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Activity Report 2012

Team CASTOR

Control, Analysis and Simulations for TOkamak Research

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

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational models and simulation

Table of contents

Team CASTOR

Keywords: Scientific Computation, Control, Numerical Methods, Flow Modeling, Magnetohydrodynamics, Environment

Creation of the Team: July 01, 2012 .

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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 [20], 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 multi-teraflop and soon 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 tools 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. Scientific Foundations

3.1. Plasma Physics

Participants: Hervé Guillard, Boniface Nkonga, Afeintou Sangam, Richard Pasquetti, Audrey Bonnement, Marie Martin, Cédric Lachat, Laure Combe, 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: 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. Software

4.1. 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. At present the software is only a private project but some parts of FluidBox are expected to be in the public domain by the end of the year.

[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

4.2. PlaTo

Participants: Hervé Guillard [contact], Laure Combe.

The developement of PlaTo (A platform for Tokamak simulation) (http://www-sop.inria.fr/pumas/plato.php) has been supported by an ADT action of the D2T an by the ANR ESPOIR. PlaTo is a suite of data and softwares dedicated to the geometry and physics of Tokamaks and its main objective is to provide the Inria large scale initiative "FUSION" teams working in plasma fluid models with a common development tool.

4.3. PaMPA

Participants: Cécile Dobrzynski [Bacchus], Hervé Guillard, Laurent Hascoët [Tropics], 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.

4.4. Cedres++

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.

4.5. Equinox

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.

5. New Results

5.1. Simulations in plasma Physics

5.1.1. Fourier-spectral element approximation of a two fluid model of edge plasma

Participants: Richard Pasquetti, Sebastian Minjeaud.

We especially 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), and on the hypothesis of electroneutrality (the density of ions and electrons are proportional). 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 coupled partial differential equations (PDE) can be set up. A high order Fourier-SEM (Spectral Element Method) code is currently developed. This Fourier-SEM code is now operational for the full set of PDEs in a 3D toroidal geometry. The torus section is discretized with quadrangular elements, within which the polynomial approximation degree is an input to the code. 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 anisropic 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. A parallel version of this code is currently developed. It remains to improve the robustness of our algorithms, i.e. to implement an efficient stabilization strategy. This could be based on the so-called spectral vanishing viscosity or entropy viscosity techniques. Up to our knowledge, this will be the first code that fully implements a two fluid ion-electron approximation (i.e. without using the drift velocity approximation), and the Braginskii closure of the governing equations.

5.1.2. Hydrodynamic model with strong Lorentz force

Participants: Audrey Bonnement, Hervé Guillard, Boniface Nkonga, Richard Pasquetti.

The thesis of A. Bonnement [1] was devoted to the development of a code based on the FluidBox/plaTo software of B. Nkonga and co-workers. It is based on a Finite volume / Finite element approach. This code is now operational in an axisymmetric geometry for a simplified PDE system in which the Lorentz force is approximated by a constant forcing field. Thus, the FluidBox/PlaTo code essentially solves the 3D axisymmetric Euler, Navier-Stokes or Braginskii PDEs to compute the ion density, momentum and energy. In the Braginskii system, the thermal diffusion and the kinematic viscosity are both non-linear and strongly anisotropic. A. Bonnement, who was co-directed by H. Guillard and R. Pasquetti, defended her thesis “Modélisation numérique bi-fluide du plasma de bord des tokamaks: application à ITER” in July 2012. A. Bonnement has provided a detailed description of the works carried out with the FluidBox/PlaTo code in her thesis manuscript. She has specially addressed one of the main difficulties related to simulations of tokamak plasmas, which is that the dynamic of the flows occurs in the vicinity of an equilibrium where the plasma pressure balances the Lorentz force. There are two ways to deal with this difficulty. The most common one in tokamak studies is to work with a set of governing equations such that this equilibrium is already contained in the formulation. This can be done by using formulations where the variables are indeed fluctuating departures from the equilibrium or by using special approximations as done in reduced MHD. The other way is purely numerical and consists to design a numerical method such that the equilibrium is an exact solution of the discrete equations. This has been the subject of the thesis of Audrey Bonnement in the framework of a finite volume method on non-structured meshes and where special Riemann solvers have been designed incorporating plasma equilibrium in the definition of the numerical fluxes. Combined with mesh refinement, this approach has been applied to some preliminary numerical experiments studying the effect of density perturbations (as a crude model of pellet injections) on the dynamics of the flow. At present, this approach is under evaluation to qualify its interest with respect to reduced MHD or formulations using a potential representation of the velocity field.

5.1.3. Finite volume methods in curvilinear system of coordinates

Participants: Hervé Guillard, Boniface Nkonga, Afeintou Sangam, Marco Bilanceri.

Finite volume methods are specialized techniques to approximate systems of conservation laws. The application of these methods to curvilinear systems of coordinate is however problematic because the space variation of the metric coefficients introduces artificial source terms. However it can be shown that whatever the curvilinear system used, a strong conservation form of the equations exists at the level of vector variables (but not at the level of the scalar components of the vectors in the curvilinear system due to the aforementioned space dependence of the metric coefficients). Based on this result, we have developed an original technique that uses an approximation of the vector form of the equation followed by local projection on the curvilinear system (here parallel to the poloidal magnetic field).

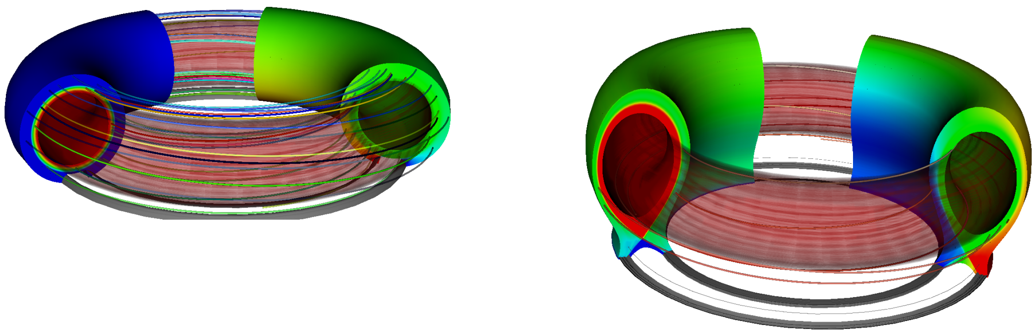

Figure 1. Density (left side) and parallel velocity (right side) color plots of the edge region of a tokamak with limiter (left plot) and tokamak with X point and divertor(right plot). Due to Bohm's boundary conditions, the parallel flux of out-flowing ions is supersonic on the limiter and divertor plates

This method has been applied to the approximation of a reduced MHD model using a decomposition of the velocity field into a parallel component and a perpendicular one given by the electric drift. The method is general and can be applied to any type of geometry. Figure 2 shows for instance the steady state density and parallel velocity fields in the edge region of a limiter tokamak (left) and of a divertor tokamak (right). Bohm's boundary conditions have been applied to the limiter and divertor plates producing a supersonic outflow velocity field.

5.1.4. Mesh singularities and triangular elements

Participants: Boniface Nkonga, Marie Martin, José Costa.

C1-finite elements as used for instance in the Jorek code are associated to isoparametric cubic-Bezier representation over quadrangles in the poloidal plane and sine-cosine Fourier expansion in the toroidal direction. Mesh singularities are associated to the structure imposed by the cubic-Bezier representation over quadrangles. In the context of the ANR-ANEMOS and in collaborations with IRFM and the Galaad team (Inria Sophia Antipolis), a geometrical toolbox is under development to manage these singularities and improve the alignment with equilibrium flux surfaces. As an alternative, we are also developing a more flexible C1-element over triangles using either Reduced-quintic (Bell) or quadratic Powell-Sabin polynomials. Optimal order of accuracy is achieved with simple boundary conditions. Many cycles of the "current hole" instability has been accurately reproduced. Additional improvement, with isoparametric formulation, will hopefully achieve this optimality for curved boundaries and improve mesh alignment to flux surfaces. We have investigated the possibility to use cubic splines representation in the toroidal direction. Indeed, for pellet injection the local resolution needed in the toroidal direction requires a large number of Fourier modes. This resolution need is very local, adapted splines representation can be more efficient. This solution is under analysis and structuration. First application is expected at end of 2013 with a possible update of Jorek in 2014.

5.1.5. Mesh adaptation Methods

Participants: Hubert Alcin [Projet Tropics], Alain Dervieux, Frédéric Alauzet [Projet Gamma, Inria-Rocquencourt].

This activity results from a cooperation between Gamma, Tropics, Castor, and Lemma company. See details in Tropics and Gamma activity reports. Its concerns Castor's subject through the current applications of mesh adaptation to flows with interfaces and to Large Eddy Simulation. It is also planned to use mesh adaptation for simplified plasma models in the context of ANEMOS ANR project.

5.1.6. Stabilization for finite / spectral element

Participants: Boniface Nkonga, Marie Martin, Richard Pasquetti, Sebastian Minjeaud.

Formulation of Reduced MHD eliminates fast acoustic waves but material, slow acoustic and Alfven waves are included in this model. On the other hand, finite element approximation, when applied to hyperbolic systems (with finite speed waves) needs additional control of the effect of unresolved scales. We have developed and validated a Taylor Galerkin Stabilizations of order 2 and 3 (TG2-TG3) for reduced MHD. This global approach has been implemented in a simplified form, validated and updated in the latest versions of the Jorek code. Even if significant improvements have been observed with this stabilization where only material and Alfven waves subscales are stabilized, more robustness is expected by taking into account slow acoustic waves. Stabilization techniques well adapted to high order approximations, like the spectral vanishing viscosity method or the entropy viscosity technique, remain to be implemented in the Fourier-SEM code.

5.1.7. Validity of the Reduced MHD and extensions

Participants: Hervé Guillard, Boniface Nkonga, Afeintou Sangam.

The available reduced MHD model in Jorek uses a set of assumption that can be reasonable close to the equilibrium and during the linear grow of instabilities. In order to obtain accurate and robust simulations of the nonlinear instabilities saturations, careful analysis and derivation of the reduced MHD has been performed, more mathematical derivations are under progress under the asymptotic analysis framework. It turns out that some of the neglected terms can be of relative importance for the saturation process when MHD instabilities move the plasma far from equilibrium.

5.1.8. High performance parallel computing

Participants: Hervé Guillard, Boniface Nkonga, Sebastian Minjeaud.

Applications under concern in this project needs to manage large meshes (10^7 to 10^9 nodes) and solve many huge sparse nonlinear systems. This makes the use of domain partitioning techniques unavoidable. In addition, since different numerical methodologies are under studies and evaluations in this project, we need to develop a quite general setting allowing the use of different data structures (element-oriented for FE vs edge-oriented for FV) and the possibility to consider different domain overlapping to efficiently communicate between processors. For this we develop the PaMPA (Parallel Mesh Partitioning and Adaptation) software in collaboration with the Bacchus team (Inria, Bordeaux). PaMPA is based on the PT-Scotch graph partitioning tool and allows on the fly mesh redistribution. Up to now, PaMPA has been tested on 10000 processors with a mesh of 20M tetrahedrons. Integration of PaMPA as an external library to the codes developed in this project is under progress and early results are promising. Similarly, the Fourier-SEM code is currently parallelized.

5.2. Optimisation and control for magnetic fusion plasmas

5.2.1. Evolutive equilibrium and transport coupling and optimization of scenarii

Participants: Jacques Blum, Cédric Boulbe, Afeintou Sangam, Gael Selig, Blaise Faugeras, Holger Heumann.

5.2.1.1. Research of optimal trajectories for the monitoring of Tokamak discharges

The direct equilibrium code CEDRES++ in its static version (resp.dynamic) computes for externally applied PF currents (resp. voltages) and given plasma current density profile the (resp. evolution of the) poloidal flux and the plasma free boundary. The research of optimal trajectories is the corresponding inverse problem : find externally applied currents (resp. voltages), such that the plasma reaches a certain desired state. This desired state is mainly (resp. the evolution of) a prescribed plasma boundary. We formulate these inverse problems as so-called optimal control problems, where the PF currents (voltages) are the so-called control variables and the poloidal flux the so-called state variable. Optimal control problems are optimization problems with PDE (partial differential equations) constraints. In our case, the Grad-Shafranov equation is the constraint and the functional to be minimized is a cost-function that measures the mismatch between the computed plasma boundary and the desired plasma boundary. The Sequential Quadratic Programming (SQP) method is known to be a very efficient algorithm for solving non-linear constrained optimization problems. We implemented in CEDRES++ the SQP method for the two cases of finding either currents or voltages that corresponds to a desired boundary or a desired evolution of the boundary. These implementations are built on the orignal Newton methods for the direct non-linear problems. For optimization problems it is of great importance that the Newton methods are 'real' Newton methods in the sense that the Newton matrices are real derivatives. In the original implementation of CEDRES++ these matrices were the discretization of analytic derivatives of the non-linear operators, hence not derivatives of the discrete problem. We had to rewrite large parts of the code to eliminate this problem. Further, we added an interface to the linear solver library UMFPACK. For the current mesh resolution level, the performance of this linear solver for the stationary problems, both in the direct and in the inverse versions, is superior to iterative linear solvers. In the case of the inverse non-stationary problem, the problem of finding voltages that correspond to a desired evolution, the memory requirements forbid the use of UMFPACK. There, we used Conjugate Gradient-type iterations. In the future, we will have to investigate if other types of iterative solvers are suitable and allow a certain parallelism that will speed up the simulation time.

5.2.1.2. A new method of coupling equilibrium and resistive diffusion equations

In the framework of Gael Selig's PhD thesis, the resistive diffusion equation has been incorporated in the evolutive equilibrium system of CEDRES++. This equation has as unknown variable the derivative of the poloidal flux with respect to the averaged minor radius of the magnetic surface. This choice was made instead of the poloidal flux itself because this is the quantity directly involved in the averaged Grad-Shafranov equation used to compute the FF' term and thus this allows us not to perform a supplementary numerical differentiation which might introduce some numerical instability. An algorithm based on a successive prediction and correction method is proposed in order to ensure the consistency between the evolution of the 2D poloidal flux in the equilibrium equation and the evolution of the poloidal flux in the 1D resistive diffusion equation. The algorithm guarantees that at the end of each time step the total plasma current Ip and the mean radius of the plasma have the same values in both systems (see fig.2). The convergence of this new code (called CEDRES-DIF) has been numerically validated and the method has been successfully compared by G. Selig to the CEDRES-CRONOS coupled code which uses another coupling algorithm.

5.2.1.3. Introduction of halo currents in the equilibrium resolution

When VDE (Vertical Displacement events) instabilities occur in a Tokamak, currents flow from the plasma to the machine vessel structures, and then return to the plasma. These currents are called halo currents . In turn, these currents induce forces on the wall when crossing with Tokamak poloidal and toroidal magnetic fields. Moreover, when VDE instabilities take place, the plasma hits the wall with all its energy. Therefore, it is worth understanding the contribution of halo currents to total plasma current and other related plasma parameters, particularly the distribution, magnitude, and temporal evolution of halo currents for large scale machine such as ITER. Even if halo currents are actually 3D phenomena, it is important to take into account their effects in 2D free boundary equilibrium codes. In halo region, the pressure can be considered as negligeable so that the current follows the magnetic field lines. The magnetic field satisfies the force free equation $jxB = 0, \nabla.B = 0$ which can be rewritten

$$-\Delta^*\Psi = \frac{1}{\mu_0 R}\frac{\partial}{\partial\Psi} f_H^2(\Psi)$$

in an axisymmetric configuration. The function $f_H(\Psi)$ is supposed to be known. This simple model has been implemented in CEDRES++ and first tests have been done. This first simplified model has to be improved to get more realistic simulations and to be validated. The choice of the function f_H, the value of the total halo current, the geometry and the size of the halo region need to be enhanced with respect to experimental data.

5.2.2. 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.

5.2.2.1. Direct use of the magnetic measurements

Equinox was not originally designed to take as magnetic inputs directly the magnetic measurements, as it should be the case in the ITM, 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 was to interpolate between the magnetic measurements (flux loops and poloidal B-probes) with a machine independent method. This has already been achieved by using toroidal harmonic functions, as a basis for the decomposition of the poloidal flux in the vacuum region, in complement to the contribution of the PF coils. 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 (Tore Supra upgrade) have been successfully conducted. In a first step the equivalents of magnetic measurements were generated using the FBE code CEDRES++. In a second step these measurements were used by the toroidal harmonics algorithm to reconstruct the plasma boundary. The results are very promising and the work on this subject is ongoing for JET.

5.2.2.2. Boundary conditions for EQUINOX

In the present version of EQUINOX the boundary condition is a flux condition (Dirichlet boundary condition) and the tangential component of the poloidal field is incorporated in the cost-function to be minimized. This is a constant criticism which is made on EQUINOX. The idea was to inverse these two boundary conditions in order to determine if this choice is determinant in the results. We tried to use the tangential poloidal field (Neumann boundary condition for the flux) as boundary condition for the boundary value problem, and to put the flux (or its tangential derivative linked to the normal component of the poloidal field) in the cost function. However no convincing results could be obtained because the numerical resolution of the boundary value problem associated with Neumann boundary conditions proved to be unstable. This might be explained by the fact that a compatibility condition has to be satisfied between the Neumann conditions and the current density in the plasma which evolves during the mixed fixed-point and optimization iterations.

5.2.2.3. Induced currents in EQUINOX

In a disruption when the total plasma current disappears, there are very important induced currents, for example in the toroidal pumped limiter. These currents are in the domain of resolution of EQUINOX. Therefore it is necessary to take them into account in the resolution of the equilibrium reconstruction problem. This has been tested on a Tore Supra disruption case. The mesh generation has been modified in order to incorporate the real structure of the limiter. The structure of the equations being solved in the code also had to be modified in order to take into account the measured induced currents.

5.3. Turbulence models

5.3.1. Hybrid RANS/LES models

Participants: Hubert Alcin [Tropics], Alain Dervieux, Bruno Koobus [University of Montpellier 2], Carine Moussaed [University of Montpellier 2], Maria-Vittoria Salvetti [University of Pisa], Stephen Wornom [Lemma].

The purpose of our works in hybrid RANS/LES is to develop new approaches for industrial applications of LES-based analyses. 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 has designed a novel type of hybrid model. This year, a novel dynamic formulation has been introduced in our models and tested. the new model has been adapted to very high Reynolds number. Carine Moussaed has presented her results in ECCOMAS (Vienna). In our set of benchmark test cases which are also ECINADS test cases, the flow past a circular cylinder at Reynolds number from 3900 to 1 Million could be passed with improved predictions of main properties like mean drag, root mean square of lift fluctuation, and base pressure.

5.3.2. Acoustics

Participants: ILya Abalakin [IMM-Moscou], Alain Dervieux [Tropics], Alexandre Carabias [Tropics], Tatyana Kozubskaya [IMM-Moscow], Bruno Koobus [University of Montpellier 2].

A method for the simulation of aeroacoustics on the basis of hybrid RANS/LES models has been designed and developed by a cooperation between the Computational Aeroacoustics Laboratory (CAL) of Intitute for Mathematical Modeling at Moscow and Inria. Further applications has been developed by the Russian team from the two common numerical scheme, the Mixed-Element-Volume at sixth-order, and the quadratic reconstruction scheme. This year the cooperation is concentrated on the study by Alexandre Carabias of a new quadratic reconstruction scheme, which extends the one developed by Hilde Ouvrard and Ilya Abalakin. This year, this scheme is also introduced in the Gamma-Sciport mesh adaptation loop.

5.4. Environmental flows

Participants: Hervé Guillard, Boniface Nkonga, Marco Bilanceri, Maria-Vittoria Salvetti [University of Pisa, Italy], Imad Elmahi [University of Oudja, Morocco].

Mobile bed and sediment transport

The numerical approximation of a model coupling the shallow-water equations with a sediment transport equation for the morphodynamics have 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. The aim of the present work is to investigate the behaviour of this time scheme in different situations related to environmental flows. This work has been published in [14] and is now applied to the study of the Nador Lagoon in Morocco.

6. Partnerships and Cooperations

6.1. National Initiatives

6.1.1. 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 Tropics.
- 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).

6.1.2. Inria initiatives

Large scale Initiative FUSION (2009–2012), http://www-math.u-strasbg.fr/ae_fusion: Modeling and numerical simulation of magnetic fusion plasmas in view of the ITER project.

6.1.3. 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".

6.2. International Initiatives

6.2.1. 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 Tunisia, the university of Paris 13, Ain Sham University in Egypt and the Department of Applied Mathematics, University of Crete in Greece.

6.3. International Research Visitors

6.3.1. Visits of International Scientists

6.3.1.1. University of Pilzen : Algebraic Multigrid Solvers

In the framework of a collaboration on algebraic multigrid solvers, Petr Vanek and Roman Kuzel of the University of Pilzen, Cezch Republic have visited CASTOR in November.

6.3.1.2. Institute of Mathematical Modeling and university of Moscow : Acoustics

The long-term scientific collaboration with IMM on acoustics focussed this year on new reconstruction schemes for noise propagation with linear and nonlinear hyperbolic models. Ludwig W. Dorodnicyn has visited us in april 2012.

6.3.1.3. University of Oujda: Environmental flows

In the framework of the Medlagoon project, Imad El Mahi has visited us in November 2012

6.3.1.4. National Taiwan University : Granular and Multiphase flows

In the wake created by the Hubert Curien project (ORCHID 08-09), Keh-Ming Shyue (Department of Mathematics, National Taiwan University) has visited us in July 2012.

7. Dissemination

7.1. Scientific Animation

B. Nkonga, H. Guillard and M. Bilanceri have participated to the CEMRACS 2012 “Numerical methods and algorithms for High performance”. Two CEMRACS projects have been supervised during the research session of this edition of CEMRACS.

7.2. Teaching - Supervision - Juries

7.2.1. Teaching

Master : Afeintou SANGAM, Fondamentals of Analysis, two weeks and half intensive courses, M1, Kwame NKrumah University Of Science and Technology (project leads by France Ambassy at Accra and Universities of GHANA in the framework of Mathematics Doctoral Sessions), GHANA

7.2.2. Supervision

PhD : Audrey Bonnement, Modélisation numérique bi-fluide du plasma de bord des tokamaks : application à ITER, University of Nice-Sophia Antipolis, 03-07-2012, H. Guillard and R. Pasquetti.

PhD : Gael Selig, Équilibre évolutif à frontière libre et diffusion résistive dans un plasma de tokamak, University of Nice-Sophia Antipolis, 20-12-2012, J. Blum.

PhD in progress : Marie Martin,Approximation des équations de la MHD réduite, Since december 1st 2009, B. Nkonga

PhD in progress : Cédric Lachat, Parallel Mesh distribution and Adaptation, Since october 1st 2009, H. Guillard and L. Hascoet

PhD in progress : Jeaniffer-Lissette Vides Higueros, Approximation des écoulements en géométrie toroidale, Since october 1st 2011, B. Nkonga and H. Guillard.

PhD in progress : José Costa, Approximation C^k, Since october 1st 2012, B. Nkonga

PhD in progress : Clément le Touze, Couplage entre modèles diphasiques à « phases séparées » et à « phase dispersée » pour la combustion cryotechnique, Since october 1st 2011, H. Guillard.

PhD in progress : Pierre Cargemel, Déraffinement adaptatif de maillages non-structurés. Since november 5 2012, H. Guillard.

7.2.3. Juries

B. Nkonga was president of the PhD juries of

- Joseph Charles, 26 Avril 2012, Sophia Antipolis/Univ. of Nice. Amélioration des performances de méthodes Galerkin discontinues d'ordre élevé pour la résolution numérique des équations de Maxwell instationnaires sur des maillages simplexes
- Julien Richard, 07 Décembre, CERFACS/Univ. Montpellier 2. Développement d'une chaine de calcul pour les interactions fluide-structure et application aux instabilités aéro-acoustiques d'un moteur à propergol solide.

acted as referee for the defense of

- Gregory Huber August 28 2012 , IUSTI/Aix-Marseille Univ. Modélisation et simulation numérique des interfaces perméables
- Mathias Malandain, January 15 2013, Univ. of Rouen, Simulation massivement parallèle des écoulements turbulents à faible nombre de Mach.

and was member of the jury of :
Elena Collado Morata, 29 Octobre, 2012, CERFACS/Univ. of Toulouse, Impact of the unsteady aerothermal environement on the turbine blades temperature.

H. Guillard acted as referee for the PhD defense of Arnaud Kurst, University of Bordeaux, October 31, 2012

8. Bibliography

Major publications by the team in recent years

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[2] B. BRACONNIER, B. NKONGA. *Relaxation method for low Mach number compressible multiphase flow*, in "Journal of Computational Physics", 2009, vol. 228(16), p. 5722-5739.

[3] P. DEGOND, F. DELUZET, A. SANGAM, M.-H. VIGNAL. *An Asymptotic Preserving scheme for the Euler equations in a strong magnetic field*, in "J. Comput. Phys.", 2009, vol. 228, n^{o} 10, p. 3540–3558, http://dx.doi.org/10.1016/j.jcp.2008.12.040.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] A. BONNEMENT. *Modélisation numérique bi-fluide du plasma de bord des tokamaks : application à ITER*, University of Nice-Sophia Antipolis, Nice, France, 2012.

[12] G. SELIG. *Equilibre évolutif à frontière libre et diffusion résistive dans un plasma de Tokamak*, University of Nice-Sophia Antipolis, Nice, France, 2012.

Articles in International Peer-Reviewed Journals

[13] C. BERTHON, B. DUBROCA, A. SANGAM. *A local entropy minimum principle for deriving entropy preserving schemes*, in "SIAM Numerical Analysis", 2012, vol. 50, p. 468-491.

[14] M. BILANCERI, F. BEUX, I. ELMAHI, H. GUILLARD, M.-V. SALVETTI. *Linearized implicit time advancing and defect correction applied to sediment transport simulations*, in "Computers & Fluids", 2012, vol. 63(30), p. 82-104, http://dx.doi.org/10.1016/j.compfluid.2012.04.009.

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[18] B. FAUGERAS, A. B. ABDA, J. BLUM, C. BOULBE. *Minimization of an energy error functional to solve a Cauchy problem arising in plasma physics: the reconstruction of the magnetic flux in the vacuum surrounding the plasma in a Tokamak*, in "ARIMA", 2012, vol. 15, p. 37-60.

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