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Activity Report 2013

Team CASTOR

Control, Analysis and Simulations for TOkamak Research

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

RESEARCH CENTER
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THEME
Earth, Environmental and Energy Sciences

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Creation of the Team: 2012 July 01.

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2. Overall Objectives

2.1. Overall Objectives

Turbulence often called "the last unsolved problem in classical statistical mechanics" from a citation by Richard Feynman is a fundamental feature of fluid flows. Its correct description impacts such diverse fields as weather prediction and ocean dynamics, aircraft and ship design or transport and instabilities in plasmas to cite but a few.
The challenge of understanding and modeling turbulence has been with us for more than 100 years with very modest results. Since the 1941 Kolmogorov theory [31], no universally valid successful theory has emerged in this field. This is certainly due to the fact that a universal theory of turbulence does not exist and that instead one has to face very different mechanisms with very different properties.

However, with emerging petaflop computers, some direct numerical simulation of fluid turbulence is becoming possible. This is specially true in application domains like transport in Tokamaks where some internal mechanism forbids the size of the turbulent eddies to go below certain limits (here, the Larmor radius). In other application areas such as classical aerodynamics, although direct numerical simulations are still out of reach, attention is becoming focused on unsteady processes and instabilities requiring the use of models beyond the RANS ones ("Reynolds averaged").
The CASTOR team is a follow-up of the team Pumas. CASTOR gathers in a new team, the activities in numerical simulation of fusion plasmas conducted in Pumas with the activities in control and optimisation done in the laboratory Jean-Alexandre Dieudonné of the University of Nice. The main objective of the CASTOR team is to contribute to the development of innovative numerical tool to improve the computer simulations of complex turbulent or unstable flows in plasma physics and to develop methods allowing the real-time control of these flows or the optimisation of scenarios of plasma discharges in tokamaks. CASTOR is a common project between Inria (http://www.inria.fr/centre/sophia) and the University of Nice Sophia-Antipolis through the laboratory Jean-Alexandre Dieudonné, UMR UNS-CNRS 7351, (http://math.unice.fr).

3. Research Program

3.1. Plasma Physics

Participants: Hervé Guillard, Boniface Nkonga, Afeintou Sangam, Richard Pasquetti, Marie Martin, Cédric Lachat, Blaise Faugeras, Jacques Blum, Cédric Boulbe, Sebastian Minjeaud.

In order to fulfil the increasing demand, alternative energy sources have to be developed. Indeed, the current rate of fossil fuel usage and its serious adverse environmental impacts (pollution, greenhouse gas emissions, ...) lead to an energy crisis accompanied by potentially disastrous global climate changes.
Controlled fusion power is one of the most promising alternatives to the use of fossil resources, potentially with a unlimited source of fuel. France with the ITER (http://www.iter.org/default.aspx) and Laser Megajoule (http://www-lmj.cea.fr/) facilities is strongly involved in the development of these two parallel approaches to master fusion that are magnetic and inertial confinement. Although the principles of fusion reaction are well understood from nearly sixty years, (the design of tokamak dates back from studies done in the '50 by Igor Tamm and Andreï Sakharov in the former Soviet Union), the route to an industrial reactor is still long and the application of controlled fusion for energy production is beyond our present knowledge of related physical processes. In magnetic confinement, beside technological constraints involving for instance the design of plasma-facing component, one of the main difficulties in the building of a controlled fusion reactor is the poor confinement time reached so far. This confinement time is actually governed by turbulent transport that therefore determines the performance of fusion plasmas. The prediction of the level of turbulent transport in large machines such as ITER is therefore of paramount importance for the success of the researches on controlled magnetic fusion.
The other route for fusion plasma is inertial confinement. In this latter case, large scale hydrodynamical instabilities prevent a sufficient large energy deposit and lower the return of the target. Therefore, for both magnetic and inertial confinement technologies, the success of the projects is deeply linked to the theoretical understanding of plasma turbulence and flow instabilities as well as to mathematical and numerical improvements enabling the development of predictive simulation tools.

3.2. Turbulence Modelling

Participants: Alain Dervieux, Boniface Nkonga, Richard Pasquetti.

Fluid turbulence has a paradoxical situation in science. The Navier-Stokes equations are an almost perfect model that can be applied to any flow. However, they cannot be solved for any flow of direct practical interest. Turbulent flows involve instability and strong dependence to parameters, chaotic succession of more or less organised phenomena, small and large scales interacting in a complex manner. It is generally necessary to find a compromise between neglecting a huge number of small events and predicting more or less accurately some larger events and trends.

In this direction, CASTOR wishes to contribute to the progress of methods for the prediction of fluid turbulence. Taking benefit of its experience in numerical methods for complex applications, CASTOR works out models for predicting flows around complex obstacles, that can be moved or deformed by the flow, and involving large turbulent structures. Taking into account our ambition to provide also short term methods for industrial problems, we consider methods applying to high Reynolds flows, and in particular, methods hybridizing Large Eddy Simulation (LES) with Reynolds Averaging.

Turbulence is the indirect cause of many other phenomena. Fluid-structure interaction is one of them, and can manifest itself for example in Vortex Induced Motion or Vibration. These phenomena can couple also with liquid-gas interfaces and bring new problems. Of particular interest is also the study of turbulence generated noise. In this field, though acoustic phenomena can also in principle be described by the Navier-Stokes equations, they are not generally numerically solved by flow solvers but rather by specialized linear and nonlinear acoustic solvers. An important question is the investigation of the best way to combine a LES simulation with the acoustic propagation of the waves it produces.

3.3. Astrophysical and Environmental flows

Participants: Didier Auroux, Hervé Guillard, Boniface Nkonga, Sebastian Minjeaud.

Although it seems inappropriate to address the modeling of experimental devices of the size of a tokamak and for instance, astrophysical systems with the same mathematical and numerical tools, it has long been recognized that the behaviour of these systems have a profound unity. This has for consequence for instance that any large conference on plasma physics includes sessions on astrophysical plasmas as well as sessions on laboratory plasmas. CASTOR does not intend to consider fluid models coming from Astrophysics or Environmental flows for themselves. However, the team is interested in the numerical approximation of some problems in this area as they provide interesting reduced models for more complex phenomena. To be more precise, let us give some concrete examples : The development of Rossby waves [1] a common problem in weather prediction has a counterpart in the development of magnetic shear induced instabilities in tokamaks and the understanding of this latter type of instabilities has been largely improved by the Rossby wave model. A second example is the water bag model of plasma physics that has a lot in common with multi-layer shallow water system.

To give a last example, we can stress that the development of the so-called well-balanced finite volume schemes used nowadays in many domains of mathematical physics or engineering was largely motivated by the desire to suppress some problems appearing in the approximation of the shallow water system.

Our goal is therefore to use astrophysical or geophysical models to investigate some numerical questions in contexts that, in contrast with plasma physics or fluid turbulence, do not require huge three dimensional computations but are still of interest for themselves and not only as toy models.

4. Application Domains

4.1. Tokamaks

In the conception of the ITER tokamak, several key challenging points have been identified. One of them is the necessity to understand and control the huge thermal loads that are directed to the divertor target plates from the scrape-off layer (SOL) region since they are at the edge of or above what can be handled by today's materials. In the same spirit, the control of ELMs type instabilities that can also result in huge energy losses impacting the plasma facing components is considered as of crucial importance for the ITER program. The optimization of scenarii for designing the discharges of ITER and WEST will be addressed as well as some problems of ionospheric plasma.

[1] Rossby waves are giant meanders in high altitude wind that have major influence on weather. Oceanic Rossby waves are also know to exist and to affect the world ocean circulation

5. Software and Platforms

5.1. FluidBox

Participants: Boniface Nkonga [contact], Hervé Guillard.

FluidBox is a software dedicated to the simulation of inert or reactive flows. It is also able to simulate multiphase, multi-material and MDH flows. There exist 2D and 3D dimensional versions. The 2D version is used to test new ideas that are later implemented in 3D. Two classes of schemes are available : a classical finite volume scheme and the more recent residual distribution schemes. Several low Mach number preconditioning are also implemented. The code has been parallelized with and without domain overlapping. The linear solver PaStiX is integrated in FluidBox. A partitioning tool exists in the package and uses Scotch.

5.2. PlaTo

Participant: Hervé Guillard [contact].

PlaTo (Platform for Tokamak simulation) is a specialized set of softwares dedicated to the geometry of Tokamaks whose main objective is to provide the researchers of the CASTOR team a common development tools. The platform integrates Fortran90 modules using the MPI communication library for parallel computations and some python and C codes. The PlaTo platform has been developed thanks to a 2010 ADT of Inria and the ANR ESPOIR. The construction of this platform integrates the following developments :

- The set-up of a (small) database corresponding to axisymmetric solutions of the equilibrium plasma equations for realistic geometrical and magnetic configurations (JET, ITER and the Tore-Supra upgrade WEST).The construction of meshes is always an important and time consuming task. PlaTo provides meshes and solutions corresponding to equilibrium solutions that will be used as initial data for more complex computations.
- A set of interfaces (PlaTo ToolBox) allowing easy transfer between different solution and mesh formats.
- Numerical templates allowing the use of 3D discretization schemes using finite element/volume methods. At present, several applications (reduced MHD, Euler equations, two fluid Euler model) are available in PlaTo .

5.3. PaMPA

Participants: Cécile Dobrzynski [Bacchus], Hervé Guillard, Laurent Hascoët [Ecuador], Cédric Lachat, François Pellegrini [Bacchus].

PaMPA (“Parallel Mesh Partitioning and Adaptation”) is a middleware library dedicated to the management of distributed meshes. Its purpose is to relieve solver writers from the tedious and error prone task of writing again and again service routines for mesh handling, data communication and exchange, remeshing, and data redistribution. An API of the future platform has been devised, and the coding of the mesh handling and redistribution routines is in progress. PaMPA will be used as a base module for the PLATO solvers, to balance dynamically, refine and coarsen its distributed mesh.

5.4. Cedres++

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras, Sylvain Bremond [CEA], Eric Nardon [CEA].

In Tokamaks, at the slow resistive diffusion time scale, the magnetic configuration in the plasma can be described by the MHD equilibirum equations inside the plasma and the Maxwell equations outside. Moreover, the magnetic field is often supposed not to depend on the azimutal angle.

Under this assumption of axisymmetric configuration, the equilibrium in the whole space reduces to solving a 2D problem in which the magnetic field in the plasma is described by the well known Grad Shafranov equation. The unknown of this problem is the poloidal magnetic flux. The P1 finite element code CEDRES++ solves this free boundary equilibrium problem in direct and inverse mode. The direct problem consists in the computation of the magnetic configuration and of the plasma boundary, given a plasma current density profile and the total current in each poloidal field coils (PF coils). The aim of the inverse problem is to find currents in the PF coils in order to best fit a given plasma shape. An evolutive version of the code has also been recently developed. This version takes into account the circuit equations in the PF coils. These equations give a time dependent relation between the voltages, the total current in the coils and the time derivative of the magnetic flux. Induced currents in passive structures like the vaccuum vessel are also considered in this dynamic equilibrium problem. This new version of the code is an important tool for plasma scenario development and Tokamak design studies.

5.5. Equinox

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras.

EQUINOX is a code dedicated to the numerical reconstruction of the equilibrium of the plasma in a Tokamak. The problem solved consists in the identification of the plasma current density, a non-linear source in the 2D Grad-Shafranov equation which governs the axisymmetric equilibrium of a plasma in a Tokamak. The experimental measurements that enable this identification are the magnetics on the vacuum vessel, but also polarimetric and interferometric measures on several chords, as well as motional Stark effect measurements. The reconstruction can be obtained in real-time and the numerical method implemented involves a finite element method, a fixed-point algorithm and a least-square optimization procedure.

6. New Results

6.1. High order approximation of the two fluid Braginskii model

Participants: Sebastian Minjeaud, Richard Pasquetti.

We work on a two fluid physical model developed in close connection with Ph. Ghendrih (IRFM). It is based on the electrostatic assumption, i.e. the magnetic field is given (the magnetic field induced by the plasma itself is negligible), on the hypothesis of electroneutrality (the density of ions and electrons are proportional) and on the Braginskii closure. On the basis of the conservation equations of density, electron and ion velocities, electron and ion temperatures and electrical charges, a set of 10 non-linear and strongly anisotropic coupled partial differential equations (PDE) can be set up. A high order Fourier-SEM (Spectral Element Method) code is currently developed to address this problem. This Fourier-SEM code is close to be operational for the full set of PDEs in a 3D toroidal geometry. The torus section is discretized with quadrangular elements and Fourier expansions are used in the toroidal direction. In time one uses an RK3 (third order Runge-Kutta) IMEX (Implicit-Explicit), so that the Lorentz terms are handled implicitly. The capability of this code to handle a strongly anisotropic diffusion in a 3D toroidal geometry has already been tested. The Braginskii closure has been implemented. The Bohm boundary conditions at the plates are also considered. In 2013, we worked on a parallel version of the code and on the robustness of our algorithms, to be able to make long time computations, e.g. a few hundreds of thermal times.

6.1.1. Parallelization of the full Braginskii (FBGKI) code.

A first parallel version of the FBGKI code is now operational. Tests were made on the Computional center of the University of Nice-Sophia Antipolis. Tests on a large number of processors have however not yet been carried out, since presently our goal is to improve the robustness of our algorithms. Our parallelization strategy is based on a domain decomposition technique in the poloidal plane, where the spectral element approximation is local. On the contrary, in toroidal direction the approximation is global since based on Fourier expansions.

6.1.2. Numerical stabilization.

A spectral vanishing viscosity (SVV) technique was implemented in the sequential version of the code. Such a stabilization technique relies on the idea of introducing viscosity in the high frequency range of the spectral element / Fourier approximation. Such an approach was first proposed for hyperbolic problems, typically the Burgers equation (E. Tadmor, 1989). Later on, it was used for the large-eddy simulation of turbulent flows. Thus, we have a large experience of the SVV stabilization for the computation of turbulent wake flows.

6.1.3. Projection techniques.

A projection technique is used to enforce the divergence free constraint of the current. Projection techniques have been developed for a long time, in the frame of the Navier-Stokes equations to provide efficient algorithms when incompressible flows are concerned. For the Braginskii system, it appears natural to make use of such techniques for the current. Different projection techniques have been implemented in the FBGKI code, from the most classical one (Chorin-Temam, 1969) to the most recent. It turns out however that using projection techniques is less straightforward for Braginskii than for Navier-Stokes. We actively work on this point in order to cure some not yet understood failures of convergence with the time-step.

In the frame of the Eurofusion program, it is planned to check this version of the code on a simple configuration proposed by the EPFL (Paolo Ricci) where experimental as well as numerical results are available.

6.2. Equilibrium reconstruction and current density profile identification

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras.

EQUINOX is a real-time equilibrium reconstruction code. It solves the equation satisfied by the poloidal flux in a computation domain, which can be the vacuum vessel for example, using a P1 finite element method and solves the inverse problem of the identification of the current density profile by minimizing a least square cost-function. It uses as minimal input the knowledge of the flux and its normal derivative on the boundary of the computation domain. It can also use supplementary constraints to solve the inverse problem: interferometric, polarimetric and MSE measurements. Part of the work reported here has been done in the frame of a RTM-JET contract [2]

6.2.1. Direct use of the magnetic measurements

The code EQUINOX was not originally designed to take as magnetic inputs directly the magnetic measurements, as it should be the case in the ITM (Integrated Tokamak Modeling European platform), but some outputs from the real-time codes APOLO at ToreSupra and XLOC at JET. These codes provide EQUINOX with the values of the flux and its normal derivative on a closed contour defining the boundary of the computation domain (this contour can be the limiter for example). As a consequence the main difficulty arising in the objective of integrating the code EQUINOX in the ITM structure is to interpolate between the magnetic measurements (flux loops and poloidal B-probes) with a machine independent method. A solution to do this is to use toroidal harmonics functions as a basis for the decomposition of the poloidal flux in the vacuum region in complement to the contribution of the PF coils. The first version of the algorithm implementing this method for EQUINOX-ITM developed in 2012 has been updated and tested during 2013:

- WEST and JET: This method can provide an alternative tool, comparable to APOLO (for Tore Supra) and FELIX (for JET), to compute the plasma boundary in real time from the magnetic measurements. Some twin experiments for WEST have been successfully conducted. In a first step the equivalents of magnetic measurements were generated using the free boundary equilibrium code CEDRES++. In a second step these measurements were used by the toroidal harmonics algorithm to reconstruct the plasma boundary. Additional calculations aiming at validating the design of the WEST magnetic diagnostics have been performed. They consisted in checking the equilibrium reconstruction accuracy with respect to: (i) a reduced number of magnetic sensors; (ii) noise on magnetic sensor and/or current measurements. Then, experiments on the possibility to reconstruct not only the plasma boundary but also the current density have been conducted. A paper on this subject is accepted for publication [13]. The same algorithm has been tested using real JET measurements in order to provide an equilibrium reconstruction code that directly uses the magnetic measurements instead of using FELIX as an intermediate preprocessing of the measurements.

- EFDA-ITM (Task WP13-ITM-IMP12-ACT3): EQUINOX-ITM has been upgraded and tested on the new gateway machine of the ITM. The Kepler actor was tested and used on 3 different tokamaks (JET, Tore Supra and WEST) (with F. Imbeaux, T. Aniel, P. Moreau, E. Nardon (CEA)). A benchmark work is on going between the codes Equal, Efit and Equinox on JET shot 74221 (with Dimitriy Yadykin and Wolfgang Zwingmann).

6.3. Evolutive equilibrium and transport coupling and optimization of scenarii

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras.

6.3.1. New developments in the direct evolutive version of CEDRES++

6.3.1.1. External circuits and saddle currents in the blankets

In the previous version of the free boundary equilibrium code CEDRES++, each PF-coil (Poloidal Field Coil) was considered separately. In the evolutive version, a voltage was applied to each coil. In the machine, PF-coils can be connected in series or in parallel with one or several power supplies. In order to consider more realistic configurations of the PF system, the model used in CEDRES++ has been generalized to circuits involving several coils and supplies connected in series or in parallel. This model has been implemented in CEDRES++ and has been tested on simple configurations with circuits composed of one supply and several coils connected in series. More complicated configurations like circuits with several supplies and coils in series and in parallel in the same circuit have to be tested. This will be done on a WEST test case. A model for saddle currents in the blankets has also been implemented. This model is actually under validation on DEMO geometry.

6.3.1.2. Coupling CEDRES++ with a feedback controller (task ITM-WP13-ITM-IMP12-ACT1-T3)

Cedres++ has been successfully coupled with a controller generated from the true TCV hybrid Simulink controller in an ITM (Integrated Tokamak Modeling) workflow. The "yoyo" discharge (shot 40475) has been reproduced. In Figure 1, the vertical position of the magnetic axis simulated matches the experimental one.

6.3.1.3. Cedres++ - transport coupling

Last year, different algorithms coupling free boundary equilibrium solvers and transport solvers (CEDRES++-diff, CEDRES++-CRONOS, CEDRES++-ETS, FREEBIE-CRONOS) have been developed. The ETS-C coupling between CEDRES++ and the transport solver under the ITM environment has been finalized this year. A simulation of a VDE test case has been performed (task WP13-ITM-IMP12-ACT1-T2). A benchmark between the different strategies has been performed in order to validate the numerical methods required to ensure stability of the coupling system and to compare the physical simulations of each model. A benchmark between CEDRES++-diff solving the resistive diffusion equation coupled to CEDRES and the CEDRES-CRONOS coupling has been performed on an ITER test case. Some divergences between the two codes appear and are not fully understood despite long investigations. This difficulty has led us to delay the introduction of non inductive terms in the resistive diffusion equation implemented in CEDRES++-diff. These developments will be realized when the different coupling strategies will be fully validated.

6.3.2. Reasearch of optimal trajectories for the preparation of Tokamak discharges

A new approach has been developed for the optimization of dynamic plasma scenarios in tokamaks. This task has been formulated as an optimal control problem, using numerical solution methods for optimization problems with PDE constraints. Due to free boundary setting, a new linearization of the non-linear equations has been introduced, which is consistent with the numerical discretization. It is this consistency that guarantees that the method converges to the optimum.

6.4. Parallel Kelvin-Helhmohltz-like instability in edge plasma

Participants: Hervé Guillard, Boniface Nkonga, Marco Bilanceri, Giorgio Giorgiani.

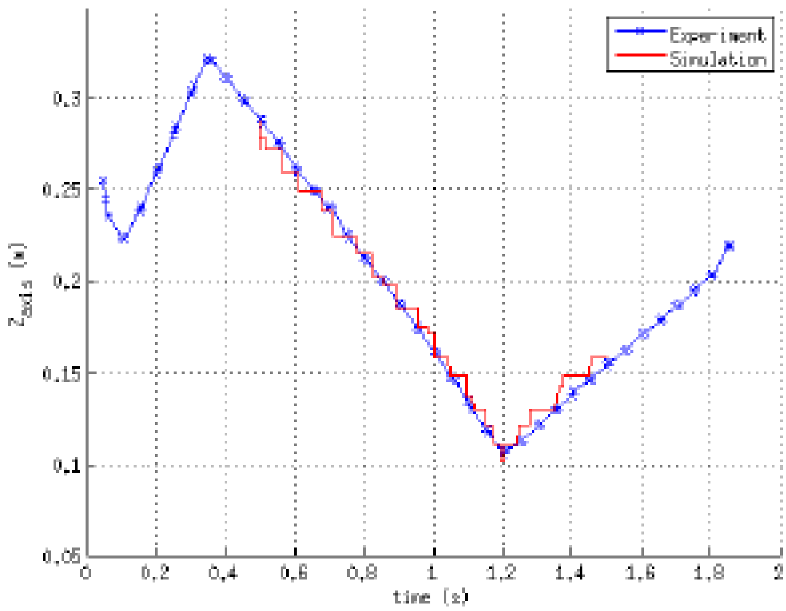

Figure 1. Simulation of Yoyo discharge on TCV - Comparison between Z axis simulated and Z axis obtained from experiments

A large part of this year activities have been devoted to the investigation of the Kelvin-Helmholtz-like instabilities that can be triggered at the core/SOL transition, the sheath acceleration at the limiter or divertor plates leading to a radial shear for the velocity. Linear stability analysis developed in Schwander et al [2] actually reveals that unstable modes at the edge-core transition can develop in the presence of core rotation. This study was also an opportunity for a benchmarking comparison with the TOKAM3X code developed in IRFM and at Marseille. Both codes have confirmed the linear stability analysis and have shown that large fluctuations grow in the shear layer downstream of the limiter on the LFS (Low Field Side), the growth of these fluctuations being accompanied by a radial drift away from the limiter. Fig. 2 displays a 3D representation of these unstable density fluctuations. Apart from the physical results, this study has also shown the large sensitivity of the solutions to the discretization and to the implementation of the Bohm's boundary conditions. It has also shown that the study of these parallel KH like instabilities is a very demanding benchmark : these simulations require large meshes and since the growth rate of these instabilities is very weak, this results in an extremely long simulation time involving an extremely large number of time steps. In the future, it is planned to investigate the saturation of the instability as well as its possible presence in diverted plasmas.

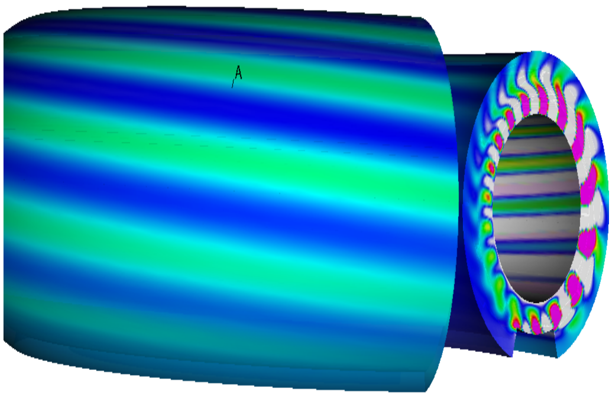

Figure 2. 3D representation of unstable density fluctuations in edge plasma tokamak with limiter. The core plasma rotates in the anti-clockwise direction M//central=0.75, safety factor q=6

6.5. Development of a two temperature model

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

A two temperature (ions - electrons) version of the code is in development. At present an approximate Riemann solver using the total energy equation and the electron entropy as main variables has been designed. This Riemann solver has been validated against standard shock tube problems and incorporated in the PlaTo platform. The implementation of this solver in toroidal geometry is in progress.

[2] Schwander et al., J. Nucl. Materials, doi:10.1016/j.jnucmat.2010.10.073 2011

6.6. Implementation of a Taylor-Galerkin stabilized Finite Element

Participants: José Costa, Marie Martin, Boniface Nkonga.

The theoretical part of Taylor-Galerkin (TG) stabilized strategy applied to MHD and reduced MHD modeling has been realized. The final method amounts to add in the formulation, a self-adjoint operator associated to the most critical hyperbolic component of the system to be solved. The design of the critical contours and the identification of associated waves to be stabilized is problem dependent and related to the Jacobian matrix. A simplified version has been developed for reduced MHD and takes into account the high anisotropy of strongly magnetized plasma under consideration here. This first implementation of the TG stabilization in Jorek, has made possible efficient and robust simulations of Edge Localized Modes (Elms) and their mitigation by Resonant Magnetic Perturbations (RMP) and pellets injections. Work under progress will use more elaborated TG formulations that will be applied to reduced and full MHD models.

6.7. Development of a full MHD Modeling

Participants: José Costa, Jeaniffer Vides, Boniface Nkonga.

The single fluid full MHD numerical model has been developed. The divergence free constraint on the magnetic field is achieved by introduction of a potential vector. The use of the potential vector has the additional advantage that the toroidal component is the magnetic flux of the Grad-Shafranov equilibrium. Therefore, using the same finite element for the computation of initial equilibrium and the evolution of perturbed system, the numerical scheme is well balanced when the projection of the momentum equation use a component parallel to the magnetic field. Indeed, at the discrete level the projection is exactly orthogonal to equilibrium sub-space. Using the potential vector as variable introduces third order derivatives in the system and classical C0 finite elements cannot be directly applied. This is why our finite element strategy uses shape/test functions whose derivatives have global continuity in space. Finite element method is designed for poloidal plane discretization using quadrangles or triangles. Validations have been performed for internal kink and tearing modes instabilities in tokamak with a circular plasma. For this configuration, all magnetic surfaces are closed and simple boundary conditions are used. Future work will address X-point configurations with Bohm boundary conditions.

6.8. Environmental and Astrophysical flows

Participants: Hervé Guillard, Boniface Nkonga, Marco Bilanceri, Maria-Vittoria Salvetti [University of Pisa, Italy], Karim Elhakim [University Ains Shams, Egypt].

The numerical approximation of a model coupling the shallow-water equations with a sediment transport equation for the morphodynamics has been studied. In shallow-water problems, time advancing can be carried out by explicit schemes. However, if the interaction with the mobile bed is weak, the characteristic time scales of the flow and of the sediment transport can be very different introducing time stiffness in the global problem. For this case, it is of great interest to use implicit schemes. The time integration stategy that we have devised is based on a defect-correction approach and on a time linearization, in which the flux Jacobians are computed through automatic differentiation. This work has been published in this reference [3]. The aim of the present work is to investigate the behavior of this time scheme for different Riemann solvers, sediment transport models and situations related to environmental flows [12]. This activity takes place in the framework of the Euromediterranée 3+3 MedLagoon program and a PHC Imhotep program. A preliminary work has begun to apply this strategy to the study of the Burulus lake in Egypt.

6.9. Ionospheric plasma

Participants: Didier Auroux, Sebastian Minjeaud.

[3] Linearized implicit time advancing and defect correction applied to sediment transport simulations Marco Bilanceri; François Beux; Imad Elmahi; Hervé Guillard; Maria Vittoria Salvetti Computers and Fluids, elsevier, 2012, 63, pp. 82-104

In order to guarantee the integrity of the european positionning system Galileo, it is fundamental to identify all the potential sources of system unavailability. One of the main sources that has been identified is the phenomenon of ionospheric scintillations which causes radio frequency signal amplitude and phase variations when satellite signals pass through the ionosphere. Scintillations appear as the turbulent aspect of a larger disturbance of the ionospheric plasma density, which has the shape of a plasma bubble. In this context and in the framework of the ANR IODISSEE, a model hierarchy aimed at representing the evolution of the ionospheric plasma was proposed (Besse and al., 2004). It is based on an asymptotic analysis of the Euler-Maxwell system thanks to typical scales of the physical parameters involved in this framework. Among these models the simplest, referred to as the Striation model, describes the evolution of the quasineutral plasma in a plane perpendicular to the earth magnetic field. The magnetic field is assumed constant, and both electron and ions inertia are neglected. In this model the mobility of charge particles is assumed infinite along the magnetic field lines so that they constitute equipotential for the electric field. This property allows the computation of the electric field by means of a two dimensional elliptic equation with coefficients integrated along the magnetic field lines. This equation is coupled to either a two or a three dimensional transport equation for the evolution of the plasma density.

6.9.1. Data assimilation

We worked on data-models coupling method to identify the parameters of the Striation model (especially, the initial data for the electronic density and the ion/neutral collision frequency). Some measurements acquired during the mission of satellite DEMETER will constitute the set of observed data. We consider this problem from an optimal control point of view. We define a cost function measuring the misfit between the observed data and the corresponding model states. This function can be seen as a function of only the input model parameters. The previous inverse problem is then equivalent to minimizing this cost function. Of course, this problem can be ill posed (over or under-determined, non convex...) and we need to add some regularization terms (mainly Tikhonov terms), using some a priori estimation of the model parameters. The effective minimization of the cost function (in order to estimate the best possible set of model parameters) relies on the computation of the adjoint state. Thanks to the help of L. Hascoet, the adjoint of the Striation code was derived and validated with the automatic differentiation tool TAPENADE. We obtained the first results of coefficients identification in very simple situations.

6.9.2. Wave Propagation

The electronic density fluctuations of the ionospheric plasma have been identified as the main causes of the scintillation phenomena since they induce some variations of the amplitudes and phases of the signals passing through the ionosphere. These fluctuations have indeed a direct influence on the refractive index of the medium. A code was developed to simulate the propagation of wave signals in the perturbed ionosphere (whose representation is obtained thanks to the Striation code). We chose to use the method of the Rytov approximations which allow to obtain sufficiently accurate results (since, e.g., it takes into account the diffraction due to the small structures) whithin a reasonable computational time (contrary to the resolution of the whole Maxwell system). This work was carried out during the Master 2 internship of Gonzalo José Carracedo Carballal (advised with P. Lafitte, Ecole Centrale Paris).

6.10. Mesh adaptative MG Methods

Participants: Gautier Brethes [Projet Ecuador], Alain Dervieux, Olivier Allain [Lemma].

Anisotropic tetrahedrization, Continuous metric

This activity concerns the use of mesh adaptation and multigrid for simplified plasma models in the context of ANEMOS ANR project.

6.11. Turbulence models

Participants: Alain Dervieux, Bruno Koobus [University of Montpellier 2], Carine Moussaed [University of Montpellier 2], Maria-Vittoria Salvetti [University of Pisa], Stephen Wornom [Lemma], Marianna Braza [IMF-Toulouse].

Large Eddy Simulation, Variational Multi-scale, hybrid models, unstructured meshes, vortex shedding

The purpose of our works in hybrid RANS/LES is to develop new approaches for industrial applications of LES-based analyses. This year, a lot of experiments have validated the dynamic version of our VMS-LES. The quality of simulations is either comparable to non-dynamic, or better. In the foreseen applications (aeronautics, hydraulics), the Reynolds number can be as high as several tenth millions, a far too large number for pure LES models. However, certain regions in the flow can be much better predicted with LES than with usual statistical RANS (Reynolds averaged Navier-Stokes) models. These are mainly vortical separated regions as assumed in one of the most popular hybrid model, the hybrid Detached Eddy Simulation model. Here, “hybrid” means that a blending is applied between LES and RANS. The french-italian team is working on a novel type of hybrid model between the VMS-LES model and a $k - \varepsilon$ one. The team has this year concentrated on the shift between the RANS boundary region and the VLES boundary one. This is also the problematic on the IDDES studies. We are working on propositions relying not only on the value of the RANS viscosity but also on its gradient. A paper is in preparation on this subject.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Principia : Expertise on the solver of the numerical tool Deeplines (3 days, 3000 euros) - B. Nkonga
- IFPEN : Studies of coarsening strategies for the meshes used in reservoir simulations - H. Guillard

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- ANR ECINADS

  Castor is associated to the ANR ECINADS project started in end of 2009, devoted to the design of new solution algorithms for unsteady compressible flows, adapted to scalable parallelism and to reverse (adjoint) Automatic Differentiation. See in the activity report of Ecuador.

- ANR ESPOIR

  The ANR ESPOIR (Edge Simulation of the Physics Of Iter Relevant turbulent transport) associates the CASTOR team with the M2P2, LPIIM and LATP laboratories in Marseille and IRFM in Cadarache to investigate edge plasma turbulence. The numerical simulation of the plasma wall interactions requires efficient codes and thus the development of advanced numerical methods and solvers. The aim of this project is to study different numerical strategies for edge plasma models in the real geometrical and magnetical configurations corresponding to the future Iter machine.

- ANEMOS : ANR-11-MONU-002

  ANEMOS : Advanced Numeric for Elms : Models and Optimized Strategies associates JAD Laboratory/Inria (Nice, Manager), IRFM-CEA (Cadarache), Maison de la Simulation (Saclay) and Inria EPI Bacchus (Bordeaux) Elms are disruptive instabilities occurring in the edge region (SOL) of a tokamak plasma. The development of Elms poses a major challenge in magnetic fusion research with tokamaks, as these instabilities can damage plasma-facing components, particularly divertor plates. The mitigation or suppression of large Elms is a critical issue for successful operation of ITER. Goal for ANEMOS is to develop and improve numerical tools in order to simulate physical mechanisms of Elms and qualifies some strategies for their control. We then need to design efficient numerical strategies on the most advanced computers available to contribute to the science base underlying of proposed burning plasma tokamak experiments such as ITER.

- ANR IODISEE : IOnospheric DIsturbanceS and SatEllite-to-Earth communications. http://iodissee.math.cnrs.fr/project/index.html. In this ANR project, CASTOR will address the use of data-models coupling method to identify the input model parameters (especially, the initial data for the electronic density).

8.1.2. *Federation on Magnetic Confinement Fusion Projects*

- FR FCM (Federation on Magnetic Confinement Fusion) project within Euratom-CEA association, "Reconstruction, simulation and control of plasma equilibrium"
- FR FCM (Federation on Magnetic Confinement Fusion) project within Euratom-CEA association, “Two-fluid numerical modelling of edge plasma in tokamak; Application to ITER”.

8.2. European Initiatives

8.2.1. *Collaborations with Major European Organizations*

EFDA (European Fusion Development Agreement)

EFDA ITM Task Force (Integrated Tokamak Modelling) CEDRES++ and Equinox are developped within the framework of the Task Force on Integrated Tokamak Modelling of the European Fusion Development Agreement.

EFDA (European Fusion Development Agreement)

JOREK, BOUT++ non-linear MHD modelling of MHD instabilities and their control in existing tokamaks and ITER

8.3. International Initiatives

8.3.1. *Participation In other International Programs*

8.3.1.1. Euromediterranée 3+3 Medlagoon program

Participants: Hervé Guillard, Marco Bilanceri.

The goal of the Medlagoon project (https://project.inria.fr/medlagoon/en) is to contribute to the design of simulations tools aimed to the integrated mathematical modeling of Mediterranean lagoons ranging from hydrodynamics and sediment transport modeling to biological models for phyto and zoo-plankton. This program associates CASTOR with the Mohamedia Engineering school and the university of Oujda in Morocco, the University of Pisa (Italy), the Polytechnic school of Tunis in Tunisia, the University of Paris 13, The Ain Sham University in Egypt and the Department of Applied Mathematics, University of Crete in Greece.

8.4. International Research Visitors

8.4.1. *Visits of International Scientists*

8.4.1.1. Internships

- Pavla Frankova, University of Pilzen : Algebraic Multigrid Solvers. In the framework of a collaboration on algebraic multigrid solvers with Petr Vanek and Roman Kuzel of the University of Pilzen, Cezch Republic, Pavla Frankova PhD student in Pilzen has visited CASTOR in November.
- Abdou Hafar, Ecole Mohamedia Ingénieur, Rabat : In the framework of the Medlagoon program, Abou Hafar PhD student has visited CASTOR in November to work on meshless methods.

9. Dissemination

9.1. Popularization

- With Maria Vittoria Salvetti of the University of Pisa, Hervé Guillard has written a popularization article "Des mathématiciens à la rescousse des lagunes méditerranéennes" [29]for the inline journal Accromath.
  Accromath is a journal of the “Centre de recherches mathématiques de l’Université de Montréal” whose aim is to popularize Mathematics and their applications for secondary school pupils and their professors.
- Redaction of the short note "Les vagues et les rivages, une question de changement de variables" http://mpt2013.fr/changement-de-variable-et-comment-les-vagues-montent-a-lassaut-des-rivages/ in the framework of Mathematics of Planet Earth 2013 (MPE2013) published 04/10/2013 (Hervé Guillard).
- Redaction of the short note "Retour vers le futur" http://mpt2013.fr/retour-vers-le-futur/ in the framework of Mathematics of Planet Earth 2013 (MPE2013) published 16/10/2013 (Jacques Blum & Didier Auroux).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Ecole d’ingénieur: D. Auroux, Optimisation, 66h, M1, Polytech Nice, Université de Nice Sophia Antipolis, France

Master: D. Auroux, Optimisation, 45h, M1, Université de Nice Sophia Antipolis, France

Ecole d’ingénieur: D. Auroux, Méthodes numériques, 36h, M1, Polytech Nucei Sophia, Université de Nice Sophia Antipolis, France

Master: J. Blum, Optimization, 30h, M1 Erasmus Mundus, Université de Nice Sophia Antipolis, France

Master: J. Blum, Optimisation et controle, 30h, M2, Université de Nice Sophia Antipolis, France

Ecole d’ingénieur: J. Blum, Commande Optimale, 37.5h, M2, Polytech Nice Sophia, Université de Nice Sophia Antipolis, France

Ecole d’ingénieur: C. Boulbe, Analyse, 68h, L2, Polytech Nice Sophia Antipolis, France

Ecole d’ingénieur: C. Boulbe, Analyse Numérique, 71.5h, L3, Polytech Nice Sophia Antipolis, France

Ecole d’ingenieur: C. Boulbe, Méthodes numérique - EDP, 66h, M1, Polytech Nice Sophia Antipolis, France

Ecole d’ingénieur: B. Faugeras, Analyse, 39h, L2, Polytech Nice Sophia Antipolis, France

Master: B. Nkonga, Finites volumes/Finites differences, 90h, M1, Université de Nice Sophia Antipolis, France

Master: B. Nkonga, Algorithmique, 35h, M1, Université de Nice Sophia Antipolis, France

Master: B. Nkonga, Calcul Parallèle, 24h, M2, Université de Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse, 40h, L1, Université de Nice Sophia Antipolis, France

Licence: A. Sangam, Mathématiques Appliquées, 50h, L3, Université de Nice Sophia Antipolis, France

Master: A. Sangam, Introduction to Finite Element, 25h, M1, Université de Nice Sophia Antipolis, France

9.2.2. Supervision

PhD : C. Lachat, Conception et validation d’algorithme de remaillage parallèles à mémoire distribuée basés sur un remailleur séquentiel", University of Nice Sophia Antipolis 13 décembre 2013, Hervé Guillard, Laurent Hascoet.

PhD : M. Martin, Modélisation fluide pour les plasmas de fusion : approximation par éléments finis de Bell, University of Nice Sophia Antipolis, 4 juin 2013, Boniface Nkonga

PhD in progress: K. Bashtova, modelling of abrasive waterjet and focused ion beam, 1st September 2013, Didier Auroux

PhD in progress : Pierre Cargemel, "Déraffinement adaptatif de maillages non structurés pour une simulation efficace des procédés EOR", September 1st 2012, Hervé Guillard.

PhD In progress : J. Costa, Modeling of Elms, Sep 2012 - July 2015, B. Nkonga

PhD in progress: A. Drogoul, Détection de structures fines en imagerie par analyse asymptotique topologique, 1st september 211, Didier Auroux, Gilles Aubert (UNS)

PhD in progress : E. Estibals, "MHD réduite: Modélisation et Simulation numérique utilisant des éléments finis stabilisés d'ordre élevés sur un maillage courbe non-structuré. Application à l'injection de glaçons et de masse dans ITER", 15th october 2013, Hervé Guillard, Afeintou Sangam.

PhD in progress: V. Groza, control and identification of etching rate function in abrasive waterjet, 1st september 2013, Didier Auroux

PhD in progress : C. Le Touze, "Etude du couplage entre modèles à phase séparée et modèles à phase dispersée pour la simulation de l'atomisation primaire en combustion cryotechnique", September 1st 2011, Hervé Guillard.

PhD in progress : J. Vides, Numerical Modeling in toroidal geometries, Oct. 2012 - July 2014, Boniface Nkonga and Hervé Guillard

9.2.3. Juries

Hervé Guillard acted as referee in the PhD thesis jury of Samuel Richard, Aix Marseille Université

Hervé Guillard was in the PhD thesis jury of Clément Surville, Aix Marseille Université

Hervé Guillard acted as referee in the PhD thesis jury of Sophie Gérald: Paris VI

Jacques Blum was referee in the PhD thesis jury of David Coulette , Université de Nancy

Jacques Blum was referee in the HdR jury of Frederic Parrenin, Université de Grenoble

Jacques Blum was in the HdR jury of Maelle Nodet, Université de Grenoble

Richard Pasquetti was president of the PhD thesis jury of A. Parades, Aix-Marseille université

Boniface Nkonga was referee in the PhD thesis jury of

- Mathias Malandain, INSA Rouen,
- Laurent Dastugue, Université Pierre-et-Marie-Curie :Paris VI
- Nicolas Kowalski, Université Pierre-et-Marie-Curie :Paris VI
- Carine Moussaed, Université Montpellier II
- Alejandro Paredes, Aix-Marseille Université

Boniface Nkonga was in the PhD thesis jury of

- Alexandre Carabias: Université de Nice Sophia Antipolis (president)
- Sébastien Le Martelot, Aix-Marseille Université

10. Bibliography

Major publications by the team in recent years

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[2] J. BLUM, C. BOULBE, B. FAUGERAS. *Reconstruction of the equilibrium of the plasma in a Tokamak and identification of the current density profile in real time*, in "Journal of Computational Physics", 2012, vol. 231, pp. 960-980, http://hal.archives-ouvertes.fr/hal-00419608

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] C. LACHAT. , *Conception et validation d'algorithmes de remaillage parallèles à mémoire distribuée basés sur un remailleur séquentiel*, Université Nice Sophia Antipolis, December 2013, http://hal.inria.fr/tel-00932602

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[12] M. BILANCERI, F. BEUX, I. ELMAHI, H. GUILLARD, M. V. SALVETTI. *Implicit time advancing combined with two finite-volume methods in the simulation of morphodynamic flows*, in "Mathematics and Computers in Simulation", 2013 [*DOI :* 10.1016/J.MATCOM.2013.07.002], http://hal.inria.fr/hal-00871717

[13] B. FAUGERAS, J. BLUM, C. BOULBE, P. MOREAU, E. NARDON. *2D interpolation and extrapolation of discrete magnetic measurements with toroidal harmonics for equilibrium reconstruction in a Tokamak*, in "Plasma Physics and Controlled Fusion", 2014, accepted, http://hal.inria.fr/hal-00862399

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[19] N. PERES, R. PASQUETTI. *Numerical study of drag reduction of a car model by active control using mico-jets*, in "CFM 2013", France, 2013, http://hal.inria.fr/hal-00875715

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[21] J. BLUM. *Optimization of trajectories in Tokamak discharges by optimal control methods*, in "GDRE CONEDP Meeting 2013 Modeling and control of systems: applications to nano-sciences, environment and energy", Grenoble, France, April 2013, http://hal.inria.fr/hal-00935992

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