



## **Final Report for National Transport Code Collaboration PTRANSP**

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PTRANSP, which is the predictive version of the TRANSP code, was developed in a collaborative effort involving the Princeton Plasma Physics Laboratory, General Atomics Corporation, Lawrence Livermore National Laboratory, and Lehigh University. The PTRANSP/TRANSP suite of codes is the premier integrated tokamak modeling software in the United States. A production service for PTRANSP/TRANSP simulations is maintained at the Princeton Plasma Physics Laboratory; the server has a simple command line client interface and is subscribed to by about 100 researchers from tokamak projects in the US, Europe, and Asia. This service produced nearly 13000 PTRANSP/TRANSP simulations in the four year period FY 2005 through FY 2008. Major archives of TRANSP results are maintained at PPPL, MIT, General Atomics, and JET. Recent utilization, counting experimental analysis simulations as well as predictive simulations, more than doubled from slightly over 2000 simulations per year in FY 2005 and FY 2006 to over 4300 simulations per year in FY 2007 and FY 2008. PTRANSP predictive simulations applied to ITER increased eight fold from 30 simulations per year in FY 2005 and FY 2006 to 240 simulations per year in FY 2007 and FY 2008, accounting for more than half of combined PTRANSP/TRANSP service CPU resource utilization in FY 2008. PTRANSP studies focused on ITER played a key role in journal articles [1,2]. Examples of validation studies carried out for momentum transport in PTRANSP simulations were presented at the 2008 IAEA conference [3]. The increase in number of PTRANSP simulations has continued (more than 7000 TRANSP/PTRANSP simulations in 2010) and results of PTRANSP simulations appear in conference proceedings, for example the 2010 IAEA conference [4,5], and in peer reviewed papers [6,8].

PTRANSP provides a bridge to the Fusion Simulation Program (FSP) and to the future of integrated modeling. Through years of widespread usage, each of the many parts of the PTRANSP suite of codes has been thoroughly validated against experimental data and benchmarked against other codes. At the same time, architectural modernizations are improving the modularity of the PTRANSP code base. The NUBEAM neutral beam and fusion products fast ion model, the Plasma State data repository (developed originally in the SWIM SciDAC project and adapted for use in PTRANSP), and other components are already shared with the SWIM, FACETS, and CPES SciDAC FSP prototype projects. Thus, the PTRANSP code is already serving as a bridge between our present integrated modeling capability and future capability. As the Fusion Simulation Program builds toward the facility currently available in the PTRANSP suite of codes, early versions of the FSP core plasma model will need to be benchmarked against the PTRANSP simulations. This will be necessary to build user confidence in FSP, but this benchmarking can only be done if PTRANSP itself is maintained and developed.

FSP code development will commence no earlier than FY 2012, according to current plans. In terms of computing capability, FSP is projected to be built from the ground up for high performance supercomputing, while PTRANSP is targeted at more modest capacity computing resources. Nevertheless PTRANSP includes high performance components. In the case of current NUBEAM and RF modules, and transport equation solver modules, parallel performance is being tested on midrange computing clusters, producing results that benefit from massively parallel computing. It will be several years before FSP is ready for use by researchers; widespread use of PTRANSP is already a reality. PTRANSP development is motivated by its research applications and its development priorities are set by user needs within the labor constraints of available development and support staff. Continued support of PTRANSP will serve user needs and will provide a well validated and trusted test bed for FSP components.

The Lehigh Fusion Research Group has carried out the following PTRANSP development projects: (1) Implemented the new MMM7.1 Multi-Mode transport model and used it to carry out detailed comparisons between predictive momentum transport simulation results and experimental data, including predictions of intrinsic rotation in tokamaks; (2) implemented a unified system of transport equations for particle, momentum and thermal transport, together with the Pereverzev-Corrigan technique for control of numerical instabilities associated with stiff transport models; and (3) implemented the “Framework for Modernization and Componentization of Fusion Modules” (FMC FM) within PTRANSP in order to provide a reliable, uniform, parallelized interface to transport modules. The FMC FM interface will be used together with MPI to parallelize the computation of transport, which is becoming more important as transport models become increasingly sophisticated and computationally intensive. The uniform interface provided by FMC FM will facilitate the implementation of a wider variety of transport models and gyrokinetic turbulence codes within PTRANSP.

The new MMM7.1 Multi-Mode transport model has been installed and validated in the PTRANSP code [9, 10]. The MMM7.1 transport model consists of the new Weiland19 for transport driven by ITG, TEM and MHD modes as well as the Horton model for transport driven by ETG modes. The Callen model for paleoclassical transport can be used along with the MMM7.1 model. A model developed for transport driven by resistive ballooning modes, has been added as another component to the MMM7.1 model [11]. Time dependent PTRANSP simulations of 16 DIII-D and 16 JET discharges were carried out and statistics were computed from the comparison of simulation results with experimental data for the temperature and toroidal angular frequency profiles [2]. It was found that PTRANSP simulation results using the new MMM7.1 model agreed with experimental data more closely than corresponding results using either the GLF23 or MMM95 transport models. The transport equations are solved self-consistently with sources and sinks of particles, angular momentum, thermal energy, and non-inductively driven current. The density, temperature, and width of the H-mode pedestal are predicted using a theory based model, while the edge rotation is taken from experimental data. An objective of this work includes the validation of the models for anomalous transport. This objective is pursued by comparing simulation results for the density, momentum and temperature profiles with experimental data. In addition to the PTRANSP simulations carried out with the MMM and GLF23 transport models, PTRANSP simulations have also been carried out using the mixed-Bohm/gyro-Bohm model.

An important new feature of the MMM7.1 transport model is the prediction of toroidal angular momentum transport and, in particular, an inward pinch of toroidal angular momentum [12]. It has been demonstrated that the “intrinsic toroidal rotation” that is observed in tokamak experiments is predicted in PTRANSP simulations using the MMM7.1 transport model. Improvements to the Weiland ion drift mode component in the MMM7.1 transport model have resulted in improved agreement with experimental data, particularly for the intrinsic toroidal rotation [12], as illustrated in Fig. 1. PTRANSP simulations have been used to develop a scaling relation for the momentum confinement time as a function of the applied torque per particle and the plasma current, as illustrated in Fig. 2.

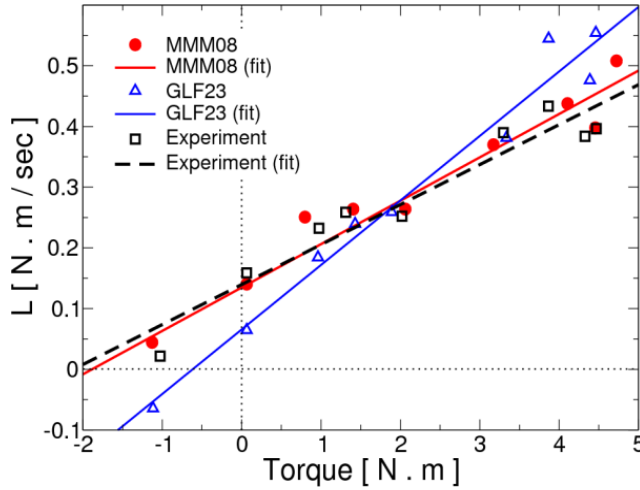


Fig. 1: Angular momentum,  $L$ , as a function of injected torque for simulations of DIII-D discharges.

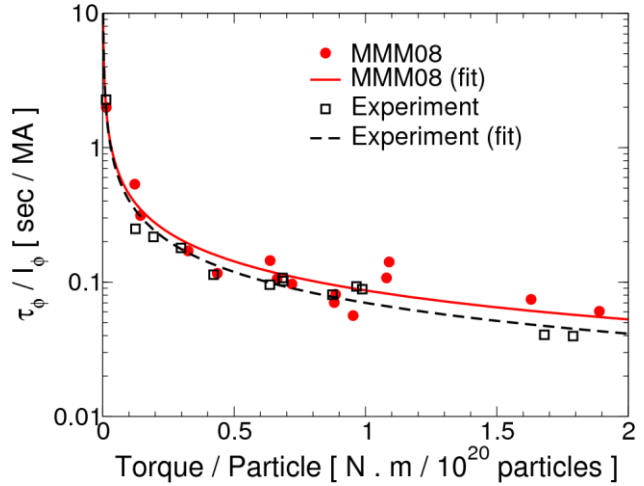


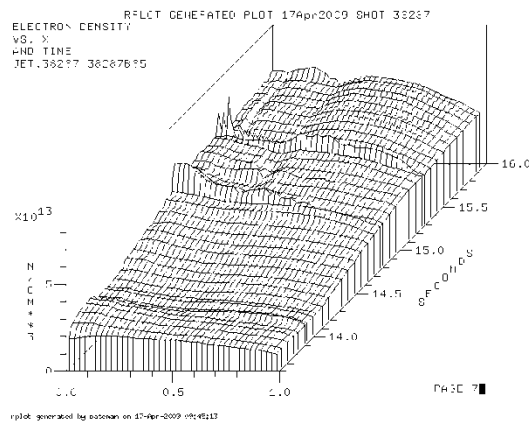
Fig. 2: Momentum confinement time,  $\tau_\phi$ , divided by plasma current,  $I_p$ , as a function of injected torque per particle for DIII-D.

A unified system of transport equations have been implemented in PTRANSP to advance the particle density, toroidal angular momentum and thermal transport equations in time [13,14]. The user can choose to predict subsets of profiles while other profiles are read in or inferred from experimental data. Boundary conditions can be computed using either experimental data or a predictive pedestal model after the predicted L-H mode transition. The NCLASS neoclassical transport module was recently implemented in PTRANSP to be used together with anomalous transport for thermal and particle transport. A gas puffing feedback loop was implemented in PTRANSP for the main plasma species, in addition to wall recycling, to control the volume averaged electron density as a function of time. PTRANSP users now have the choice of evolving the transport equations for both impurity and main gas ions, given input boundary conditions as a function of time, or evolving only the main gas ions (usually hydrogenic ions), given a  $Z_{eff}$  profile or impurity density profiles that are read from input data as a function of time [13]. The implementation of the charge neutrality condition in PTRANSP includes the effects of fast ions, multiple species of impurities and multiple species of main gas ions as a function of radius and time. Sawtooth crashes mix the fast ion profiles and all of the thermal particle species profiles, as well as momentum and temperature profiles.

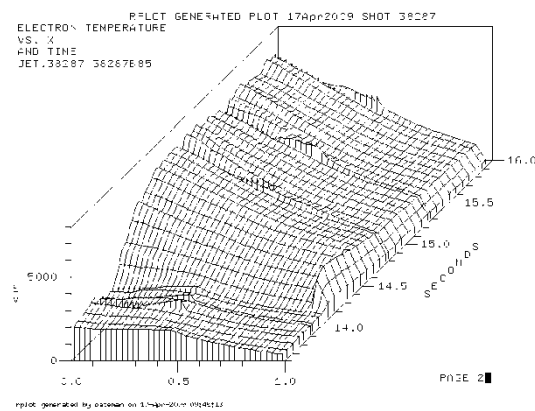
Anomalous impurity and hydrogenic particle transport coefficients are computed using either the new MMM7.1 transport model or the older MMM95 transport model. Five channels of transport coefficients — hydrogenic and impurity particle, toroidal angular momentum, electron and ion thermal — are computed self-consistently with the new MMM7.1 transport model. An example is illustrated in Figures 3 and 4 below of a simulation in which all five channels were computed self-consistently as a function of radius and time using the MMM7.1 transport model, together with a transition from L- to H-mode and sawtooth oscillations.

Three techniques are now available in PTRANSP to control the numerical instabilities that are associated with stiff transport and flow-shear suppression of transport. The Pereverzev-Corrigan technique [15] was recently implemented in PTRANSP to provide a simple, fast, easy-to-use method for controlling numerical instabilities. Newton's method, which was previously implemented in PTRANSP by members of the Lehigh group [16], is less reliable and requires more computational time, although it has the advantage of evolving transients more accurately. Time smoothing methods, which were previously available in PTRANSP, are the least accurate method for time-dependent evolution of plasma profiles.

These improved numerical stabilization techniques facilitated full-length ITER simulations (up to 5000 seconds of plasma time) using the GLF23 and Multi-Mode transport models [1,2, 4,5,]. It was found that toroidal rotation driven by neutral beam injection can play a significant role in improving energy confinement and, consequently, improving fusion power performance. Reference [1] was one of the most frequently referenced publications in Nuclear Fusion during 2008.



*Fig. 3: Electron density as a function of radius and time from a PTRANSP simulation using the MMM08 model.*



*Fig. 4: Electron temperature as a function of radius and time from a PTRANSP simulation using the MMM08 model.*

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## Utilization of PTRANSP

- PTRANSP code is used in two ways
  - Analysis mode: PTRANSP uses temperature, density and magnetic  $q$  profiles from external code or from experimental data
    - Refined power deposition and current drive sources returned iteratively to external code for improved plasma simulations
  - Predictive mode
    - Heating and current profiles evolve using theory based transport models
    - Compute evolution of temperature, toroidal angular rotation frequency profiles and fusion power
- The TRANSP/PTRANSP code includes high fidelity heating and current drive source models, as well as accurate models for fast particles, equilibrium and atomic physics.
  - TRANSP is used for interpretive analysis of nearly all tokamak experiments around the world
  - In the predictive TRANSP mode of operation, theory-based transport models are used to advance the transport equations forward in time
- More than 7000 TRANSP/PTRANSP simulations in FY2010

## Modules Included in the PTRANSP Code

- MHD Equilibrium Codes: TEQ, VMEC, ESC, SCRUNCH2, ISOLVER, JSOLVER
- RF Heating and Current Drive Modules:
  - Electron cyclotron: TORAY, GENRAY
  - Ion cyclotron: TORIC
    - TORIC MPI demonstrated 30x speedup
    - New MIT solver, high resolution (255 modes)
  - Lower Hybrid: LSC, CQL3D (Fokker planck); GENRAY (geometrical optics)
- NUBEAM MPI: can be used for beam deposition current drive, beam torque, as well as slowing down, pitch angle scattering and thermalization of beam ions and fusion ions
  - Parallel processing scales with 4000 Monte-Carlo particles per processor
- Anomalous Transport Models: GLF23, Coppi-Tang, MMM95, MMM7.1, JETTO, TGLF
  - FMCFM interface implemented for common transport interface
- Atomic Physics: ADAS module
- Nuclear Cross-sections: PREACT Module
- Sawtooth Crashes and Reconnection: Porcelli or Park-Montecello for trigger and Kadomtsev model for reconnection
- Neoclassical Resistivity and Transport: NCLASS, Sauter, Chang-Hinton, KAPISN
- Paleoclassical electron thermal transport: MODPALEO
- Pedestal Model: PEDESTAL or input from EPED1 for pedestal shape and ELM trigger
- Control of numerical instabilities: choice of techniques implemented, needed particularly when using stiff transport models
- GCNM-P (General Atomics) solver tested using PTRANSP generated Plasma State pairs

## Recent Operational Improvements

- Plasma State (facilitates interaction with other codes) used for data structures such as profiles. Contains data for axisymmetric MHD equilibrium, plasma and source profiles (1-D and 2-D), as well as associated scalar data
- Data handling, visualization, GUIs, and EIVis