RESEARCH CENTRE

Inria Center at Université Côte d'Azur

IN PARTNERSHIP WITH:

CNRS, Université Côte d'Azur

2022 ACTIVITY REPORT

Project-Team CASTOR

Control, Analysis and Simulations for TOkamak Research

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

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

Inria

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Project-Team CASTOR

Creation of the Project-Team: 2014 July 01

Keywords

Computer sciences and digital sciences

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

A6.5. – Mathematical modeling for physical sciences

Other research topics and application domains

B4. – Energy

B4.2.2. – Fusion

1 Team members, visitors, external collaborators

Research Scientists

- Hervé Guillard [Team leader, INRIA, Senior Researcher, HDR]
- Florence Marcotte [INRIA, Researcher]

Faculty Members

- Didier Auroux [UNIV COTE D'AZUR, Professor, HDR]
- Jacques Blum [UNIV COTE D'AZUR, Emeritus, HDR]
- Cédric Boulbe [UNIV COTE D'AZUR, Associate Professor]
- Boniface Nkonga [UNIV COTE D'AZUR, Professor, HDR]
- Francesca Rapetti-Gabellini [UNIV COTE D'AZUR, Associate Professor, from Jun 2022, HDR]
- Afeintou Sangam [UNIV COTE D'AZUR, Associate Professor]

Post-Doctoral Fellows

- Ashish Bhole [UNIV COTE D'AZUR]
- Paul Manix [INRIA, until Oct 2022]
- Alexandre Vieira [UNIV COTE D'AZUR, from Sep 2022]

PhD Students

- Guillaume Gros [UNIV COTE D'AZUR, from Oct 2022]
- Junior Yves Audrey Iroume [IRGM - YAOUNDE, from Jun 2022 until Aug 2022]
- Louis Lamerand [UNIV COTE D'AZUR]

Technical Staff

- Blaise Faugeras [CNRS, Engineer, HDR]

Administrative Assistant

- Montserrat Argente [INRIA]

Visiting Scientists

- Dinshaw Balsara [UNIV NOTRE DAME, USA]
- Arno Roland Ngatcha Ndengna [ENSP DOUALA, from Jun 2022]
- Raphael Onguene [UNIV DOUALA, from Nov 2022]
- Jeaniffer Vides Higueros [UNIV COTE D'AZUR, from Sep 2022]

2 Overall objectives

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 and Laser Megajoule 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 Université Côte d'Azur. 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, Université Côte d'Azur and CNRS through the laboratory Jean-Alexandre Dieudonné, UMR UNS-CNRS 7351, LJAD.

3 Research program

3.1 Plasma Physics

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
   - MHD instabilities
2. Numerical methods and simulations
   - High order methods
   - Curvilinear coordinate systems
   - Equilibrium simulation
   - Anisotropy

- Solving methods and parallelism

3. Identification and control

   - Inverse problem: Equilibrium reconstruction
   - Open loop control

4 Application domains

4.1 MHD and plasma stability in tokamaks

Participants: Hervé Guillard, Boniface Nkonga, Afeintou Sangam, Ali Elarif, Ashish Bhole.

The magnetic equilibrium in tokamaks results from a balance between the Lorentz force and the pressure gradient. Using Ampère law, a convenient description of this equilibrium is provided by the Grad-Shafranov equation. Of course, the magnetic equilibrium solution of the Grad-Shafranov equation is required to be stable. Actually any loss of MHD stability can lead to the end of the existence of the plasma, the so-called disruptions that can affect negatively the integrity of the machine. The primary goal of MHD (Magneto-Hydro-Dynamics) studies is therefore to determine the stability domain that constraints the operational range of the machine.
A secondary goal of MHD studies is to evaluate the consequences of possible disruptions in term of heat loads and stresses on the plasma facing components. In modern machines in the so-called H-mode some mild instabilities leading to a near oscillatory behavior are also known to exist. In particular, the so-called ELMs (Edge Localized Modes) are of particular importance since they can have large effects on the plasma facing components. The control and understanding of these instabilities is therefore of crucial importance for the design of future machines as ITER. Unfortunately, ELM occur in the edge plasma and their modeling requires to take in account not only the intricate magnetic topology of this region where co-exist both open and closed field lines but also the existence of molecular and atomic processes involving neutrals.

At present, the linear theory of MHD stability is relatively well understood. However, the description of the non-linear behavior is far from being complete. As a consequence and due to the intrinsic difficulty of the subject, only a few numerical codes worldwide have been developed and validated for non linear MHD in tokamaks. One of these codes is the JOREK code developped since 2006 from a collaborative work between CEA-Cadarache (main developer), LABRI Bordeaux, LJAD-UCA and Inria. A comprehensive description of JOREK is given in [22]

4.2 Long term plasma evolution and optimization of scenarii

Participants: Didier Auroux, Jacques Blum, Cédric Boulbe, Blaise Faugeras, Hervé Guillard.

The magnetic equilibrium evolves in time due to diffusion processes on the slow resistive diffusive time scale and moreover it has to be monitored with active and passive control based on external coils, current drive, heating system, particle or pellets injections. This set of control mechanism has to be modeled and this is the goal of real time codes or global evolution codes.
In the same order of ideas, the steering and control of the plasma from the beginning to the end of the discharge require the research of optimal trajectories through the space of operational parameters. This is usually performed in an empirical way in present Tokamaks, but the complexity of the problem requires today the use of optimization techniques for processes governed by MHD and diffusion-type equations.

4.3 Turbulence and models for the edge region of tokamaks

Participants: Didier Auroux, Louis Lamerand, Francesca Rapetti.

The edge region of the plasma is characterized by low temperature and density leading to an increase of the collision frequency that makes the edge plasma nearly collisional. This combined with the intricate magnetic topology of this region makes the development of kinetic codes adapted to the edge regions a real long term adventure. Consequently the fluid approach remains a standard one to study edge plasma turbulence. The use of optimal control theory to derive simplified models matching data either experimental or derived from direct numerical simulations is part of the objectives of the team.

4.4 Understanding magnetogenesis in stellar systems

Participants: Didier Auroux, Paul Mannix, Florence Marcotte.

The considerable diversity of long-lived magnetic fields observed in the Universe raises fundamental questions regarding their origin. Although it is now widely accepted that such fields are sustained by a dynamo instability in the electrically conducting fluid layers of astrophysical bodies, in most cases the very nature of the flow motions powering the dynamo is essentially unknown, and the conditions required for amplifying large-scale magnetic fields in non-convective stellar systems are poorly understood. We claim that optimal control represents a powerful tool to investigate the nonlinear stability of fully 3D, unsteady magnetohydrodynamic flows with respect to the dynamo instability. Nonlinear optimisation can be also used as a physical diagnostic to gain novel understanding of the mechanisms that are most favorable to dynamo action in a natural system.

5 Social and environmental responsibility

5.1 Impact of research results

The main objective of the CASTOR team is to contribute to the development of the numerical tools used for the simulation of fusion plasma. Since the design of the next generation of fusion reactors relies on numerical simulation, the works done in CASTOR contribute to the search of a clean and decarbonated energy.

6 New results

6.1 First equilibrium reconstruction for ITER with the code NICE

Participants: Blaise Faugeras, Jacques Blum, Cédric Boulbe.

We have realize a first application of the IMAS compatible code NICE to equilibrium reconstruction for ITER geometry. The inverse problem has been formulated as a least square problem and the numerical methods implemented in NICE have been used to solve this optimization problem. A numerical experiment where a reference equilibrium is computed from which a set of synthetic magnetic measurements are extracted have been done to validate this approach ([7]).

6.2 High-order finite elements in tokamak free-boundary plasma equilibrium computations

Participants: F. Rapetti, B. Faugeras, C. Boulbe.

We wish to compute numerically the equilibrium for a hot plasma in a tokamak. For such a problem in an axisymmetric configuration, we present a non-overlapping mortar element approach, that couples piece-wise linear finite elements in a region that does not contain the plasma and reduced Hsieh-Clough-Tocher finite elements elsewhere, to approximate the magnetic flux field on a triangular mesh of the poloidal tokamak section. This approach has the flexibility to achieve easily and at low cost higher order regularity for the approximation of the flux function in the domain covered by the plasma, while preserving accurate meshing of the geometric details in the rest of the computational domain and simplifying the inclusion of ferromagnetic parts.

6.3 Linearized equilibrium evolution model

Participants: Blaise Faugeras.

Plasma control engineers need simple state-space linear ODE models to develop and test controlers. Such a linearized plasma equilibrium evolution model has been developed and implemented in the code NICE. It can be written as $dX/dt = AX + BU$, $Y = CX$ where X is the vector of currents in the coils and in the passive structures, U is the vector of voltages in the power supplies and Y is the vector of output variables to be controlled (position of the magnetic axis, Xpoint, gaps, ...). Matrices A, B and C are computed thanks to the Jacobian of the non-linear model used in the Newton iterations.

6.4 Coupling Nice-Metis

Participants: J.F. Artaud, C. Boulbe, B. Faugeras.

In [21], a new model describing the evolution of the diamagnetic function f which appears in the right hand side of the well known Grad-Shafranov equation has proposed. This model has been implemented in the free boundary equilibrium code NICE. This new version of the code has been tested. A first version of the coupling of Nice with the fast transport solver has started in Matlab. This coupling should be more robust than the last version of the coupling NICE-METIS which was using the current diffusion equation for the evolution of the right hand side of the Grad-Shafranov equation. This work is done in the framework of the workpackage WPSA EUROFUSION H-EUROPE. The ungoing development of a simulator for JT60SA discharges has demanded the development of new functionalities in the code NICE. Originally the f function was decomposed in a basis of Legendre polynomials. However numerical oscillations lead us to to test other possible decomposition basis. The best results were obtained with splines and a basis of spline functions is now used. The static inverse mode of NICE can also now use a desired value for the boundary poloidal flux in addition to the desired plasma boundary points. And finally the code now gives the possibility to use given eddy currents in passive structures in static direct and inverse modes.

6.5 Turbulence and models for the edge region of tokamaks

Participants: Didier Auroux, Louis Lamerand, Francesca Rapetti-Gabellini.

The high-dimensional and multiscale nature of fusion plasma flows require the development of reduced models to be implemented in numerical codes capable of capturing the main features of turbulent transport in a sufficiently short time to be useful during tokamak operation. This paper goes further in the analysis of the dynamics of the $\kappa - \epsilon$ model based on the turbulent kinetic energy κ and its dissipation rate ϵ [Baschetti et al., Nuc. Fus 61, 106020 (2021)] to improve the predictability of the transverse turbulent transport in simulation codes. Present 1D results show further capabilities with respect to current models (based on constant effective perpendicular diffusion) and on the standard quasi-linear approach. The nonlinear dependence of D in κ and ϵ estimated from two additional transport equations allow to introduce some non-locality in the transport model. This is illustrated by the existence of parameter ranges with turbulence spreading. The paper also addresses another issue related to the uncertainties on the inherent free parameters of such reduced model. The study proposes a new approach in the fusion community based on a variational data assimilation involving the minimisation of a cost function defined as the distance between the reference data and the calculated values. The results are good, and show the ability of the data assimilation to reduce uncertainties on the free parameters, which remains a critical point to ensure the total reliability of such an approach, [5].

6.6 Coupling Hermite-Bezier quadrangular elements and Clough Tocher triangular elements

Participants: Ashish Bhole, Boniface Nkonga, Hervé Guillard, Francesca Rapetti-Gabellini.

The Jorek code for MHD studies uses fourth order C1 quadrangular finite elements. This leads to results with high spatial accuracy. However with this type of elements, the description of the boundary is difficult and moreover with polar meshes, geometrical singularities appear on X-points and magnetic axis. By relying on composite meshes, we have studied the coupling of the Hermite-Bezier quadrangular elements used in Jorek and of Clough Tocher triangular elements for an easier representation of the boundary and treatment of the mesh singularities. First results for the Poisson model problem with Dirichlet boundary conditions can be found in [16].

6.7 High-order Whitney finite elements in electromagnetics modeling

Participants: Francesca Rapetti-Gabellini, Ana Alonso Rodriguez (Univ. di Trento, Italy).

We recall the classical tree-cotree technique in magnetostatics. We extend it in the frame of high-order finite elements in general domains. We focus on its connection with the question of the invertibility of the final algebraic system arising from a high-order edge finite element discretization of the magnetostatic problem formulated in terms of the magnetic vector potential. With the same purpose of invertibility, we analyse another classically used condition, the Coulomb gauge. We conclude by underlying that the two gauges can be naturally considered in a high order framework without any restriction on the topology of the domain [11].

We propose to extend results on the interpolation theory for scalar functions to the case of differential k-forms. More precisely, we consider the interpolation of fields in the finite element spaces of trimmed polynomial k-forms of arbitrary degree $r \geq 1$, from their weights, namely their integrals on k-chains. These integrals have a clear physical interpretation, such as circulations along curves, fluxes across surfaces, densities in volumes, depending on the value of k. In this work, for $k = 1$, we rely on the flexibility of the weights with respect to their geometrical support, to study different sets of 1-chains in T for a high order interpolation of differential 1-forms, constructed starting from "good" sets of nodes for a high order multi-variate polynomial representation of scalar fields, namely 0-forms. We analyse the growth of the generalized Lebesgue constant with the degree r and preliminary numerical results for edge elements support the nonuniform choice, in agreement with the well-known nodal case. Results are given in [4].

It is well known that Lagrange interpolation based on equispaced nodes can yield poor results. Oscillations may appear when using high degree polynomials. For functions of one variable, the most celebrated example has been provided by Carl Runge in 1901, who showed that higher degrees do not always improve interpolation accuracy. His example was then extended to multivariate calculus and in this work we show that it is meaningful, in an appropriate sense, also for Whitney edge elements, namely for differential 1-forms, as explained in [15].

6.8 MHD model applied to massive material injections

Participants: Ashish Bhole, Boniface Nkonga, José Costa, Guido Huijsmans, Stanislas Pamela, Matthias Hoelzl.

Massive material injection experiments in tokamaks consist of the injection of neutral gases (such as deuterium, neon, argon, etc.), also called impurities, into the tokamak plasma giving rise to complex gas-plasma interactions. The atomic reactions during the interactions produce charged ions at different ionization levels. Multi-fluid MHD equations are appropriate candidates for gas-plasma interactions, where each fluid is characterized by its ionization level. In recent work, under the assumption of coronal equilibrium, the single fluid impurity transport modeling is proposed for the gas-plasma interactions, which provided satisfactory results for MMI simulations with the reduced MHD models. We have used this single fluid modeling in the context of the single-temperature full MHD model to obtain significant results. To get to this point, we had to face three critical challenges. : First, the Galerkin FEMs give central approximations to the differential operators. Their use in the simulation of the convection-dominated flows may lead to dispersion errors yielding entirely wrong numerical solutions. Secondly, high-order, high-resolution numerical methods are known to produce high wave-number oscillations in the vicinity of shocks/discontinuities that in the numerical solution adversely affect the method's stability. Thirdly, the aligned helpful mesh in this context of high anisotropy had drawbacks at critical points of the magnetic field. Then, we propose a numerical treatment for the geometric singularity at the polar grid center. The result is a stabilized bi-cubic Hermite Bézier FEM in the computational framework of the nonlinear magnetohydrodynamics (MHD) code JOREK.

6.9 Treatment of grid singularities in the bi-cubic Hermite-Bézier approximations

Participants: A. Bhole, B. Nkonga, H. Guillard, M. Wu, B. Mourain.

JOREK uses high-order isoparametric bi-cubic Hemite-Bézier finite element method (FEM) to numerically approximate fusion plasma models. One of the distinguishing feature of JOREK's numerical method is the construction of multi-block, flux-aligned grids with curved elements. Such grids may contain geometrically singular points, such as polar grid center, where FEM is not well defined. These singular points may act as a source of numerical error polluting the numerical solution. We have proposed a numerical treatment for the geometric singularity at the polar grid center encountered in the application of the isoparametric bi-cubic Hemite Bézier FEM and implemented the treatment in JOREK. The treatment applies a set of new basis functions at the polar grid center in the numerical algorithm where the new basis functions are simply the linear transformations of the original basis functions. The proposed polar treatment enforces the C1 regularity in the physical space, preserves the order of the accuracy of the interpolation and improves the stability and accuracy of the numerical approximation near the polar grid center. The treatment is also applicable for the bi-cubic Hermite FEM.

6.10 Numerical methods for shear shallow water model

Participants: B. Nkonga, A. Bhole, C. Praveen, J. Iroume, A. Ngatcha, R. Onguéné, A. Djifendjou.

The shear shallow water model is a higher-order model for shallow flows, which includes some shear effects that are neglected in the classical shallow models. The model is a non-conservative hyperbolic system that can admit shocks, rarefactions, shear, and contact waves. For non-conservative hyperbolic systems, the notion of weak solutions are related to the path used to connect the states. We construct an exact solution for the Riemann problem assuming a linear path in the space of conserved variables. A similar approach gives approximate Riemann solvers. We compare the exact solutions with those obtained from a path-conservative finite volume scheme on some representative test cases. This work, carried out in collaboration with Indian colleagues, is leading to a Franco-Indian project proposal this year. This proposal CEFIPRA (Indo-French Centre for the Promotion of Advanced Research), developed during the visits to France and India, aims to continue the work by including the erosion, the transport of sediments, and the presence of complex obstacles by a strategy of immersed-boundaries.

Activities of the year were also organized around the three-month stays in Nice of Cameroonian students: Arno Ngatcha and Junior Iroumé. A. Ngatcha has a background in Applied Mathematics and is in the last year of his thesis with A. Djifendjou (Douala). J. Iroumé is a doctoral student of R. Onguene, in the last year of his thesis on geophysics and coastal hydrology, including acquiring topographic and rainfall data. Their three-month stay in Nice was from July 1st to September 30th, 2022. We have also requested additional funding from the Simons Foundation and used additional funding from à CNRS project. The visit was an opportunity to consolidate the bases of what can constitute research activity for the two students in the following decades after their graduation and within the Cameroun context. The objective was to develop through these two students the scientific basis for local solutions to flooding phenomena in the coastal city of Douala. A one-week stay at the CEMRACS summer school (October 7-13, 2022) allowed the students to create links with other Ph.D. students and researchers working in Europe on similar issues. In addition, J. Iroumé went to Toulouse from August 27th to September 1st, 2022, to participate in a topographic and bed-load granular measurements campaign. The data collected will be analyzed and used as a basis for the study and numerical simulation of sediment transport in rivers with high floods. The different achievements of this year would constitute chapters of theses of the two students. In addition, research reports are in preparation for publication.

6.11 Parameter identification for a MHD model

Participants: Alexandre Viera, Didier Auroux, Hervé Guillard, Florence Marcotte.

The goal of this study is to identify different parameters used in a reduced MHD model. We mainly focus in two directions. First, the identification of the fluid viscosity and magnetic resistivity. Secondly, the identification of an initial condition leading to a super-critical unstable equilibrium. In order to solve these problems, optimal control techniques will be used. This mainly uses two ingredients: the computation of the gradient of the cost functional, and algorithms to solve optimization problems. In this regard, we used the Tapenade software in order to differentiate a code implementing a reduced MHD model using Hsieh-Clough-Tocher finite elements. This approach let us compute the exact gradient of a cost functional with respect to the discretization scheme, and not an approximation computed through a discretization of the continuous adjoint equation. The computed gradient obtained is then used in an optimisation loop to minimize a cost functional measuring the distance between the computed and a target solution. Numerical experiments show that the optimization problem converge and allows to recover the value of the viscosity and resistivity corresponding to the target solution.

6.12 Nonlinear acoustic streaming in standing waves

Participants: Hervé Guillard.

Acoustic streaming is a secondary mean steady flow generated by and superimposed on a primary oscillatory flow. When a compressible fluid experiences a high-frequency oscillation (e.g. from a sound source) the nonlinear interactions can often lead to a pattern of time-dependent vortical flows or steady circulations in the flow field. A numerical investigation of the acoustic streaming motion (of the Rayleigh type) in a compressible gas inside two-dimensional rectangular enclosure has been realized last year and submitted for publication. This year, work on this subject has concentrated on the theoretical aspect of the problem and the search for a model to simulate these flows. Preliminary results have been presented at the conference : Essentially hyperbolic problems: unconventional numerics, and applications

6.13 Entropy Stability of two temperature MHD model

Participants: Hervé Guillard, Afeintou Sangam.

We have enriched the work [23] by the study of the entropy property of the model and the scheme proposed to solve it and have established the entropy dissipation of the model. Following [20], entropy preservation is proved while minimum principle preservation of the suggested scheme is under the investigation.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

Participants: Blaise Faugeras, Cédric Boulbe.

A contract has been signed with the English Tokamak UKAEA STEP for a license and a training session on the use of the code NICE.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

AMFoDUC

Title: Advanced Modeling of Flows in Douala City in the strong Urbanization and Climate

Duration: 2021 ->

Coordinator: Raphael Onguene (ziongra@yahoo.fr)

Partners:

- Université de Douala (Cameroun)

Inria contact: Boniface Nkonga

Summary: The project will bring together students (masters and PhDs) and experts from Cameroun and France to work towards developing simulation tools for the interaction of fluvial flows and coastal flows along the Gulf of Guinea and particularly the city of Douala. The project will require the development of new mathematical tools in the analysis of the SSW, which will also be beneficial to the team towards developing appropriate understanding of new methodologies specific to the context of Guinea Gulf. Currently, there is no other known project in this direction. We aim to further engage neighboring countries along the Gulf of Guinea towards developing a complete simulation tool and further training in geophysical modeling and simulation. In collaboration with our colleague of Bangalore (India/University Côte d'Azur collaboration), we have developed a numerical framework (platform) bringing together the components that are necessary for the deployment of new applications in the context of the SSW modeling. It takes full advantage of massively parallel computational and can serve as a practical engineering tool. These tools are quite flexible, developed in the Finite volume framework and can deal with structured as well as unstructured meshes. On the top of this basis, our objective is to develop additional modules that will take into account the specificities of coastal flows in the Gulf of Guinea and contribute to the Douala Sustainable City project. The collected data will help to design the appropriate scaling to be used in the derivation of simplified modeling to be include in the SSW framework. They will also gives some guidelines for strategies of numerical validations.

8.2 European initiatives

8.2.1 Horizon Europe

Cédric Boulbe and Blaise Faugeras participate to the Eurofusion Workpackage WPSA

Boniface Nkonga and Hervé Guillard participate to the EuroFusion workpackage 01 (Tokamak exploitation)TSVV

8.3 National initiatives

8.3.1 ANR Sistem

Participants: Didier Auroux, Jacques Blum, Cédric Boulbe, Blaise Faugeras, Francesca Rapetti-Gabellini.

Member of the ANR SISTEM , Oct. 2019 - Sept. 2023 coordinated by the M2P2 Institute of Aix-Marseille Univ. "SImulations with high-order schemes of tranSport and TurbulencE in tokaMak" programme Modeles numeriques 2019, Contact : Francesca Rapetti

8.3.2 ANR DYNSEED

Participants: Didier Auroux, Florence Marcotte, Paul Mannix.

"Graines minimales de dynamos célestes" May 2020-2022, PI : Florence Marcotte.

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

- Francesca Rapetti has been co-organizer of the Workshop 2225 (Oberwolfach) in June 2022 on Hilbert Complexes: Analysis, Applications, and Discretizations. See details on https://www.mfo.de/occasion/2225

- Francesca Rapetti has been co-organiser of the MS 4000/147 at the ECCOMAS 2022 conference (Oslo) in June 2022 on Optimal control and parameter estimation for plasmas. See details on https://www.eccomas2022.org/admin/Files/FileAbstract/MS147.pdf

- Florence Marcotte has co-organised the Rencontres Nicoises de Mécanique des Fluides at Laboratoire J.A. Dieudonné in June 2022. See details http://doeblin.unice.fr/spip.php?article194&lang=fr.

9.1.2 Journal

Member of the editorial boards

- Francesca Rapetti is member of the editorial board of the Advances in Computational Mathematics (ACOM) journal by Springer.
- Didier Auroux is member of the editorial board of ESAIM: Proceedings and Surveys.
- J.Blum is member of the editorial Board of the Journal of Scientific Computing JSC.
- Cédric Boulbe is managing editor of the journal SMAI Journal of Computational Mathematics.

9.1.3 Invited talks

- Francesca Rappeti:
  - ECCOMAS 2022, Oslo, 05-09/06/2022 (talk : On a generalization of the Lebesgue constant)
  - Colloquium UCA, 27/06/2022 (seminar: Basics on polynomial interpolation on simplices)
  - EDP seminar, UCA Nice, 13/10/2022 (seminar: Maxwell equations in a discrete framework
- Hervé Guillard: Low Mach number limits, Examples and counter-examples In Essentially hyperbolic problems: unconventional numerics, and applications October 9 - 14, 2022 - Monte Verità, Ascona
- Didier Auroux: Nudging and backward-forward approach for data assimilation, Workshop on Data Assimilation, July 11-15 2022, Imperial College, London.
- Jacques Blum: ITER: de la physique des plasmas à la modélisation mathématique, journée en l'honneur de Pierre Baras, Chambéry, octobre 2022
- Florence Marcotte : Isaac Newton Institute for Mathematical Sciences, University of Cambridge, Dynamos in planets and stars: similarities and differences, 14/09/2022 (Invited seminar); Festival de Théorie d'Aix-en-Provence, Chaos Control, Feedback and Model Reduction, 04/07/2022 (Invited seminar)

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- Ecole d'ingénieur, D. Auroux, Mathématiques financières, 66h équivalent TD, niveau M1, Université Côte d'Azur
- Ecole d'ingénieur, D. Auroux, Probabilités et statistiques, 24h équivalent TD, niveau L3, Université Côte d'Azur
- Licence : F. Rapetti, Cours Mathématiques 2,60h équivalent TD, L2, Université Côte d'Azur
- Licence : F. Rapetti, TD Mathématiques 2,12h équivalent TD, L2, Université Côte d'Azur
- Licence : F. Rapetti, TD Introduction au calcul scientifique, 24h équivalent TD, L2, Université Côte d'Azur
- Licence : F. Rapetti, TP Introduction au calcul scientifique, 40h équivalent TD, L2, Université Côte d'Azur
- Ecole d'ingénieur, C. Boulbe, Analyse Numérique 1, 45.5h équivalent TD, niveau L3, Université Côte d'Azur
- Ecole d'ingénieur, C. Boulbe, Analyse numérique 2, 45.5h équivalent TD, niveau L3, Université Côte d'Azur

- Ecole d'ingénieur, C. Boulbe, Algèbre linéaire et Matlab, 26h équivalent TD, Université Côte d'Azur
- Ecole d'ingénieur, C. Boulbe et D. Auroux, Projet 1, 48h équivalent TD, Université Côte d'Azur
- Licence : A. Sangam, Fondements Mathématiques 3, 24 h, Semestre 3 de la Licence, Université Côte d'Azur, France
- Licence : A. Sangam, Équations Différentielles 1, 32 h, Semestre 5 de la Licence, Université Côte d'Azur, France
- Licence : A. Sangam, Équations Différentielles 2, 33 h, Semestre 5 de la Licence, Université Côte d'Azur, France
- Licence : A. Sangam, Intégration et Théorie de la Meseure, 4 h, Semestre 5 de la Licence, Université Côte d'Azur, France
- Licence : A. Sangam, Introduction à l'Analyse Fonctionnelle, 9 h, Semestre 6 de la Licence, Université Côte d'Azur, France
- Master : A. Sangam, Analyse de Fourier et Distributions, 72 h, Semestre 1 des Masters Mathématiques Fondamentales/Mathématiques Pures et Appliquées, Université Côte d'Azur, France
- Master : A. Sangam, Optimisation et Éléments Finis, 18 h, Semestre 2 des Masters Mathématiques Fondamentales/Mathématiques Pures et Appliquées, et Ingénierie Mathématique, Université Côte d'Azur, France
- Ecole d'ingénieur/Master: B. Nkonga, Méthode des éléments finis, 24h, M2, Polytech Nice Sophia, Université Côte d'Azur
- Ecole d'ingénieur/Master: B. Nkonga, Eléments finis mixtes, 24h, M2, Polytech Nice Sophia, Université Côte d'Azur
- Ecole d'ingénieur/Master, H. Guillard, Développement durable et enjeux de gouvernance, 16h, M2, Polytech Nice Sophia, Université Côte d'Azur

9.2.2 Supervision

PhD in progress: Louid Lamerand, PhD student fully payed by the ANR project SISTEM, who is working with Didier Auroux and Francesca Rapetti on"data assimilation" and "model reduction": it consists in developing a simplified model for a physical phenomenon, here the heat transport in a tokamak, whose parameters are calibrated through either experimental measurements or accurate long-run computations with existing codes. With respect to the existing codes, the one based on the reduced model should provide an accurate and physically meaningful solution in a much shorter time, since October 2020.

PhD in progress: Guillaume Gros, PhD student payed by CNRS (Eurofusion) and Polytech Nice Sophia, is working with Blaise Faugeras and Cédric Boulbe on the developpement of a discharge numerical simulator in a Tokamak.

10 Scientific production

10.1 Major publications

[1] J. Blum, C. Boulbe and B. Faugeras. 'Reconstruction of the equilibrium of the plasma in a Tokamak and identification of the current density profile in real time'. In: *Journal of Computational Physics* 231 (2012), pp. 960–980. URL: https://hal.archives-ouvertes.fr/hal-00419608.

[2] D. A. Di Pietro, J. Droniou and F. Rapetti. 'Fully discrete polynomial de Rham sequences of arbitrary degree on polygons and polyhedra'. In: *Mathematical Models and Methods in Applied Sciences* (Aug. 2020). DOI: 10.1142/S0218202520500372. URL: https://hal.archives-ouvertes.fr/hal-02356810.

[3] S. Pamela, A. Bhole, G. Huijsmans, B. Nkonga, M. Hoelzl, I. Krebs and E. Strumberger. 'Extended full-MHD simulation of non-linear instabilities in tokamak plasmas'. In: *Physics of Plasmas* 27.10 (Oct. 2020), p. 102510. DOI: 10.1063/5.0018208. URL: https://hal.inria.fr/hal-02974031.

10.2 Publications of the year

International journals

[4] A. Alonso Rodríguez, L. Bruni Bruno and F. Rapetti. 'Towards nonuniform distributions of unisolvent weights for high-order Whitney edge elements'. In: *Calcolo* 59.37 (28th Sept. 2022). URL: https://hal.science/hal-03114568.

[5] D. Auroux, P. Ghendrih, L. Lamerand, F. Rapetti and E. Serre. 'Asymptotic behaviour, non-local dynamics and data assimilation tailoring of the reduced $\kappa - \varepsilon$ model to address turbulent transport of fusion plasmas'. In: *Physics of Plasma* (23rd Aug. 2022). URL: https://hal.archives-ouvertes.fr/hal-03811621.

[6] A. Bhole, B. Nkonga, S. Pamela, G. Huijsmans and M. Hoelzl. 'Treatment of polar grid singularities in the bi-cubic Hermite-Bézier approximations: isoparametric finite element framework'. In: *Journal of Computational Physics* (2022). DOI: 10.1016/j.jcp.2022.111611. URL: https://hal.archives-ouvertes.fr/hal-03781896.

[7] B. Faugeras, J. Blum and C. Boulbe. 'First equilibrium reconstruction for ITER with the code NICE'. In: *Journal of Instrumentation* 17.02 (25th Feb. 2022), p. C02024. DOI: 10.1088/1748-0221/17/02/c02024. URL: https://hal.archives-ouvertes.fr/hal-03590775.

[8] E. de Los Santos, A. M. Alonso Rodríguez and F. Rapetti. 'Construction of a spanning tree for high-order edge elements'. In: *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields* (28th Nov. 2022). URL: https://hal.archives-ouvertes.fr/hal-03426095.

[9] P. Mannix, Y. Ponty and F. Marcotte. 'Systematic Route to Subcritical Dynamo Branches'. In: *Physical Review Letters* 129.2 (July 2022), p. 024502. DOI: 10.1103/physrevlett.129.024502. URL: https://hal-cnrs.archives-ouvertes.fr/hal-03862091.

[10] B. Nkonga and P. Chandrashekar. 'An exact Solution for some Riemann Problems of the shear shallow water model'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 56.4 (2022), pp. 1115–1150. DOI: 10.1051/m2an/2022032. URL: https://hal.inria.fr/hal-03603315.

[11] F. Rapetti, A. A. Rodríguez and E. de Los Santos. 'On the tree gauge in magnetostatics'. In: *Physics* 5.1 (13th Jan. 2022), pp. 52–63. DOI: 10.3390/j5010004. URL: https://hal.archives-ouvertes.fr/hal-03426096.

[12] M. Wu, X. Wang, B. Nkonga, B. Mourrain, G. Xu, Q. Ni and Y. Liu. 'Flux-aligned quad mesh generation in magnetohydrodynamic simulation'. In: *Journal of Computational Physics* 466 (Oct. 2022), p. 111393. DOI: 10.1016/j.jcp.2022.111393. URL: https://hal.archives-ouvertes.fr/hal-03714937.

[13] M. Yoshida, G. Giruzzi, N. Aiba, J. Artaud, J. Ayllon-Guerola, L. Balbinot, O. Beeke, E. Belonohy, P. Bettini, W. Bin et al. 'Plasma physics and control studies planned in JT-60SA for ITER and DEMO operations and risk mitigation'. In: *Plasma Physics and Controlled Fusion* 64.5 (22nd Mar. 2022), p. 054004. DOI: 10.1088/1361-6587/ac57a0. URL: https://hal.archives-ouvertes.fr/hal-03650684.

International peer-reviewed conferences

[14] A. R. Ngatcha Ndengna, B. Nkonga, A. Njifenjou and R. Onguene. 'Sediment transport models in Generalized shear shallow water flow equations'. In: CARI 2022 - Colloque Africain sur la Recherche en Informatique et en Mathématiques Appliquées. Dschang, Cameroon, 2022. URL: https://hal.inria.fr/hal-03735893.

Reports & preprints

[15] A. Alonso Rodríguez, L. Bruni Bruno and F. Rapetti. *Whitney edge elements and the Runge phenomenon.* 10th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03893138.

[16] A. Bhole, H. Guillard, B. Nkonga and F. Rapetti. *Coupling finite elements of class C1 on composite curved meshes for second order elliptic problems.* 26th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03913143.

[17] A. Bhole, B. Nkonga, J. Costa, G. Huijsmans, S. Pamela and M. Hoelzl. *Stabilized bi-cubic Hermite Bézier finite element method with application to Gas-plasma interactions occurring during massive material injection in Tokamaks.* 11th Oct. 2022. URL: https://hal.archives-ouvertes.fr/hal-03811224.

[18] C. Boulbe, B. Faugeras and F. Rapetti. *Tokamak free-boundary plasma equilibrium computations in presence of non-linear materials.* 5th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03423469.

[19] E. Zampa, A. Alonso Rodríguez and F. Rapetti. *Using the FES framework to derive new physical degrees of freedom for finite element spaces of differential forms.* 5th Dec. 2022. URL: https://hal.archives-ouvertes.fr/hal-03884149.

10.3 Cited publications

[20] C. Berthon, B. Dubroca and A. Sangam. 'An entropy preserving relaxation scheme for ten-moments equations with source terms'. In: *Communications in Mathematical Sciences.* Communications in Mathematical Sciences 13.8 (2015), pp. 2119–2154. DOI: 10.4310/CMS.2015.v13.n8.a7. URL: https://hal.inria.fr/hal-01255069.

[21] H. Heumann. 'A Galerkin method for the weak formulation of current diffusion and force balance in tokamak plasmas'. In: *J. Comput. Phys.* 442 (2021), p. 110483. DOI: 10.1016/j.jcp.2021.110483. URL: https://doi.org/10.1016/j.jcp.2021.110483.

[22] M. Hoelzl, G. Huijsmans, S. Pamela, M. Becoulet, E. Nardon, F. Artola, B. Nkonga, C. Atanasiu, V. Bandaru, A. Bhole et al. *The JOREK non-linear extended MHD code and applications to large-scale instabilities and their control in magnetically confined fusion plasmas.* 2020. arXiv: 2011.09120 [physics.plasm-ph].

[23] A. Sangam, É. Estibals and H. Guillard. 'Derivation and numerical approximation of two-temperature Euler plasma model'. In: *Journal of Computational Physics* 444 (Nov. 2021), p. 48. DOI: 10.1016/j.jcp.2021.110565. URL: https://hal.inria.fr/hal-03543365.