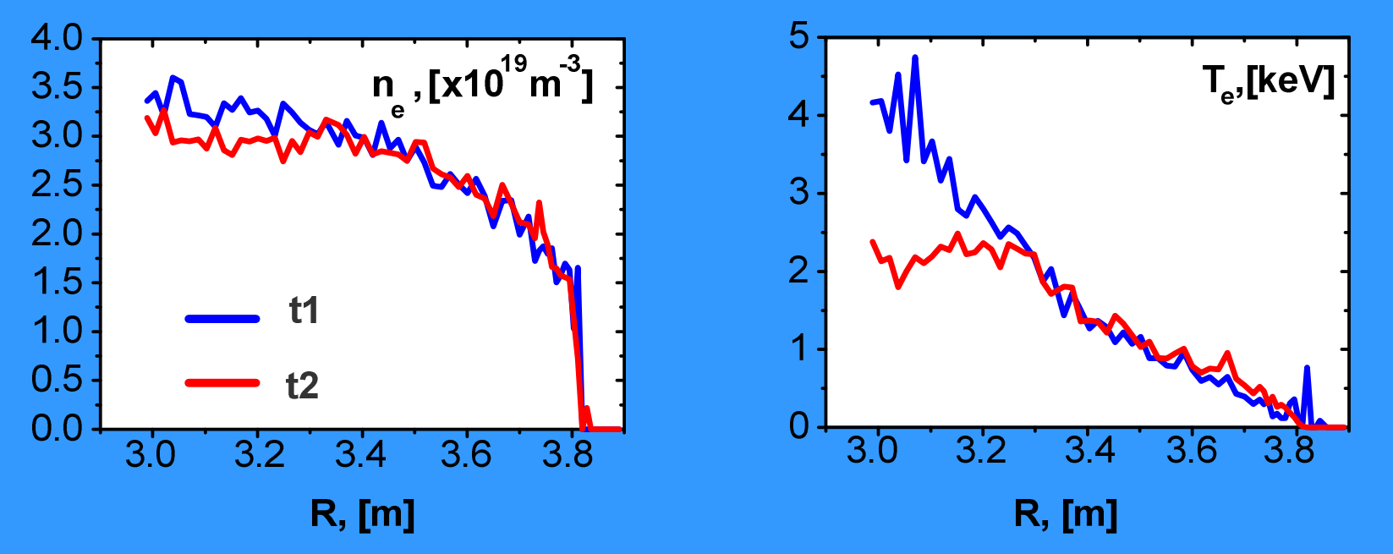
Benchmarking of the ETS impurity solver against SANCO impurity code was done for conditions of low confinement mode discharge, assuming interpretative parabolic profiles for density and temperature of main ions and interpretative equilibrium provided by EFIT equilibrium reconstruction code. Boundary conditions in both codes were given by the total impurity concentration at the last closed magnetic surface, assuming the coronal distribution at the corresponding ion temperature. Good agreement is achieved for carbon and argon concentration in comparison between two codes.

Modelling of JET discharge #81856 [for details about experiment see M.-L. Maypral, EX/4-3]



The ETS was applied for the impurity simulations of JET shot #81856 (ITER like wall) with two phases of 3.5 MW of auxiliary heating delivered by ICRH and NBI respectively. The ICRH results in a substantial increase of both effective charge, Zeff, and radiative power, P^{RAD}, compared to the NBI phase.

The plasma contamination during the ICRH phase can be caused either by an increased source of impurities or by changes in their transport.



• No essential difference between density and temperature profiles during NBI and ICRH phases

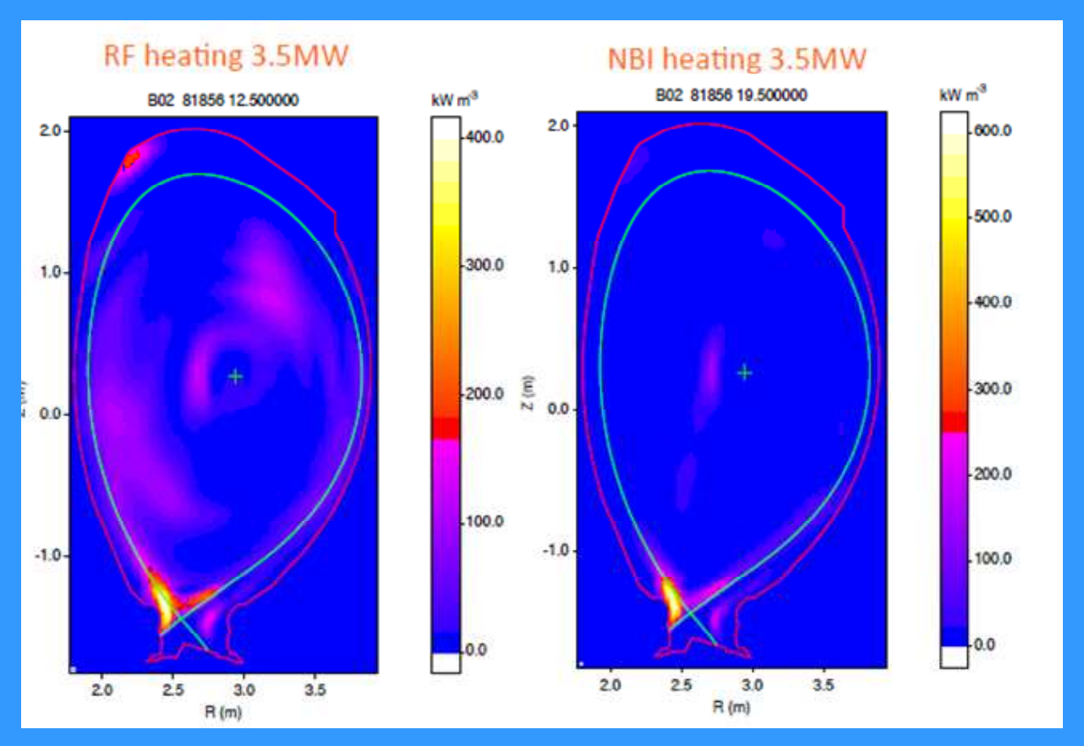
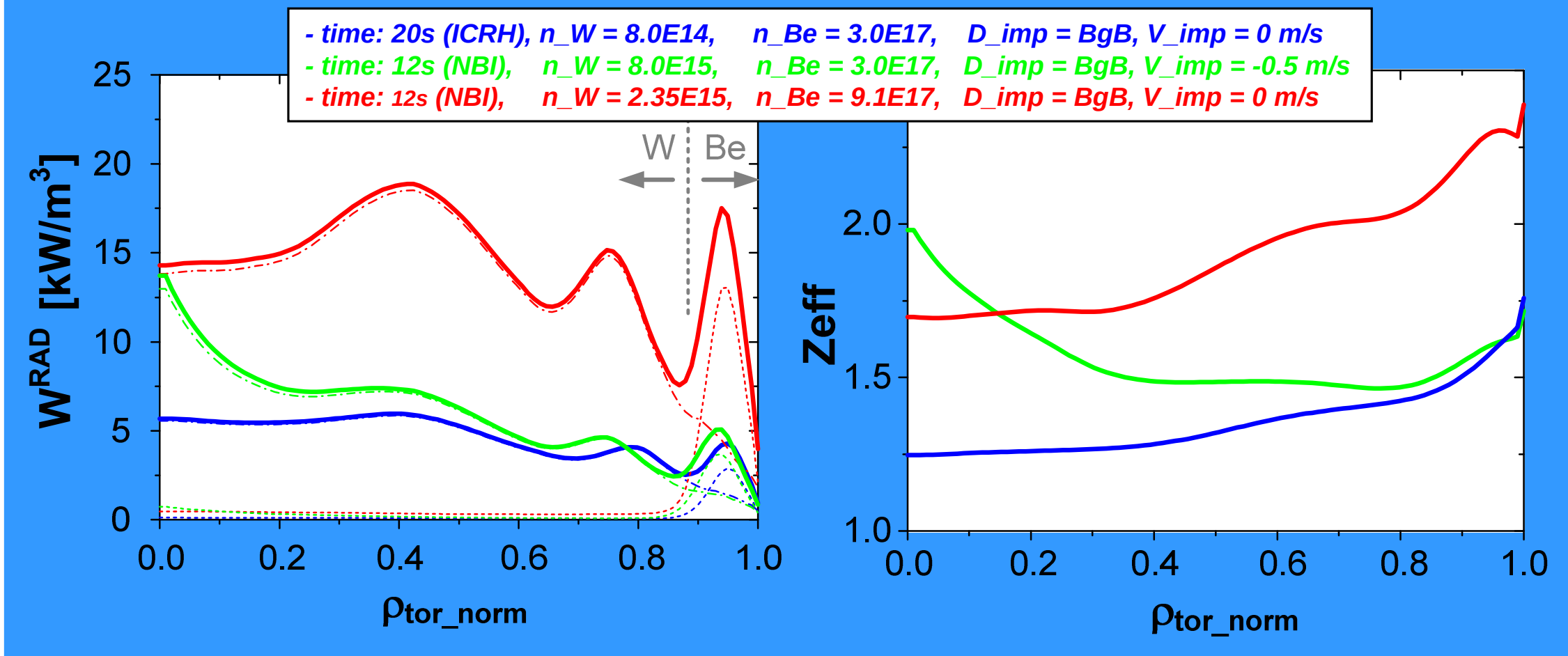
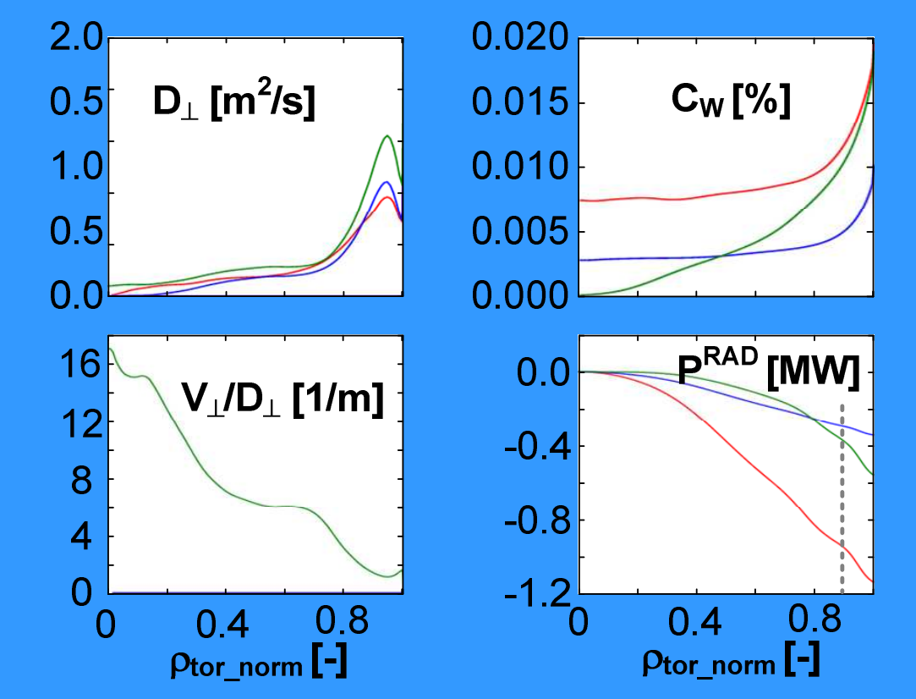


figure from D.Van Eester

• No radiation peaking in the core, the increase is quite uniform

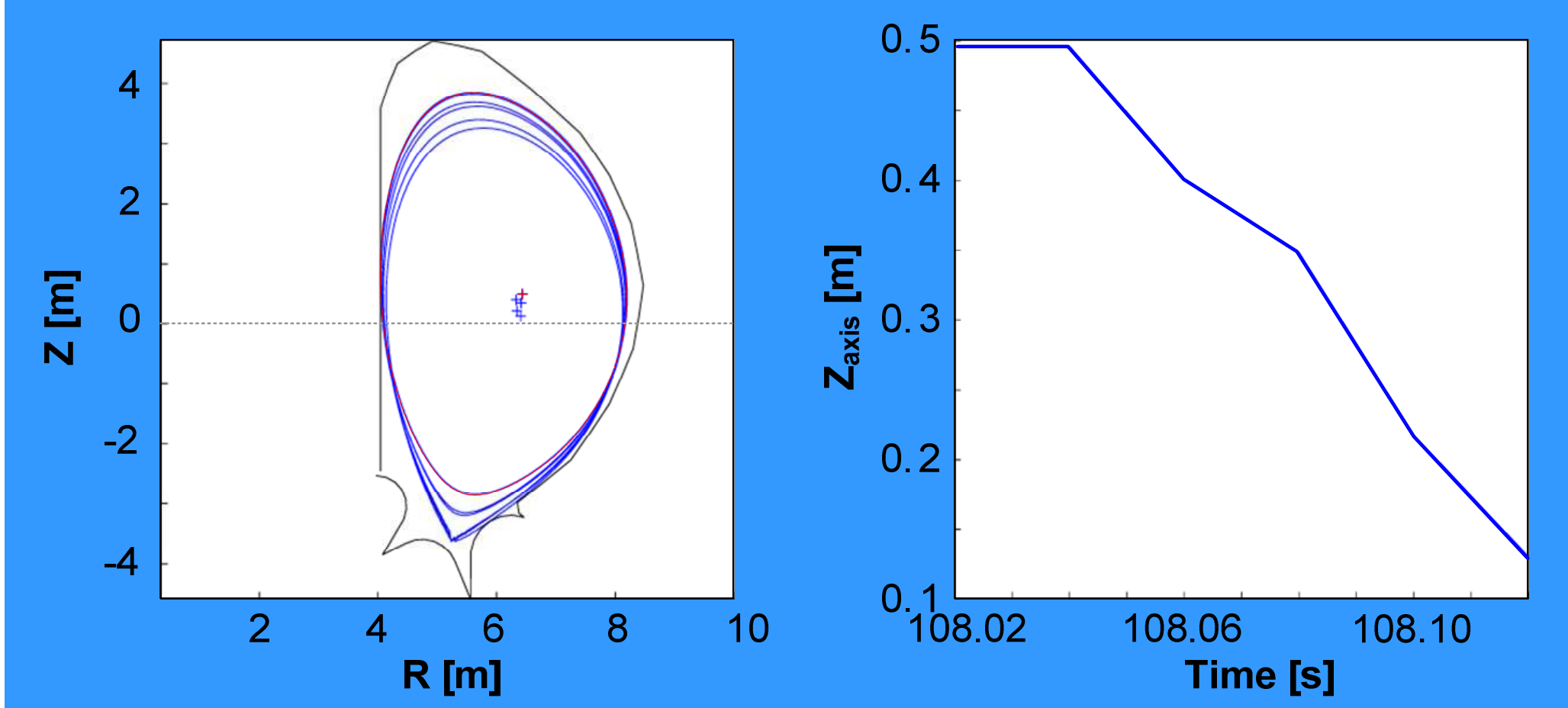




Starting with the NBI phase the Be and W sources were adjusted through their boundary values to match the experimentally measured impurity concentration and radiative losses (*nW = 8.0·1014 m-3; nBe = 3.0·1017 m-3*) for Be and W impurity densities assuming zero impurity convective velocity (blue curves). Taking these results as a reference the impurity distribution during the ICRH phase has been first simulated by assuming a radially constant negative impurity convective velocity of -0.5 m/s. This results in an increase of WRAD and Zeff, mostly at the magnetic axis, where impurities start to accumulate (green curves). Such W^{RAD} profile appeared to be inconsistent with the bolometric measurements showing a rather flat profile of radiative power during the ICRH phase. In addition, taking into account a small volume contribution from the plasma centre, the total radiative losses change only within a few percents compared to the factor 2.5 measured in experiment. At the next step (green curves)., the reference case has been repeated with zero convective velocity and increased (roughly by factor 3) impurity sources (boundary densities are *nW = 2.35·1015 m-3; nBe = 9.1·1017 m-3*). In this case a much better agreement with measurements for WRAD profile and Zeff is obtained. These simulations indicate that an increased impurity source is a possible reason for the W accumulation during the ICRH phase of #81856, although the effect of the radially shaped convective velocity can not be excluded.

Proofs of principle

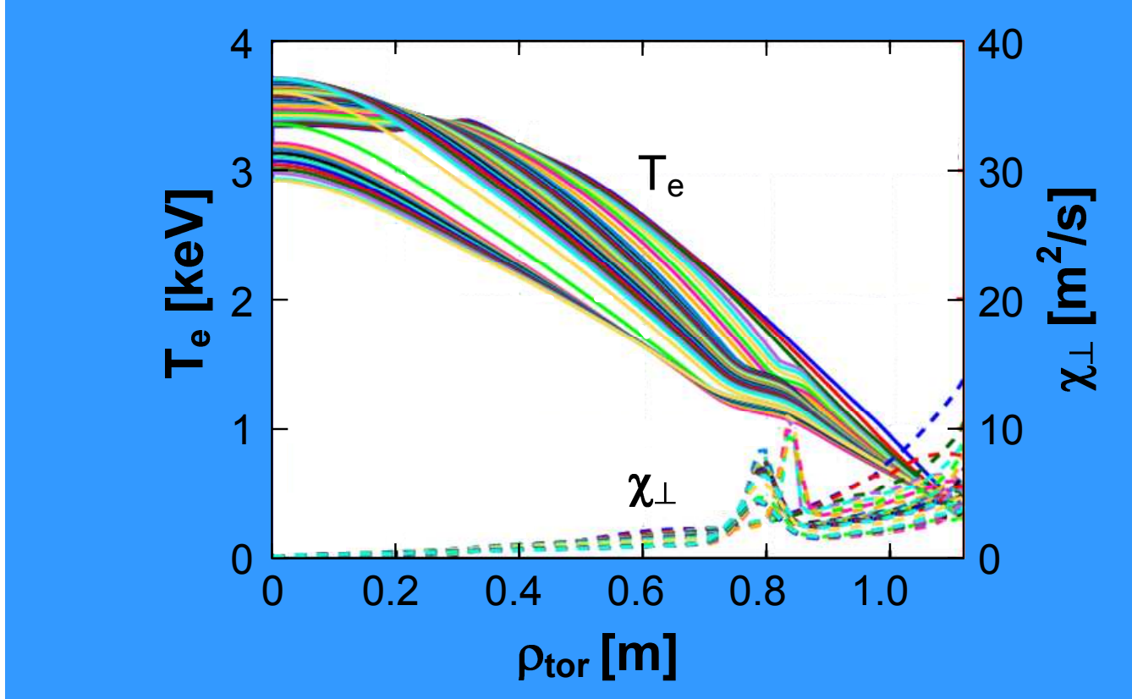
Free Boundary Equilibrium



The VDE is forced by imposing a substantial voltage in two of the poloidal field coils (PFC1 and PFC6). As a result, the plasma moves downwards on a ~100 ms timescale, which is consistent with other modelling studies.

Imposed VDE (left, time evolution of the last closed magnetic flux surface; right, time evolution of the magnetic axis height)

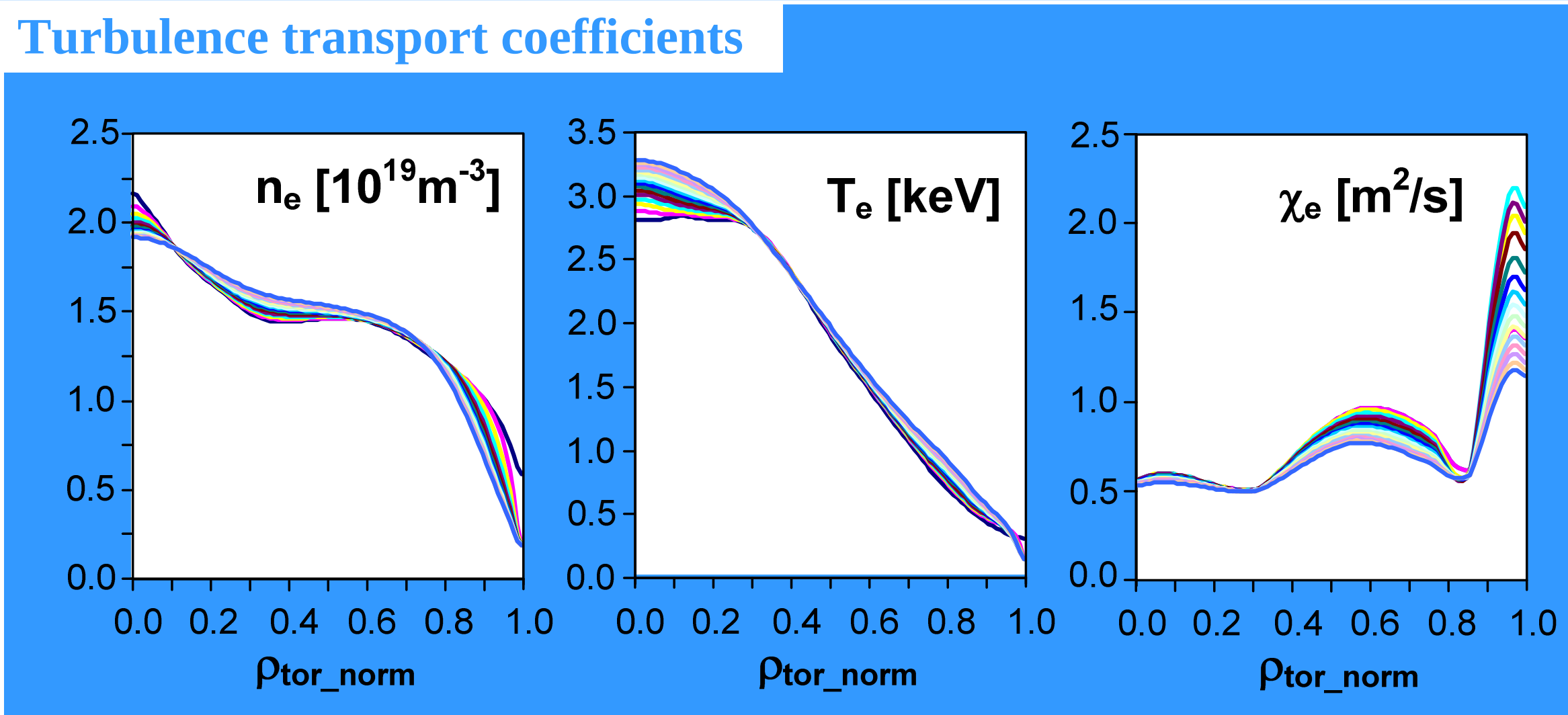
Neoclassical Tearing Mode



The module for the Neoclassical Tearing Mode, NTMwf, implemented in the ETS workflow, simulates the time behaviour of the NTMs, resistive instabilities breaking the flux surfaces into magnetic islands at the rational surfaces q=m/n. The modes are destabilized by a loss of bootstrap current proportional to the plasma pressure. The simulated modes grow starting from the specified onset time up to the saturated state. Their growth affects the local electron and ion temperature and density by changing the perpendicular transport coefficients around the mode location. The transport is modified by the NTMwf module, which adds a Gaussian perturbation of given amplitude and width to the unperturbed transport coefficients. This approach enables the reproduction of density and temperature profiles very close to the experimental ones.

The increase of the radial transport due to the magnetic island leads to the flattening of temperature profile around 2/1 surface. The mode grows on a resistive time scale to a saturated island width of 8 cm in about 150ms of time evolution; this leads to the 16% drop in the stored energy.

Turbulence transport coefficients



Transport-turbulence coupled computations: relaxation of electron density and temperature profiles (over 15 transport time steps) due to GEM transport coefficients

GEM is run remotely on HPC-FF on 256 cores while the main part of the workflow, which is serial, is run on the ITM computing cluster.

GEM is implemented as a chain of 8 flux tubes, from 0 to 7, with the i-th case at normalised toroidal flux radius [(2i+1)/16]^0.7. Each flux tube takes parameters from its profile location, runs for 10 gyro-Bohm times and returns transport coefficients.

The sharp rise at the edge is due to the nonlinear processes occurring when long-wavelength turbulence is present. In the core, by contrast, the parallel electron coupling is much more stiff and the nonlinear long-wavelength character of edge turbulence is absent.

Conclusions

The new modular transport simulator ETS developed by the ITM-TF was applied to simulate the conditions of several discharges in JET and ITER. The simulations were mostly aiming to module cross-verification, proof of the functionality of workflows coupling, i.e. FBE and turbulence codes to the transport solver. The ETS workflow was successfully benchmarked against major existing codes.

Furthermore, several equilibrium solvers have been benchmarked within the ETS workflow. A close agreement was obtained.

Impurity simulations for JET discharge 81856 show that the increased radiation during the ICRH phase as compared to the NBI phase can be explained for example by an increased W source. The impurity densities at the boundary for the NBI and ICRH phase, leading to a good agreement between the measured and simulated radiative power under condition of the Bohm-gyroBohm impurity diffusion and zero convection, have been estimated.

The ETS workflow simulation including the NTM module demonstrates the modification of temperature profile as a consequence of increased radial transport due to a magnetic island. The 2/1 mode grows on a resistive time scale to a saturated island width of 8 cm in about 150ms of time evolution, inducing the 16% drop in the stored energy.

A version of the ETS workflow coupled to the FBE code CEDRES++ has been set up. A first test simulation of a VDE in ITER finds a VDE timescale of 100ms, which is consistent with that found by other studies. A key upcoming step will be the implementation of a magnetic control system inside the ETS-CEDRES++ workflow, which is needed for free boundary scenario simulations.

A proof of principle of turbulence-transport coupling was demonstrated with the ETS-GEM coupled simulations. The generic behaviour of turbulence driven transport is observed: a sharp rise at the edge due to nonlinear processes, combined with a relatively moderate transport up to the mid radius, due to stronger parallel electron coupling reducing long-wave contributions.

TH/P2-01, 24th IAEA Fusion Energy Conference, October 8-13, 2012, San Diego, California, USA