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Activity Report 2014

Project-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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Project-Team CASTOR

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Creation of the Team: 2012 July 01*, updated into Project-Team:* 2014 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 [50], 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: Jacques Blum, Cédric Boulbe, Blaise Faugeras, Hervé Guillard, Holger Heumann, Sebastian Minjeaud, Boniface Nkonga, Richard Pasquetti, Afeintou Sangam, Giorgio Giorgiani.

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: 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. New Software and Platforms

5.1. Free boundary equilibrium codes

5.1.1. CEDRES++

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras, Holger Heumann, 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 vacuum 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. A version of CEDRES++ is avalaible in the environment of the european projet Eurofusion WPCD.

5.1.2. FEEQS.M

Participant: Holger Heumann.

FEEQS.M (Finite Element Equilibrium Solver in Matlab) is a MATLAB implementation of the numerical methods in [15] to solve equilibrium problems for toroidal plasmas. Direct and inverse problems for both the static and transient formulations of plasma equilibrium can be solved. FEEQS.M exploits MATLAB's evolved sparse matrix methods and uses heavily the vectorization programming paradigm, which results in running times comparable to C/C++ implementations. FEEQS.M complements the production code CEDRES++ in being considered as fast prototyping test bed for computational methods for equilibrium problems. This includes aspects of numerics such as improved robustness of the Newton iterations or optimization algorithms for inverse problems. The latest developments aim at incorporating the resistive diffusion equation.

5.2. 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.

5.3. VacTH

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras.

VacTH implements a method based on the use of toroidal harmonics and on a modelization of the poloidal field coils and divertor coils for the 2D interpolation and extrapolation of discrete magnetic measurements in a tokamak. The method is generic and can be used to provide the Cauchy boundary conditions needed as input by a fixed domain equilibrium reconstruction code like EQUINOX (see [45]). It can also be used to extrapolate the magnetic measurements in order to compute the plasma boundary itself. The proposed method and algorithm are detailed in [13] and results from numerous numerical experiments are presented. The method is foreseen to be used in the real-time plasma control loop on the WEST tokamak (see [46]).

5.4. FBGKI

Participants: Sébastian Minjeaud, Richard Pasquetti.

The Full Braginskii solver considers the equations proposed by Braginskii (1965), in order to describe the plasma turbulent transport in the edge part of tokamaks. These equations rely on a two fluid (ion - electron) description of the plasma and on the electroneutrality and electrostatic assumptions. One has then a set of 10 coupled non-linear and strongly anisotropic PDEs. FBGKI makes use in space of high order methods: Fourier in the toroidal periodic direction and spectral elements in the poloidal plane. The integration in time is based on a Strang splitting and Runge-Kutta schemes, with implicit treatment of the Lorentz terms (DIRK scheme). The spectral vanishing viscosity (SVV) technique is implemented for stabilization. Static condensation is used to reduce the computational cost. In its sequential version, a matrix free solver is used to compute the potential. The parallel version of the code is under development.

5.5. Platforms

5.5.1. 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.

5.5.2. Plato

Participants: Hervé Guillard [contact], Boniface Nkonga, Giorgio Giorgiani, Afeintou Sangam, Elise Estibals.

PlaTo (A platform for Tokamak simulation) is a suite of data and softwares dedicated to the geometry and physics of Tokamaks. Plato offers interfaces for reading and handling distributed unstructured meshes, numerical templates for parallel discretizations, interfaces for distributed matrices and linear and non-linear equation solvers. Plato provides meshes and solutions corresponding to equilibrium solutions that can be used as initial data for more complex computations as well as tools for visualization using Visit or Paraview. The use of this platform for large scale simulation has been validated up to $\mathcal{O}(1000)$ CPU [14] [10]

The numerical schemes used in the platform are of finite element or finite volume type. To deal with the geometry of tokamaks, Plato uses curved prisms made of a tensor product of unstructured triangular meshes in the poloidal plane by 1D meshes in the toroidal direction. The numerical strategy uses 3D finite volume schemes for the first-order terms and P1 finite element for second-order terms. Several models (anisotropic diffusion, Grad-Shafranov equilibrium, reduced MHD model) have been validated and are presently available. In addition, a stabilized finite element method using a tensor product of C^1 (Powell-Sabin) triangular element by 1D cubic splines in the toroidal direction has been recently developed and is presently in a validation phase.

5.5.3. Jorek-Inria

Participants: Hervé Guillard, Boniface Nkonga, Emmanuel Franck [Tonus, Inria Nancy - Grand Est], Ahmed Ratnani [IPP Garching].

https://gforge.inria.fr/projects/jorek/

Jorek-Inria is a new version of the JOREK software, for MHD modeling of plasma dynamic in tokamaks geometries. The numerical approximation is derived in the context of finite elements where 3D basic functions are tensor products of 2D basis functions in the poloidal plane by 1D basis functions in the toroidal direction. More specifically, Jorek uses curved bicubic isoparametric elements in 2D and a spectral decomposition (sine, cosine) in the toroidal axis. Continuity of derivatives and mesh alignment to equilibrium surface fluxes are enforced. Resulting linear systems are solved by the PASTIX software developed at Inria-Bordeaux.

The new formulation of the Jorek-Inria code extends this approximation strategy by introducing more flexibility and a variety of finite elements used in the poloidal plane and in the toroidal direction. It also proposes a sparse matrix interface SPM (Sparse Matrix Manager) that allows to develop clean code without a hard dependency on any linear solver library (i.e. PetSc, Pastix, Mumps, ...). It is expected that the two developments PlaTo and Jorek-Inria will merge in the next years.

6. New Results

6.1. Physics

6.1.1. Physical studies

6.1.1.1. Parallel Kelvin-Helmholtz instability

Participants: Hervé Guillard, Marco Bilanceri, Céline Colin [CEA], Philippe Ghendrih [CEA], Giorgio Giorgiani, Boniface Nkonga, Frédéric Schwander [M2P2, AMU], Eric Serre [M2P2, AMU], Patrick Tamain [CEA].

In the scrape-off layer (SOL) of tokamaks, the flow acceleration due to the presence of limiter or divertor plates rises the plasma velocity in a sonic regime. These high velocities imply the presence of a strong shear between the SOL and the core of the plasma that can possibly trigger some parallel shear flow instability. The existence of these instabilities, denoted as parallel Kelvin-Helmholtz instability in some works have been investigated theoretically in [51] using a minimal model of electrostatic turbulence composed of a mass density and parallel velocity equations. This work showed that the edge plasma around limiters might indeed be unstable to this type of parallel shear flow instabilities. In this work, begun in 2013, we have performed large scale 3D simulations using the PlaTo platform of the same simple mathematical model to investigate this question. The numerical results confirm that in agreement with the theoretical expectations as well as with other numerical methods, the sheared flows in the SOL are subject to parallel Kelvin-Helmholtz instabilities. However, the growth rate of these instabilities is low and these computations require both a sufficient spatial resolution and a long simulation time. This makes the simulation of parallel Kelvin-Helmholtz instabilities a demanding benchmark but it also allows us to validate the parallel implementation of the PlaTo platform up to up to $\mathcal{O}(1000)$ CPU [14].

6.2. Numerical developments

6.2.1. Numerical developments

6.2.1.1. Conformal hexahedral mesh coarsening by agglomeration

Participants: Hervé Guillard, Pierre Cargemel, Youssef Mesri [IFPEN].

This work has been realized in the framework of a PhD contract with IFPEN that aims to produce a coarsening software for hex-dominant meshes. Reservoir simulation involves to compute dynamic flow of different phases in a porous medium. The initial state of the reservoir is usually pre-computed via geo-statistics methods extrapolating measures of the terrain. Therefore, the input of reservoir simulation is given as a very fine mesh containing heterogeneous data and numerical simulation on this fine mesh is usually non-practical. This work is therefore devoted to the study of an agglomeration strategy, to dynamically coarsen this fine hex-dominant mesh. The adaptivity may be driven by physics and/or geometric estimators. Ideally, the coarsening should be applied locally in low gradient regions, whereas high gradient regions keep the fine mesh. This work has been presented in the 23rd International meshing Roundtable [26]. The planned sequel of this work consists to use the notion of Central Voronoi Tesselation (CVT) to treat the regions where the mesh is not structured and to apply this strategy in different physical contexts from plasma physics to petroleum engineering.

6.2.1.2. Mapped Fourier Methods for stiff problems in toroidal geometry

Participant: Hervé Guillard.

Due to the particular geometry of tokamaks, a lot of numerical codes developed for their numerical simulations use Fourier methods. Fourier spectral or pseudo-spectral methods are extremely efficient for periodic problems. However this efficiency is lost if the solutions have zones of rapid variations or internal layers. For these cases, a large number of Fourier modes are required and this makes the Fourier method unpractical in many cases. This work investigates the use of mapped Fourier method as a way to circumvent this problem. Mapped Fourier method uses instead of the usual Fourier interpolant the composition of the Fourier interpolant with a mapping in such a way that in the computational space, the functions to represent are not stiff. This work gives some examples of the usefulness of this method and apply it to a simple model of pellet injection in tokamaks as an example of its potential interest for complex multi dimensional problem [34].

6.2.1.3. Multislope MUSCL method for general unstructured meshes

Participants: Hervé Guillard, Clément Le touze [ONERA], Angelo Murrone [ONERA].

To increase the accuracy in finite volume method, the concept of MUSCL reconstruction has been introduced in the pioneering work of van Leer in the 70'. This technique is still one of the most efficient to deal with the existence of discontinuous solutions in numerical simulations. In the MUSCL technique, a discontinuous linear approximation of the solution is reconstructed on each control volume. The main approximation problem of this method is therefore to reconstruct the slope of the solution.

The multislope concept has been recently introduced in the literature to deal with MUSCL reconstructions on triangular and tetrahedral unstructured meshes in the finite volume cell-centered context. Dedicated scalar slopes are used to compute the interpolations on each face of a given element, in opposition to the monoslope methods in which a unique limited gradient is used. The multislope approach reveals less expensive and potentially more accurate than the classical gradient techniques. Besides, it may also help the robustness when dealing with hyperbolic systems involving complex solutions, with large discontinuities and high density ratios. In this work, we have designed a generalized multislope MUSCL method for cell-centered finite volume discretizations. The method is freed from constraints on the mesh topology, thereby operating on completely general unstructured meshes. Moreover optimal second-order accuracy is reached at the faces centroids and the scheme is L^∞ stable. Special attention has also been paid to equip the reconstruction procedure with well-adapted dedicated limiters, potentially CFL-dependent. We have shown in [18] the ability of the method to deal with completely general meshes, while exhibiting second-order accuracy.

6.2.1.4. Development of a two temperature model

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

A two temperature (ions - electrons) model for non-magnetized plasma has been designed. The numerical scheme is a finite volume method with an approximate Riemann solver using the total energy equation and the electron entropy as main variables. This Riemann solver has been validated against standard shock tube problems and incorporated in the PlaTo platform. The solver has been implementated in toroidal geometry and tested successfully on realistic particular flows encountered in this context. The development of a reduced MHD model based on this two temperature scheme is currently studied.

6.2.1.5. Entropy Preserving Schemes for Conservation Laws

Participants: Christophe Berthon [University of Nantes], Bruno Dubroca [CEA/DAM/CESTA and University of Bordeaux 1], Afeintou Sangam.

A relaxation-type scheme has been proposed to approximate weak solutions of Ten-Moments equations with source terms [*2*]. These equations model compressible anisotropic flows. Following the technique introduced in [44], the proposed scheme is proved to be entropy preserving.

6.2.1.6. Eurofusion WPCD: Free boundary equilibrium code and control

Participants: Cédric Boulbe, Blaise Faugeras, Jean François Artaud [IRFM CEA Cadarache], Vincent Basiuk [IRFM CEA Cadarache], Emiliano Fable [Max-Planck-Institut für Plasmaphysik, Garching], Philippe Huyn [IRFM CEA Cadarache], Eric Nardon [IRFM CEA Cadarache], Jakub Urban [IPP, Academy of Sciences of the Czech Republic, Prague].

Our team is involved in the integrated modelling WPCD (Work Package Code Development) Eurofusion. This project is the continuation of the EFDA-ITM project. The goal of WPCD is to provide a european tool for tokamak simulations. Different physical codes can be coupled using Kepler environment. Machine description and physical data have been described using CPO (Consistent Physical Objet) which are used as standardized inputs and outputs for the codes.

In this project, we participate in the coupling of a free boundary equilibrium solver, the European Transport Solver (ETS) and a plasma shape and position controller. The workflow coupling TCV hybrid Simulink controller and Cedres++ using PF circuit connections has been finalized and tested on the TCV tokamak.
A new workflow coupling Cedres++ with ETS and the TCV controller has been developed and is being tested on a TCV test case. This workflow is an evolution of the coupling CEDRES++ - ETS described in [12].
A successful benchmark between the three free boundary equilibrium codes CEDRES++([15] [47]) , FREEBIE ([43]), and SPIDER ([49]) has been done on static test cases. This activity will be continued to compare the time dependent versions of the three codes.

6.2.1.7. Optimal control for scenario optimization of discharges in tokamaks

Participants: Jacques Blum, Holger Heumann.

In this project we aim for an automatic determination of optimal voltage evolutions via an optimal control formulation based on a system of partial differential equations that describes the evolution of plasma equilibrium in a tokamak. Optimal voltage evolutions are the one that ensure that the evolution of the plasma runs through predescribed, user-defined states, defined e.g. as desired evolution of shape or position. The system of partial differential equations describing the evolution of the plasma is non-linear and we use a finite element formulation together with implicit time stepping for the discretization [15]. With this approach we end up with a large but finite dimensional optimization problem with non-linear constraints. We are using SQP (sequential quadratic programming), known to be one of the fastest methods of such problems, to solve the finite-dimensional optimization problem. The performance of SQP relies on accurate derivatives of the objective function and the constraints. The derivatives related to the free boundary, derived and implements during H. Heumann's PostDoc 2011/2012 for a static optimal control problem, appeared here again and are one of the important building blocks for treating the transient case. Both in CEDRES++ and FEEQ.M we have now the capability to solve first test cases to define optimal voltage evolutions. In contrast to the static case, where the linear algebraic systems in the SQP iteration remain reasonable small, the solution of the corresponding linear system in the transient case becomes very time-consuming, which somehow limits the applicability. We are testing variants of SQP, such as BFGS-like updates for the reduced Hessian, to see whether we could speed up and improve robustness of our calculations. Fast iterative solver for large sparse linear systems is another option that we started to investigate. Fast iterative solver for linear system in transient optimal control problems governed by partial differential equations is a very active area of research and we hope to benefit from the latest developments.

6.2.1.8. Boundary reconstruction for the WEST tokamak with VacTH

Participants: Jacques Blum, Sylvain Bremond [IRFM CEA Cadarache], Cédric Boulbe, Blaise Faugeras, Holger Heumann, Philippe Moreau [IRFM CEA Cadarache], Eric Nardon [IRFM CEA Cadarache], Remy Nouailletas [IRFM CEA Cadarache], François Saint Laurent [IRFM CEA Cadarache].

This work is under progress in collaboration with the CEA. The control of the plasma in the future WEST tokamak requires the identification of its boundary in real time during a pulse. The code VacTH under development in the team enables such an identification. Several numerical developments and experiments have been conducted in order to prepare the control of the plasma in the WEST tokamak. The equilibrium code CEDRES++, also developed in the team, is used to simulate a real plasma and to generate synthetic magnetic measurements from which the plasma boundary is reconstructed using the code VacTH. A control algorithm developed by the colleagues from the CEA then uses this knowledge of the plasma shape to adapt the currents flowing in the poloidal field coils in order to achieve a desired evolution of the plasma.

6.2.1.9. Equilibrium reconstruction for ASDEX UpGrade (AUG) with Vacth-Equinox

Participants: Blaise Faugeras, Rui Cohelo [IPFN, IST, Lisbonne], Patrick Mccarthy [National University of Ireland University College Cork].

Within the framework of the WPCD EUROFUSION the code VacTH-Equinox has been adapted to enable equilibrium reconstruction for AUG. The identification of the current density pedestal required the development of a specific regularization scheme allowing weaker regularization close to the plasma boundary and stronger close to the magnetic axis.

6.2.1.10. Taylor-Galerkin stabilized Finite Element

Participants: José Costa, Boniface Nkonga.

The theoretical part of Taylor-Galerkin/Variational multi-scales (TG/VMS) strategy applied to MHD and reduced MHD modeling has been achieved last year. The final method amounts to add in the finite element 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. We have focused this year on the validations of this strategy and the improvement of the linearization used for stabilization. For application to plasma configurations with X-point, we need to reconsider the consistency with equilibrium and the Bohm boundary conditions on open flux walls.

6.2.1.11. Toward full MHD numerical modeling with $\mathcal{C}^1$ FE

Participants: José Costa, Giorgio Giorgiani, Hervé Guillard, Boniface Nkonga.

In this context the single fluid full MHD model is considered and 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. However, using the potential vector as variable introduces higher order derivatives in the system and classical C0 finite elements cannot be directly applied. This is why our finite element strategies use shape/test functions whose derivatives have global continuity in space (smooth finite elements). The global approach uses cross product shape/test functions between poloidal(2D) and toroidal(1D). In the 2D poloidal plane, discretization uses either quadrangular or triangular elements.

This year we have focused on the numerical analysis associated to the full MHD discretization in configurations with open flux surfaces. In order to derive efficient strategies for the full MHD in the potential vector formulation, the Gauge condition on the potential vector and the boundary conditions have been enforced by penalizations. For the Gauge condition it gives rise to element contributions but also boundary integrals that should be computed on curved surfaces that sometime fitted the magnetic surfaces. Equations are formulated in semi-conservative form such as to apply integration by part. Therefore, boundary conditions can be viewed as evolution of fluxes or variables. Integral formulation on the boundary is very useful for higher order finite elements and also for easier treatment of corners. Indeed in this context the boundary conditions are edges/surfaces oriented and boundary corners are driven by the neighborhood edges penalizations. This strategy is the one that will be used for future developments.

2D Quadrangular Cubic Bezier Finite Elements: This finite element is used for a while for reduced MHD models in the software Jorek. Reduced MHD is used to project the momentum equation in a space orthogonal to the equilibrium. When full MHD models are used, the momentum equation needs to be projected in the equilibrium space and this projection should be consistent with the Grag-Shafranov equilibrium that is used to compute the initial state. This has been achieved by a proper computation of the JxB contribution in the momentum equation, taking into account the poloidal variation of the toroidal component of the magnetic field. Detailed analysis has been performed. The next year will be devoted to implementations and numerical validations.

2D Triangular Powel-Sabin Finite Elements: In order to avoid some mesh singularities when using quadrangular meshes for complex geometries and flux surfaces shapes, triangular elements are a possible option. It is not so easy to derive smooth finite element on triangle with reduced number of degree of freedom. The Bell reduced-quintic finite elements we have considered in the previous years have too much unknowns (6 per vertex). Powell-Sabin splines are piecewise quadratic polynomials with a global $\mathcal{C}^1$-continuity and 3 unknowns per vertex, they have a local support, they form a convex partition of unity, they are stable, and they have a geometrically intuitive interpretation involving control triangles. Construction of the Powel-Sabin splines needs some geometrical tools that have been developed: Minimum area enclosing triangle of a set of control points (sequential and parallel). This construction is applied to each vertex of the triangular mesh and used to derive the local shape/test functions. These Powel-Sabin splines have been used successfully in the area of computer aided geometric design for the modeling and fitting of surfaces. We have used the Powell-Sabin (PS) splines for the approximation of elliptic partial differential equations (including Grad-Shafranov) in a rectangular domain. In this context have recovered the optimal rate of convergence (order 3). Preliminary result has been obtained for hyperbolic isothermal 2D Euler equations with TG/VMS stabilization. Our aim in the coming years is to apply these PS splines to full MHD in a toroidal geometry.

6.2.1.12. Genuinely multidimensional Riemann Solver

Participants: Jeaniffer Vides, Boniface Nkonga.

Multidimensional Riemann solvers were pioneered by Abgrall. Abgrall, Maire, Nkonga, Després and Loubere have extensively developed them especially as node-solvers for Lagrangian hydrodynamics. Another strain of work comes from explorations by Wendroff and Balsara who took a space-time approach. In this work, the resolved state is obtained via space-time integration over a wave model, just as was done by Wendroff and Balsara. However, an algebraic approach is used for the development of the fluxes. It is, therefore, shown that the multidimensional fluxes can be obtained by application of jump conditions at the boundaries of the wave model. The problem is of course over determined with the result that the shock jump conditions are only satisfied approximately in a least squares sense. Even so, this work gives us new perspective on multidimensional Riemann solvers. The litteral satisfaction of the shock jump conditions (up to least squares approximation) makes it easier to understand multidimensional Riemann solvers as a natural extension of the one-dimensional Riemann solvers. Contributions have also been made on the development of a minimalist wave model, which might help in reducing dissipation. Further innovations are reported on the assembling of fluxes based on the structure of the wave model, and those innovations are potentially useful. For MHD the CT approach consists of constraining the transport of magnetic field so that the divergence is always kept zero. The method relies on exploiting the dualism between the flux components and the electric field. Since the electric field is needed at the edges of the mesh, the multidimensional Riemann solver can also provide the electric field. By running an extensive set of simulations, it is shown that the multidimensional Riemann solver is robust and can be used to obtain divergence-free formulations for MHD that perform well on several stringent calculations. Future work will improve this strategy by enriching the description of the strongly interaction of waves.

6.2.1.13. Multi scales approximations of "Shallow water" flows

Participants: Jeaniffer Vides, Boniface Nkonga.

The terminology "Shallow water" is used to characterize thin flows on curved surfaces. It is customary for this type of flows to use the incompressible Navier-Stokes equations to asymptotically derive reduced models for the evolution of the depth integrated speed and the thickness of the flow. Reduced model are mainly hyperbolic and finite volume method are often used for their numerical approximation. Approximations strategies are generally structured as follow:

- Construction of a global coordinate system associated with an assumed analytical surface.
- Reduction of the model relatively to the global coordinate system
- Approximation of the surface by a finite number of elements.
- Approximation of the reduced model using the discrete surface.

In the context of real applications, it is presumptuous to expect an analytical formulation of the surface. From the data provided by observation satellites, we can usually extract a discrete description of the surfaces that drives thin flow. Therefore, it is more practical to use the discrete description as the starting point of the resolution strategy. This is the angle of approach that we have considered. We locally define two mesh scales: the element scale and the cell scale. The discrete mapping and the reduced model are defined at the element scale and the average values that evolve in time are defined at the cell scale. First applications have been successfully performed. We will now continue your investigations and include relevant physics at each scale, including sheared flows. We will also examine the use of multi dimensional Riemann solver in this context.

6.2.1.14. Computational Magnetohydrodynamics with Discrete Differential Forms

Participants: Holger Heumann, Ralf Hiptmair [SAM, ETH Zürich, Switzerland], Cecilia Pagliantini [SAM, ETH Zürich, Switzerland].

Differential forms, or equivalently exterior calculus, are a natural framework for electromagnetics; not only for a better understanding of the theoretical foundation, but also for the development of numerical methods. Keywords are the Hodge decomposition or the de Rham complex that are at the bottom of recent development of efficient multigrid methods or stable mixed finite element methods. Thinking in terms of such co-ordinate free differential forms offers considerable benefits as regards to the construction of structure preserving spatial discretizations.

In the present project, we aim at developing a new approach for the numerical treatment of resistive magnetohydrodynamics where a Galerkin discretization of the electromagnetic part based on finite element exterior calculus (FEEC) will be coupled to advanced finite volume methods for the approximation of the balance laws for the fluid.

The latest developments involved the extension and analysis of the stablized Galerkin schemes for advection of differential forms introduced in [48] to the case of time-dependent and non-regular flow fields.

6.2.1.15. Hamilton-Jacobi Formulation for Vlasov-Poisson

Participants: Holger Heumann, Eric Sonnendrücker [IPP, Max-Planck-Institute Garching, Germany], Philip J. Morrison [Institute for Fusion Studies, Austin, USA].

The phase space mapping induced by the solution of the Vlasov-Poisson problem is a symplectic mapping (or canonical transformation in physics literature) solving Hamilton's equations. In this project we are developing numerical methods that are based on this formulation. We derived and implemented new finite difference schemes for the corresponding Hamilton-Jacobi equation, that circumvent the projection of the distribution function inherent in Lagrangian methods. First numerical results for standard test problems show the ability of increased resolution of fine-scale effects.

6.2.1.16. Entropy viscosity technique

Participants: Richard Pasquetti, Jean-Luc Guermond [Texas A & M University], Boyan Popov [Texas A & M University].

The entropy viscosity technique allows to address hyperbolic equations by introducing a strongly non linear viscous term where needed, especially at shocks. The basic idea is to set up a viscosity from the residual of the entropy inequality together with a $O(h)$ upper bound proportional to the local wave speed. In view of addressing situations where vaccum may appear in the tokamak, we have considered the shallow water equations with topography and in situations where dry-wet transitions occur. Using a RK scheme in time and a spectral element method (SEM) in space, we have proposed a variant of the entropy technique, that mainly consists of using the viscosity upper bound in the dry parts, to obtain satisfactory results. This work was presented in [30], [22] and a publication is under review.

6.2.1.17. Bohm boundary conditions

Participants: Sébastian Minjeaud, Richard Pasquetti.

In the frame of the ANR project ESPOIR, our partners have proposed a penalty method to enforce the Bohm criterion (Mach number greater than one at the tokamak plates). This approach has been justified by considering a "minimal transport model" that consists of a 1-dimensional non linear hyperbolic system of two equations, that govern the evolutions of the density and velocity. The approach and further developments are described in three recent papers published in the journal of computational physics. Considering the same hyperbolic system, we have proposed a direct way to enforce the Bohm criterion in the frame of an explicit time marching. Using a SVV stabilized SEM it is then possible to resolve the same problem with spectral accuracy. This paper is now in press and will be published as a JCP note.

6.2.1.18. A numerical scheme for fluid-particules flows

Participants: Florent Berthelin, Thierry Goudon, Sebastian Minjeaud.

We propose a numerical scheme for the simulation of fluid-particles flows with two incompressible phases. The numerical strategy is based on a finite volume discretization on staggered grids, with a flavor of kinetic schemes in the definition of the numerical fluxes. We particularly pay attention to the difficulties related to the volume conservation constraint and to the presence of a close-packing term which imposes a threshold on the volume fraction of the disperse phase. We are able to identify stability conditions on the time step to preserve this threshold and the energy dissipation of the original model. The numerical scheme is validated with the simulation of sedimentation flows.

6.2.1.19. Identification and forecast of ionospheric disturbances

Participants: Didier Auroux, Sebastian Minjeaud.

In the framework of ANR IODISSEE, in order to identify (and forecast) ionospheric disturbances leading to temporary losses of satellite-to-earth communications (GPS, Galileo), we used Striation software for data assimilation. We obtained the adjoint code thanks to automatic differentiation (Tapenade software from Inria). As the data from Demeter satellite were not available, we extracted synthetic data from a generic model run, and we tried to identified some physical parameters (electronic density, atomic mass, number of particles) of the initial condition from the observations. For a small physical time scale (approximately 1 hour), the identification works very well, and it is possible to retrieve the initial condition from a sparse and noisy observations, allowing us to forecast the evolution of the ionospheric plasma - and then to forecast the disturbances and plasma bubbles that trap GPS and Galileo signals. For longer physical time windows (5 to 10 hours), the identification does not work anymore. We plan to work with real data, if possible, and also with a more complex model (for instance Dynamo software).

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

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

- 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 to qualify 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 IODISSEE : 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).

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

- EUROfusion Grant agreement number 633053. Enabling Research program.
  - JOREK, BOUT++ non-linear MHD modelling of MHD instabilities and their control in existing tokamaks and ITER.
  - Synergetic numerical-experimental approach to fundamental aspects of turbulent transport in the tokamak edge. Grant agreement number 633053.
- EUROfusion WPCD (Working Package Code Development)
  - ACT1: Extended equilibrium and stability chain (participation)
  - ACT2: Free boundary equilibrium and control (participation and coordination)

8.3. International Initiatives

8.3.1. Inria Associate Teams

8.3.1.1. AMOSS

Title: Advanced Modeling on Shear Shallow Flows for Curved Topography : water and granular flows.

International Partner (Institution - Laboratory - Researcher):

NCKU (TAIWAN)

Our objective here is to generalize the promising modeling strategy proposed by S. Gavrilyuk (2012-2013) to genuinely 3D shear flows and also take into account the curvature effects related to topography. Special care will be exercised to ensure that the numerical methodology can take full advantage of massively parallel computational platforms and serve as a practical engineering tool. Cross validations will be achieved by experiments and numerical simulations with applications to landslides.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

In the context of the AMoSS Team :

- Key-Ming Shyue of the National Taiwan University, Juilly 3 to July 13 2014, Numerical Methods: Implicit and Thinc interpolation.
- Chih-Yu Kuo, Associate Research Fellow, Research Center for Applied Sciences, Academia Sinica, Taipei, Taiwan,
- Chyan-Deng Jan, Professor, National Cheng Kung University, Tainan, Taiwan. Workshop on the Modeling of dry granular flows, CIRM Marseille: September 8 to September 13 2014.

9. Dissemination

9.1. Teaching - Supervision - Juries

9.1.1. 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 Nice 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 Numérique, 71.5h, L3, Polytech Nice Sophia Antipolis, France

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

Master: B. Nkonga, Analyse Numérique, 40h, M1, Université de Nice Sophia Antipolis, France

Ecole d'ingénieur/Master: B. Nkonga, Méthode des éléments finis, 24h, M2, Polytech Nice Sophia, France

Ecole d'ingénieur/Master: B. Nkonga, Calcul Parallèle, 24h, M2, Polytech Nice Sophia, France

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

Licence: A. Sangam, Modélisation, 10h, L1, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse, 50h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Méthodes Numériques et Formelles, 40h, L2, Université 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

Master: R. Pasquetti, module “Modèles de turbulence”, 20 h, Masters MSC & IMAG2E, Université de Nice Sophia Antipolis, France.

9.1.2. Supervision

PhD: Giovanni Ruggiero, Une étude comparative de méthodes d'assimilation de données pour des modèles océaniques, Université de Nice Sophia Antipolis, 13 mars 2014, J. Blum et Y. Oumières

PhD: Jeaniffer Vides, Schémas de type Godunov pour la modélisation hydrodynamique et magnéto-hydrodynamique, Université de Nice Sophia Antipolis, 21 octobre 2014

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 : E. Estibals, "MHD réduite: Modélisation et Simulation numérique utilisant des éléments finis stabilisés d'ordre élevé 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 : 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.

9.1.3. Juries

Jacques Blum was referee in the PhD thesis jury of Ngoc Minh Trang Vu, Université Grenoble Alpes.

Jacques Blum was in the PhD thesis jury of Giovanni Ruggiero, Université de Nice Sophia Antipolis.

Boniface Nkonga was referee in the HDR jury of Marina Olazabal, Université de Bordeaux.

Boniface Nkonga was referee in the PhD thesis jury of Eliam Erichon, Université de Marseille.

Boniface Nkonga was referee in the PhD thesis jury of Pascal Jacq, Université de Bordeaux.

Boniface Nkonga and Hervé Guillard were in the PhD thesis jury of Jeaniffer Vides, Université de Nice Sophia Antipolis.

Richard Pasquetti was referee in the PhD thesis jury of Y. Eulalie, Université de Bordeaux, Bordeaux.

Richard Pasquetti was referee in the PhD thesis jury of R. Cheaytou, Université d'Aix-Marseille.

Richard Pasquetti was president of the PhD thesis jury of B. Bensiali, Marseille.

9.2. Popularization

Contribution of B. Nkonga to a Newspaper in the local Journal La Marseillaise www.lamarseillaise.fr/.../30371-90-mathematiciens-en-fusion-a-luminy

Contribution of B. Nkonga to the Iter interfaces news. http://www.itercad.org/Interfaces/Interfaces51.pdf

B. Nkonga and H. Guillard was organizers of the summer school CEMRACS 2014 on Numerical modeling of plasmas, July 21 - August 29, CIRM, Marseille

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