IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

Activity Report 2018

Project-Team CASTOR

Control, Analysis and Simulations for TOkamak Research

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

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

Table of contents

Project-Team CASTOR

Creation of the Team: 2012 July 01, updated into Project-Team: 2014 July 01

Keywords:

Computer Science and Digital Science:

A6. - Modeling, simulation and control
A6.1. - Methods in mathematical modeling
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.6. - Optimization
A6.2.7. - High performance computing
A6.2.8. - Computational geometry and meshes
A6.3. - Computation-data interaction
A6.3.1. - Inverse problems
A6.3.2. - Data assimilation
A6.3.4. - Model reduction
A6.4. - Automatic control
A6.4.1. - Deterministic control
A6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

B4. - Energy
B4.2.2. - Fusion

1. Team, Visitors, External Collaborators

Research Scientists

Hervé Guillard [Inria, Senior Researcher, HDR]
Holger Heumann [Inria, Researcher, until Jun 2018]
Sebastian Minjeaud [CNRS, Researcher]
Richard Pasquetti [CNRS, Emeritus Senior Researcher, HDR]

Faculty Members

Jacques Blum [Univ Côte d'Azur, Professor, Team Leader, HDR]
Cédric Boulbe [Univ Côte d'Azur, Associate Professor]
Francesca Rapetti [Univ Côte d'Azur, Associate Professor, HDR]
Boniface Nkonga [Univ Côte d'Azur, Professor]
Afeintou Sangam [Univ Côte d'Azur, Associate Professor]

Post-Doctoral Fellow

Mireille Coury [Univ Côte d'Azur, until Sep 2018]

PhD Students

Ashish Bhole [Univ Côte d'Azur]
Ali Aboudou Elarif [Inria]

Xiao Song [CEA]

Technical staff

Blaise Faugeras [CNRS]
Alexis Loyer [Inria, until Sep 2018]

Interns

Ayoub Belhachmi [CNRS, from Mar 2018 until Aug 2018]
Zhenyu Xu [Univ de Nice - Sophia Antipolis, from Mar 2018 until Aug 2018]

Administrative Assistant

Montserrat Argente [Inria]

External Collaborator

Didier Auroux [Univ Côte d'Azur]

2. Overall Objectives

2.1. Presentation

In order to fulfill 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 sufficiently 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.

CASTOR gathers the activities in numerical simulation of fusion plasmas 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 and CNRS 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.

The main reseach topics are:

1. Modelling and analysis
   - Fluid closure in plasma
   - Turbulence
   - Plasma anisotropy type instabilities
   - Free boundary equilibrium (FBE)
   - Coupling FBE – Transport
2. Numerical methods and simulations
   - High order methods
   - Curvilinear coordinate systems
   - Equilibrium simulation
   - Pressure correction scheme
   - Anisotropy
   - Solving methods and parallelism
3. Identification and control
   - Inverse problem: Equilibrium reconstruction
   - Open loop control
4. Applications
   - MHD instabilities : Edge-Localized Modes (ELMs)
   - Edge plasma turbulence
   - Optimization of scenarii

4. Application Domains

4.1. Nuclear fusion

The activity of Castor is mainly applied to nuclear fusion, in particular on the WEST, JET and ITER Tokamaks. Several tools developped in the project are used on those machines like equilibrium reconstruction, ELMs simulations...

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Jacques Blum has received the "Grand Prix de la Ville de Nice".
- Blaise Faugeras and Holger Heumann have been nominated as ITER Scientist Fellows.

6. New Software and Platforms

6.1. CEDRES++

KEYWORDS: 2D - Magnetic fusion - Plasma physics

FUNCTIONAL DESCRIPTION: 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.

- Participants: Blaise Faugeras, Cédric Boulbe, Holger Heumann and Jacques Blum
- Partners: CNRS - CEA - Université de Nice Sophia Antipolis (UNS)
- Contact: Cédric Boulbe

6.2. Equinox

KEYWORDS: 2D - Problem inverse
FUNCTIONAL DESCRIPTION: 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.

- Participants: Blaise Faugeras, Cédric Boulbe and Jacques Blum
- Contact: Blaise Faugeras

6.3. FBGKI

Full Braginskii
FUNCTIONAL DESCRIPTION: 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.

- Contact: Sebastian Minjeaud

6.4. FEEQS.M

Finite Element Equilibrium Solver in MATLAB
KEYWORDS: Finite element modelling - Optimal control - Plasma physics

FUNCTIONAL DESCRIPTION: FEEQS.M (Finite Element Equilibrium Solver in Matlab) is a MATLAB implementation of the numerical methods in [Heumann2015] 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.

[Heumann2015]: Heumann, H., Blum, J., Boulbe, C., Faugeras, B., Selig, G., Ané, J.-M., Brémond, S., Grandgirard, V., Hertout, P., Nardon, E.: Quasi-static free-boundary equilibrium of toroidal plasma with CEDRES++: Computational methods and applications. In: Journal of Plasma Physics 81 (2015)

- Participant: Holger Heumann
- Contact: Holger Heumann
- URL: https://scm.gforge.inria.fr/svn/holgerheumann/Matlab/FEEQS.M

6.5. Fluidbox

FUNCTIONAL DESCRIPTION: 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.

- Participants: Boniface Nkonga, Mario Ricchiuto, Michael Papin and Rémi Abgrall
- Contact: Boniface Nkonga

6.6. Jorek-Inria

FUNCTIONAL DESCRIPTION: 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.

RELEASE FUNCTIONAL DESCRIPTION: 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, ...).

- Participants: Ahmed Ratnani, Boniface Nkonga, Emmanuel Franck and Hervé Guillard
- Contact: Hervé Guillard
- URL: https://gforge.inria.fr/projects/jorek/

6.7. Plato

A platform for Tokamak simulation

FUNCTIONAL DESCRIPTION: 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.

- Participants: Afeintou Sangam, Boniface Nkonga, Elise Estibals, Giorgio Giorgiani and Hervé Guillard
- Contact: Hervé Guillard

6.8. VacTH

KEYWORD: Problem inverse
FUNCTIONAL DESCRIPTION: VacTH implements a method based on the use of toroidal harmonics and on a modelization of the poloidal field coils and divertor coils to perform the 2D interpolation and extrapolation of discrete magnetic measurements in a tokamak and the identification of the plasma boundary. 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. It can also be used to extrapolate the magnetic measurements in order to compute the plasma boundary itself. The method is foreseen to be used in the real-time plasma control loop on the WEST tokamak.

- Contact: Blaise Faugeras

6.9. NICE

Newton direct and Inverse Computation for Equilibrium
KEYWORDS: 2D - C++ - Scientific computing - Finite element modelling - Plasma physics - Optimal control - Optimization - Identification
FUNCTIONAL DESCRIPTION: The NICE code is under development. Its goal is to gather in a single modern, modular and evolutionary C++ code, the different numerical methods and algorithms from VACTH, EQUINOX and CEDRES++ which share many common features. It also integrates new methods as for example the possibility to use the Stokes model for equilibrium reconstruction using polarimetry measurements.

- Contact: Blaise Faugeras

7. New Results

7.1. Block-structured meshes

Participants: Hervé Guillard, Alexis Loyer, Jalal Lakhlili [IPP Garching], Ahmed Ratnani [IPP Garching].

Due to the highly anisotropic character of strongly magnetized plasmas, a crucial point for numerical simulations is the construction of meshes that are aligned on the magnetic flux surfaces computed by Grad-Shafranov equilibrium solvers. This work has studied an original method for the construction of flux aligned grids that respect the magnetic equilibrium topology and that can be applied to block-structured meshes using C^1 finite element methods (Hermite-Bézier/Cubic spline). The method relies on the analysis of the singularities of the magnetic flux function and the construction of the Reeb graph that allows the segmentation of the physical domain into sub-domains that can be mapped to a reference square domain. Once this domain decomposition has been done, the mapping of the sub-domain to reference patches can be done using integration along the streamlines of the flux function [16]. This work was performed in the framework of the EoCoE European project (see section 8.2.1.1).

7.2. Unstructured triangular meshes for tokamaks

Participants: Hervé Guillard, Alexis Loyer, Adrien Loseille [Gamma3 team, Inria Saclay].

The construction of block-structured flux aligned grids that respect the magnetic equilibrium topology experiences difficulties in the SOL region of the tokamaks where the flux lines cross the material walls. As an alternative to the use of block structured meshes, we have studied the construction of unstructured triangular meshes using constrained anisotropic Delaunay mesh generation [16]. This work was also performed in the framework of the EoCoE European project (see section 8.2.1.1).

7.3. Simulations of hydraulic jumps with a turbulent Shallow Water model

Participants: Hervé Guillard, Argiris Delis [Technical University of Crete, Greece], Yih-Chin Tai [National Cheng Kung University, Taiwan].

We have pursued the work realized in 2017, on a new model designed for the computation of turbulent hydraulic jumps. This model is able to describe the oscillatory nature of turbulent hydraulic jumps and as such corrects the deficiency of the classical shallow water equations. The comparisons with experiments performed at Tainan University are very satisfactory given the simplicity of the model. A journal paper [3] on this subject have been published and these results have been presented at the ETAMM2018 (Emerging Trends in Applied Mathematics and Mechanics 2018) conference.

7.4. 2D C^1 triangular elements

Participants: Hervé Guillard, Ali Elarif, Boniface Nkonga.

In order to avoid some mesh singularities that arise when using quadrangular elements for complex geometries and flux aligned meshes, the use of triangular elements is a possible option that we have studied in the past years. In particular, we have developped the geometric tools necessary for the construction of Powell-Sabin splines and have applied these methods for the approximation of some simple hyperbolic PDE systems (namely the Euler equation of fluid dynamics [6]). The PhD thesis of Ali Elarif that has begun in october 2017 is devoted to the study of the applicability of these methods to more complex PDE models encountered in plasma physics and to an extension towards other triangular C^1 elements (Clough-Tocher elements). The work realized this year has allowed to apply these finite element spaces to the approximation of elliptic equations and to design penalization methods to enforce non-homogeneous Dirichlet boundary conditions. In particular, the use of reduced Clough-Tocher elements has been applied to obtain solution of the free-boundary non-linear Grad-Shafranov equation. The results show that the use of these C^1 elements produce results that are smoother than the ones obtained with low order P1 elements.

7.5. Equilibrium reconstruction at JET using Stokes model for polarimetry

Participant: Blaise Faugeras.

This paper presents the first application to real JET data of the new equilibrium code NICE which enables the consistent resolution of the inverse equilibrium reconstruction problem in the framework of non-linear free-boundary equilibrium coupled to the Stokes model equation for polarimetry. The conducted numerical experiments enable first of all to validate NICE by comparing it to the well-established EFIT code on 4 selected high performance shots. Secondly the results indicate that the fit to polarimetry measurements clearly benefits from the use of Stokes vector measurements compared to the classical case of Faraday measurements, and that the reconstructed p' and ff' profiles are better constrained with smaller error bars and are closer to the profiles reconstructed by EFTM, the EFIT JET code using internal MSE constraints.

7.6. Operational plasma boundary reconstruction with the NICE-VacTH code on WEST Tokamak

Participant: Blaise Faugeras.

A new regularization term has been proposed for the inverse problem of plasma boundary reconstruction using an expansion of the poloidal flux in toroidal harmonics. It has been implemented in the VacTH code and is used successfully on the WEST Tokamak.

7.7. Equilibrium reconstruction with NICE at WEST and within the framework of the European Integrated Tokamak Modelling WPCD project

Participant: Blaise Faugeras.

The adaptation of NICE to IMAS (the ITER standard using IDS as data type) has been carried on. Equilibrium reconstructions using IMAS have been performed on real JET measurements and are now performed routinely at WEST.

7.8. Equilibrium reconstruction with Equinox at JET

Participant: Blaise Faugeras.

The adaptation of NICE to IMAS the ITER standard using IDS as data type has been carried on. Equilibrium reconstructions using IMAS have been performed on real JET measurements and are now performed routineley at WEST.

7.9. Evolutive mode and iron model in NICE

Participants: Blaise Faugeras, Jacques Blum, Cédric Boulbe.

The capabilities of the equilbirum code NICE have been extended. The evolutive direct model and the iron model of the free boundary equilibrium code CEDRES++ have been ported in NICE.

7.10. Coupling CEDRES++ - WEST controller in IMAS

Participants: Cédric Boulbe, Jakub Urban [IPP Prague].

The free boundary equilibrium code has been fully adapted to IMAS and has been coupled to the magnetic controller of WEST. The code CEDRES++ simulate the plant and the controller provide the voltages applied to the PF supplies. This coupling has enabled to develop a tool in Python to interface easily Simulink controllers with IMAS. With that tool, it is possible to run a controller installed on a distant computer and to run it from IMAS. As a test case, the WEST controller has been interfaced with IMAS and coupled to CEDRES++ using an IMAS python workflow.

7.11. Spectral Element method for high order partial differential equations

Participants: Sebastian Minjeaud, Richard Pasquetti.

The Korteweg-de Vries equation has been addressed as an interesting model of high order partial differential equation. In [9] it is shown that it is possible to develop reliable and effective schemes, in terms of accuracy, computational efficiency, simplicity of implementation and, if required, conservation of the lower invariants, on the basis of a (only) H^1-conformal Galerkin approximation, namely the Spectral Element Method. The proposed approach is *a priori* easily extensible to other partial differential equations and to multidimensional problems.

7.12. Recent advances in Spectral element methods on simplicial meshes

Participants: Richard Pasquetti, Francesca Rapetti.

R. Pasquetti and F. Rapetti have investigated the cubature points based triangular spectral element method. Using cubature points, both for interpolations and quadratures, shows the advantage of yielding a diagonal mass matrix. Accuracy results are provided in [10], for elliptic problems in non polygonal domains, using various isoparametric mappings. The capabilities of the method are here again clearly confirmed.

7.13. Full-MHD with Jorek

Participants: Boniface Nkonga, Ashish Bhole.

In the context of A. Bohle PhD, we have developped a strategy to improve the formulation of finite element space in the context of iso-parametric finite elements with singular parametrization. This result in a set of constraints to be applied in the numerical formulation to fit in the well defined approximated space. Applied to interpolations, we recover the optimal order of convergence of the numerical approximation. Next step is applications to the resolution of reduced-MHD and then full-MHD.

7.14. A discontinuous Galerkin method for a two dimensional resistive MHD model

Participants: Ashish Bhole, Boniface Nkonga, Praveen Chandrashekar.

We consider the numerical approximation of two dimensional incompressible magnetohydrodynamics equations with vorticity and current as the dynamical variables. We construct a discontinuous Galerkin (DG) method for the MHD model written in symmetric form. The numerical flux is based on a Riemann solver and the scalar fluxes of velocity and magnetic field are computed using a Galerkin method. The performance of the method is demonstrated on some standard instability problems relevant to magnetically confined fusion reactors.

7.15. Fluctuation splitting Riemann solver for a non-conservative shear shallow water flow

Participants: Ashish Bhole, Boniface Nkonga, Sergey Gavrilyuk.

We propose a fluctuation splitting finite volume scheme for a non-conservative modeling of shear shallow water flow (SSWF). This model was originally proposed by Teshukov and was extended to include modeling of friction by Gavrilyuk (2018). We develop a cell-centered finite volume code to validate the proposed scheme with the help of some numerical tests. As expected, the scheme shows first order convergence. The numerical simulation of 1D roll waves shows a good agreement with the experimental results. The numerical simulations of 2D roll waves show similar transverse wave structures as observed by Gavrilyuk (Paper in revision at JCP).

7.16. Automating the design of Tokamak experiment scenarios

Participants: Jacques Blum, Holger Heumann, Xiao Song.

The real-time control of plasma position, shape and current in a tokamak has to be ensured by a number of electrical circuits consisting of voltage suppliers and axisymmetric coils. Finding good target voltages/currents for the control systems is a very laborious, non-trivial task due to non-linear effects of plasma evolution. We introduce here an optimal control formulation to tackle this task and present in detail the main ingredients for finding numerical solutions: the finite element discretization, accurate linearizations and Sequential Quadratic Programming. Case studies for the tokamaks WEST and HL2M highlight the exibility and broad scope of the proposed optimal control formulation.

7.17. Multiscales scheme for the MHD model in a tokamak

Participants: Hervé Guillard, Afeintou Sangam.

Recently, in [21], it is proven that the Reduced MHD equations are a singular limit of the Full MHD system when the inverse ratio parameter goes to zero. In this limit, the toroidal dynamics is almost entirely decoupled from the incompressible poloidal dynamics. From a numerical point of view, in this limit, the propagation of fast magnetosonic waves severely constraints the time step in explicit schemes. A possible remedy is therefore to design a semi-implicit time stepping strategy allowing an implicit handling of the fast waves but retaining an explicit treatment of the slow ones. In this work, we have derived a linear simplified model in two dimensions that retains the main characteristics of the formal passage from the Full MHD equations to the Reduced MHD system. A semi-implicit numerical scheme free of time step restrictions based on the fast wave velocity has been constructed for this model. The extension of this numerical scheme to the Full MHD model is under investigation.

7.18. Asymptotic Transport Models for heat and mass transport in reactive porous media

Participants: Bruno Dubroca, Afeintou Sangam.

Charrier and *Dubroca* in [20], have suggested an approach to derive rigously a family of models of mass and heat transfer in reactive porous media. At a microscopic level they proposed a model coupling the Boltzmann equation in the gas phase, the heat equation and appropriate interface conditions, including adsorption-deposition reactions. Then an asymptotic expansion mixing homogenization and fluid limit leads to a system of coupled diffusion equations where the effective diffusion tensors are defined from the microscopic geometry of the material. Open questions paved their work. We solve one of them, consisting in setting adequate conditions on interest models that ensure the uniqueness of solutions of the first order expansion. They are based on the concept of thermodynamically closed in average system.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. Inria Project Lab: FRATRES (Fusion Reactors Research and Simulation)

- Participants : Inria project-teams : CASTOR, IPSO, TONUS,
- Partners : IRFM-CEA, Max Planck Institute-IPP Garching, LJLL-Jussieu, IMT-Toulouse

Controlled nuclear fusion can be considered as an example of grand challenge in many fields of computational sciences from physical modelling, mathematical and numerical analysis to algorithmics and software development and several Inria teams and their partners are developing mathematical and numerical tools in these areas.

Since january 2015, H. Guillard is coordinating the Inria Project Lab FRATRES (https://team.inria.fr/ipl-fratres/) to organize these developments on a collaborative basis in order to overcome the current limitations of today numerical methodologies. The ambition is to prepare the next generation of numerical modelling methodologies able to use in an optimal way the processing capabilities of modern massively parallel architectures. This objective requires close collaboration between a) applied mathematicians and physicists that develop and study mathematical models of PDE; b) numerical analysts developing approximation schemes; c) specialists of algorithmic proposing solvers and libraries using the many levels of parallelism offered by the modern architecture and d) computer scientists. This Inria Project Lab will contribute in close connection with National and European initiatives devoted to nuclear Fusion to the improvement and design of numerical simulation technologies applied to plasma physics and in particular to the ITER project for magnetic confinement fusion.

Contact : Hervé Guillard

8.1.2. Defi : Infiniti : INterFaces Interdisciplinaires NumérIque et ThéorIque

- Participants: HervéGuillard, AnnaDegioanni[LAMPEA Aix-en-Provence], SilvanaCondemi[ADES, Marseille], ZhenyuXu

In the framework of the "Defi : Infiniti : INterFaces Interdisciplinaires NumérIque et ThéorIque" of the “Mission pour l’Interdisciplinarité” of CNRS, this work has associated Hervé Guillard to Anna Degioanni of the Laboratory LAMPEA - Laboratoire Méditerranéen de Préhistoire Europe-Afrique of Aix-en-Provence and Silvana Condemi of the ADES (Anthropologie bio-culturelle, droit, éthique et santé - UMR 7268) laboratory in Marseille. The purpose of this work was to propose a numerical model and to realize a software allowing paleo-anthropologist and pre-historians to study numerically the propagation and diffusion of Homo Sapiens in Europe between 50 000 and 30 000 years BP. A 6 month internship of Ms Zhenyu Xu, 3rd year student at the polytech’Nice school of engineers has been devoted to this project and the results have been presented at the "Journée de restitution 2018 du Défi Infiniti", (http://www.cnrs.fr/mi/spip.php?article1440&lang=fr)

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. EoCoE

Title: Energy oriented Centre of Excellence for computer applications

Programm: H2020

Duration: October 2015 - October 2018

Coordinator: CEA

Partners:

- Barcelona Supercomputing Center - Centro Nacional de Supercomputacion (Spain)
- Commissariat A L Energie Atomique et Aux Energies Alternatives (France)
- Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique (France)
- Consiglio Nazionale Delle Ricerche (Italy)
- The Cyprus Institute (Cyprus)
- Agenzia Nazionale Per le Nuove Tecnologie, l’energia E Lo Sviluppo Economico Sostenibile (Italy)
- Fraunhofer Gesellschaft Zur Forderung Der Angewandten Forschung Ev (Germany)
- Instytut Chemii Bioorganicznej Polskiej Akademii Nauk (Poland)
- Forschungszentrum Julich (Germany)
- Max Planck Gesellschaft Zur Foerderung Der Wissenschaften E.V. (Germany)
- University of Bath (United Kingdom)
- Universite Libre de Bruxelles (Belgium)
- Universita Degli Studi di Trento (Italy)

Inria contact: Michel Kern

The aim of the present proposal is to establish an Energy Oriented Centre of Excellence for computing applications, (EoCoE). EoCoE (pronounce “Echo”) will use the prodigious potential offered by the ever-growing computing infrastructure to foster and accelerate the European transition to a reliable and low carbon energy supply. To achieve this goal, we believe that the present revolution in hardware technology calls for a similar paradigm change in the way application codes are designed. EoCoE will assist the energy transition via targeted support to four renewable energy pillars: Meteo, Materials, Water and Fusion, each with a heavy reliance on numerical modelling. These four pillars will be anchored within a strong transversal multidisciplinary basis providing high-end expertise in applied mathematics and HPC. EoCoE is structured around a central Franco-German hub coordinating a pan-European network, gathering a total of 8 countries and 23 teams. Its partners are strongly engaged in both the HPC and energy fields; a prerequisite for the long-term sustainability of EoCoE and also ensuring that it is deeply integrated in the overall European strategy for HPC. The primary goal of EoCoE is to create a new, long lasting and sustainable community around computational energy science. At the same time, EoCoE is committed to deliver high-impact results within the first three years. It will resolve current bottlenecks in application codes, leading to new modelling capabilities and scientific advances among the four user communities; it will develop cutting-edge mathematical and numerical methods, and tools to foster the usage of Exascale computing. Dedicated services for laboratories and industries will be established to leverage this expertise and to foster an ecosystem around HPC for energy. EoCoE will give birth to new collaborations and working methods and will encourage widely spread best practices.

8.2.2. Collaborations in European Programs, Except FP7 & H2020

EuroFusion Consortium

CASTOR participates to the following EuroFusion consortium projects :

Enabling research contract 2014-2018. (B. Nkonga, H. Guillard, A. Sangam) CfP-WP15-ENR-01/IPP-05, Grant agreement No 633053. «Global non-linear MHD modeling in toroidal X-point geometry of disruptions, edge localized modes, and techniques for their mitigation and suppression »

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 International Partners

8.3.1.1. Informal International Partners

- The team collaborates with TUC (Technical University of Crete, Prof. Argyris Delis) on extension of the shallow water model to turbulent flows. These common works overlap with the collaboration with Taiwan in the framework of the former AMOSS associate team.
- Collaboration with TIFR-Bangalore on MHD, one month invited at Bangalore (B. Nkonga and A. Bhole) C. Praveen will have 2months as invited professor at UCA in 2019.

8.3.2. Participation in Other International Programs

ITER Contracts (B. Nkonga):

- ITER IO/17/CT/4300001505: 2017-2019, "Non-linear MHD simulations for ITER QH-mode plasma with and without 3D magnetic field perturbations from in-vessel ELM control coils". (150KE)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

- IPL FRATRES Workshop 2018. Alsace, November 21-23 (https://team.inria.fr/ipl-fratres/2018-ipl-meetings-ipl-workshop-alsace/)

- Final Summary meeting, Inria Paris, November 19 (https://team.inria.fr/ipl-fratres/final-summary-meeting/)

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- C. Boulbe is layout editor of the free journal SMAI-Journal of Computational Mathematics.
- J. Blum is member of
  - the editorial board of the Journal of Scientific Computing (JSC),
  - the scientific committee of the collection "Mathématiques et Statistiques" of the ISTE publications,
  - editor in chief of the ISTE Open Science journal: "Mathématiques appliquées et stochastiques".
- F. Rapetti is member of the editorial board of the Advances in Computational Mathematics (ACOM) journal by Springer

9.1.2.2. Reviewer - Reviewing Activities

- Hervé Guillard has been reviewer for the Journal of Computational physics, Computers and Fluids and International Journal for Numerical methods in Fluids.

9.1.3. Invited Talks

- Hervé Guillard, "Low Mach and multiphase flows", Workshop on numerical and physical modeling in multiphase flows: a cross-fertilisation approach, Paris, February 1-2, 2018, https://workshopmultiphase.wixsite.com/mpf2018
- Hervé Guillard, "Tokamesh : A software for mesh generation in Tokamaks", Renewable Energy meets High Performance Computing: Final Conference of the Energy-Oriented Centre of Excellence, Nicosia, Cyprus, September 17-18, 2018, https://www.eocoe.eu/events/final-eocoe-conference-cyprus
- Jacques Blum, "Algorithmes de contrôle optimal pour l'identification de l'équilibre du plasma et pour l'optimisation de scénarios dans un Tokamak", Marseille, November 29, 2018, https://plasmas2018.sciencesconf.org/resource/page/id/3

9.1.4. Leadership within the Scientific Community

- H. Guillard is coordinator of the topic "Turbulence and transport of edge plasma" within the Fédération FR-FCM

9.1.5. Scientific Expertise

- H. Guillard has acted as scientific expert for the FRS-FNRS (Fonds de la Recherche Scientifique - FNRS Fédération Wallonie-Bruxelles) and PRACE (Partnership for Advanced Computing in Europe).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

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

Ecole d'ingénieur: D. Auroux, Méthodes numériques, 36h, M2, Polytech Nice Sophia, Université de Nice Sophia Antipolis, France

Ecole d'ingenieur: D. Auroux, Projet, 35h, L3, Polytech Nice Sophia Antipolis, France

Master: J. Blum, Optimisation, 36h, M1, 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, Projet, 35h, L3, Polytech Nice Sophia Antipolis, France

Licence: S. Minjeaud, module Eléments de calcul différentiel, 18 h, L3, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, module Méthodes numériques en EDP, 62 h, M1, Université de Nice Sophia Antipolis, France.

Licence: S. Minjeaud, module Compléments de calcul différentiel, 20 h, L3, Université de 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, Eléments finis mixtes, 24h, M2, Polytech Nice Sophia, France

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

Licence: A. Sangam, Analyse, 70h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse Numérique, 86h, L3, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Projet tuteuré en laboratoire, 15h, L3 Physique, Université Nice Sophia Antipolis, France

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

9.2.2. Supervision

- PhD : Julie Llobel, "Schémas Volumes Finis à mailles décalées pour la dynamique des gaz", Université Cote d'Azur, Thierry Goudon et Sebastian Minjeaud
- PhD in progress : Ali Elarif, "Simulation numérique des instabilités magnétohydrodynamique dans les Tokamaks", since October 2017, Hervé Guillard
- PhD in progress: Xiao Song, "Model-based control-oriented scenario construction in tokamaks", since October 2016, Blaise Faugeras and Holger Heumann
- PhD in progress: Ashish Bhole, Numerical improvements and validations of the stabilized full MHD with applications to tokamaks, October 2017, Boniface Nkonga

9.2.3. Juries

- Hervé Guillard was referee in the HDR jury of Jean-Philippe BRAEUNIG, October 19, 2018, “Contributions à l'étude de schémas numériques de type Volumes Finis et de leurs applications pratiques”.
- F. Rapetti was examinator in the jury of Matteo Valentinuzzi PhD defense at CEA in Cadarache on December, the 17th, 2018, "Numerical modelling of power flux densities on tokamak plasma facing components by using advanced coupling techniques for kinetic and fluid codes"

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

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[2] Q. CARMOUZE, F. FRAYSSE, R. SAUREL, B. NKONGA. *Coupling rigid bodies motion with single phase and two-phase compressible flows on unstructured meshes*, in "Journal of Computational Physics", 2018 [*DOI :* 10.1016/J.JCP.2018.08.023], https://hal.inria.fr/hal-01865705

[3] A. I. DELIS, H. GUILLARD, Y.-C. TAI. *Numerical simulations of hydraulic jumps with the Shear Shallow Water model*, in "SMAI Journal of Computational Mathematics", 2018, vol. 4, pp. 319-344, https://hal.inria.fr/hal-01946806

[4] B. FAUGERAS, F. ORSITTO. *Equilibrium reconstruction at JET using Stokes model for polarimetry*, in "Nuclear Fusion", October 2018, vol. 58, n^{o} 10 [*DOI :* 10.1088/1741-4326/AAD751], https://hal.archives-ouvertes.fr/hal-01936062

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[7] H. HEUMANN, F. RAPETTI, X. SONG. *Finite element methods on composite meshes for tuning plasma equilibria in tokamaks*, in "Journal of Mathematics in Industry", December 2018, vol. 8, n^{o} 1, https://hal.archives-ouvertes.fr/hal-01948902

[8] F. LIU, G. T. A. HUIJSMANS, A. LOARTE, A. M. GAROFALO, W. M. SOLOMON, M. HOELZL, B. NKONGA, S. PAMELA, M. BECOULET, F. ORAIN, D. VAN VUGT. *Nonlinear MHD simulations of QH-mode DIII-D plasmas and implications for ITER high Q scenarios*, in "Plasma Physics and Controlled Fusion", January 2018, vol. 60, n^{o} 1, pp. 1-13 [*DOI :* 10.1088/1361-6587/AA934F], https://hal.archives-ouvertes.fr/hal-01589770

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Invited Conferences

[11] A. DEGIOANNI, H. GUILLARD, B. NKONGA, S. CONDÉMI. *Modélisation mathématique de l'entrée de l'Homme moderne en Europe*, in "Journée de restitution 2018 "Défi Infiniti"", Paris, France, October 2018, https://hal.inria.fr/hal-01959157

[12] H. GUILLARD. *Fast waves and incompressible models*, in "Workshop on numerical and physical modelling in multiphase flows: a cross-fertilisation approach", Paris, France, February 2018, https://hal.inria.fr/hal-01949646

Conferences without Proceedings

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Research Reports

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