RESEARCH CENTRE

**Inria Centre at Université Côte d'Azur**

**IN PARTNERSHIP WITH:**

**Université Côte d'Azur, CNRS**

2024

ACTIVITY REPORT

Project-Team

# CASTOR

## Control for plAsma inSTability, Optimization and model Reduction

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

**DOMAIN**

**Digital Health, Biology and Earth**

**THEME**

**Earth, Environmental and Energy Sciences**

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# Project-Team CASTOR

*Creation of the Project-Team: 2024 December 01*


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B4. – Energy

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# 1 Team members, visitors, external collaborators

## Research Scientists

- Hervé Guillard [Team leader, INRIA, Senior Researcher, until Oct 2024]
- Blaise Faugeras [CNRS, Researcher]
- Hervé Guillard [INRIA, from Nov 2024, Emeritus]
- Florence Marcotte [INRIA, Researcher]

## Faculty Members

- Francesca Rapetti-Gabellini [Team leader, UNIV COTE D'AZUR, Professor, from Nov 2024]
- Didier Auroux [UNIV COTE D'AZUR, Professor]
- Jacques Blum [UNIV COTE D'AZUR, Emeritus]
- Cédric Boulbe [UNIV COTE D'AZUR, Associate Professor]
- Boniface Nkonga [UNIV COTE D'AZUR, Professor]
- Francesca Rapetti-Gabellini [UNIV COTE D'AZUR, Professor, until Oct 2024]
- Afeintou Sangam [UNIV COTE D'AZUR, Associate Professor]

## Post-Doctoral Fellows

- Alexandre Vieira [INRIA, Post-Doctoral Fellow, from Apr 2024 until Sep 2024]
- Alexandre Vieira [UNIV COTE D'AZUR, Post-Doctoral Fellow, until Mar 2024]

## PhD Students

- Guillaume Gros [UNIV COTE D'AZUR]
- Louis Lamerand [UNS, ATER, until Aug 2024]
- Clément Mariot [INRIA, from Oct 2024]

## Interns and Apprentices

- Anais Antonini [INRIA, Intern, from May 2024 until Jul 2024]
- Toi Takouda [INRIA, Intern, from Jul 2024 until Oct 2024]

## Administrative Assistant

- Nathalie Nordmann [INRIA]

# 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 (International Thermonuclear Experimental Reactor) 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.

Another research axis, focused on astrophysical plasma, has also been developed within the team Castor over the past year. While smaller in terms of human resources, this new axis is also complementary to the research axis focused on tokamak plasma, and both share several common features: in both cases, the team specializes in the simulation of physical processes that couple flows and magnetic fields, and more specifically processes that can be described using the magneto-hydro-dynamic (MHD) equations, compressible or not. In both cases, a common objective is to investigate the conditions that trigger MHD instabilities in the considered systems, whether to prevent them (as with tokamak, where the stakes are operational) or to understand the evolution of astrophysical flows (as with stellar plasma, where the stakes are observational). And in both cases, such investigations require extensive use of numerical optimization methods and raise the need for model reduction techniques that are well-suited for MHD systems. Disclosing the main mechanisms involved in transitional and turbulent flows is a common goal of plasma in tokamaks and stars. The central idea is to use optimization techniques to identify the spatial structure of perturbations that kickstart nonlinear transitions in the flow. The aim is thus to identify initial, possibly localized flow structures or events that most easily bring the flow on the verge of turbulent transition.

CASTOR gathers the activities in numerical simulation of fusion plasmas with the activities in control and optimization 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 optimization of scenarios of plasma discharges in tokamaks.

CASTOR is a common project team between the Inria Center at Université Côte d'Azur and the J.A. Dieudonné laboratory (LJAD), UMR CNRS 7351 of Université Côte d'Azur. Researchers from Inria and from the two teams in the LJAD (namely "Numerical Modelling & Fluids Dynamics" , "PDE & Numerical Analysis"), join the forces to analyze and solve (even with HPC approaches) real applications involving magnetized plasma, possibly in collaboration with reseachers from other laboratories.

# 3 Research program

## 3.1 Plasma Physics

The main reseach topics are:

1. Modeling 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
   - Dynamo effects in plasmas

# 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 (Magneto-Hydro-Dynamics) 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 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, ELMs occur in the edge plasma and their modeling requires to take in account not only the intricate magnetic topology of this region where both open and closed field lines co-exist 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-UniCA and Inria. A comprehensive description of JOREK is given in [17]

### 4.2 MHD flows for liquid metal blankets

**Participants:** Herve Guillard, Boniface Nkonga, Stephane Abide, Praveel Chandrashekara.

Understanding of the physics and control of thermonuclear fusion reactions has progressed in recent decades, with several fusion reactors operated experimentally worldwide. Most explored configurations use a confinement system fueled by a Deuterium-Tricium (DT) plasma mixture. Magnetic confinement is the most advanced strategy for harnessing fusion energy for electrical power production. In this context, a strong magnetic field confined the DT plasma. Plasma activity is subject to instabilities (i.e., edge-localize modes and disruptions) that release significant flows of electrons, neutrons, alpha particles, and heat (thermal and radiative) outwards from the plasma confinement. A nuclear blanket protects the superconducting coils from the adverse effects of plasma activity and interfacing with several other components essential to the machine's operation.

Liquid metal blanket face-to-plasma components offer an alternative to the most demanding protection challenges. They could withstand heat fluxes without permanent damage and open the door to entirely new magnetic fusion operating regimes. Liquid lithium surfaces are an innovation that could fulfill the promise of fusion power in electricity generation.

We are interested in the numerical modeling of liquid metal flowing as part of the blanket protection. This thin layer of metal flow is a promising alternative to protect against possible melting damages that Disruptions and MHD instabilities can cause in fusion devices. The liquid metal blanket will operate according to the principles of magnetohydrodynamics (MHD), which are the same principles that produce the Dynamo effect.

The 2024 work focuses on modeling aspects and numerical challenges associated with the dynamic of a thin layer of metal flow under a strong magnetic field. This work is sufficiently mature to involve a PhD student in collaboration with IRFM/CEA in the coming years.

### 4.3 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.

### 4.4 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.

## 4.5 High order accuracy methods

**Participants:** Blaise Faugeras, Herve Guillard, Boniface Nkonga, Francesca Rapetti.

We analyze the accuracy and robustness of C1 Finite Element (FE) for plasma equilibrium computations in presence of strongly anisotropic phenomena. Aligned Hermite Bezier (HB) FEs and non-aligned reduced Hiesh-Clough-Tocher (rHCT) FEs are coupled by the mortar element method for composite meshes.

**Participants:** Herve Guillard, Boniface Nkonga.

The Bezier approximation is now well-established in CAD (Computer Aided Design). Conversely, the Hermite finite element produces a higher continuity approximation space. By combining these two strategies, we will derive a Hermite-Bezier approximation that will help to capture smooth geometries with few finite elements, accurately represent anisotropies arising in plasma physics.

Furthermore, cubic Hermite and other high-order solution spaces have convergence advantages in finite element simulations compared with linear solution spaces and give rise to continuous properties between elements. A proper mapping between the local and global finite element spaces ensures the continuity of field solutions in these finite element problems. By the 2024 investigations, we provide the main steps of this construction in the context of a given parametric curve. The proposed work also opens the door for fully 3D finite element formulations for tokamaks and stelerator devices.

**Participants:** Ana Alonso Rodriguez, Francesca Rapetti.

We study Nédélec FEs of the first and second family for high order approximations in H(curl) and H(div). We have developed a geometric approach for constructing physical degrees of freedom for sequences of finite element spaces of Nédélec type (first and second families). In the last works, we have shown that high order polynomial interpolation with Nédélec edge elements can suffer from a Runge phenomenon similar to that well known for high order polynomial interpolation with Lagrange nodal elements.

## 4.6 Understanding magnetogenesis in stellar systems

**Participants:** Didier Auroux, 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 optimization 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

On the one hand, the 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.

On the other hand, with the study of astrophysical plasmas and the understanding of instabilities, it could be possible to place additional constraints on the structure of the optimized disturbance that can be exploited for experimental purposes to design a way of kickstarting self-excited dynamos at sustainable energy cost in the laboratory.

# 6 New software, platforms, open data

## 6.1 New software

### 6.1.1 CEDRES++

**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.

**Contact:** Cédric Boulbe

**Participants:** Blaise Faugeras, Cédric Boulbe, Holger Heumann, Jacques Blum

### 6.1.2 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.

**Contact:** Blaise Faugeras

**Participants:** Blaise Faugeras, Cédric Boulbe, Jacques Blum

#### 6.1.3 FBGKI

**Name:** 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

#### 6.1.4 FEEQS.M

**Name:** 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)

**URL:** https://scm.gforge.inria.fr/svn/holgerheumann/Matlab/FEEQS.M

**Contact:** Holger Heumann

**Participant:** Holger Heumann

#### 6.1.5 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.

**Contact:** Boniface Nkonga

**Participants:** Boniface Nkonga, Mario Ricchiuto, Michael Papin, Remi Abgrall

#### 6.1.6 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 Contributions:** 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, ...).

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

**Contact:** Hervé Guillard

**Participants:** Ahmed Ratnani, Boniface Nkonga, Emmanuel Franck, Hervé Guillard

#### 6.1.7 Plato

**Name:** 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.

**Contact:** Hervé Guillard

**Participants:** Afeintou Sangam, Boniface Nkonga, Elise Estibals, Giorgio Giorgiani, Hervé Guillard

#### 6.1.8 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

#### 6.1.9 NICE

**Name:** 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

#### 6.1.10 CTFEM

**Keyword:** Finite element modelling

**Functional Description:** ctfem is a set of module to solve PDE with C1 finite element methods. Its main application area is reduced MHD systems as used for the modeling of fusion plasmas in tokamaks. In these models, fourth order appear and thus pure Galerkin approximations require the use of C1 finite element methods. At present, ctfem uses the Clough-Tocher family of finite element and has been used to solve the Grad-Shafranov, incompressible Navier-Stokes and reduced MHD equations.

**Contact:** Hervé Guillard

**Participants:** Ali Aboudou Elarif, Hervé Guillard, Boniface Nkonga

# 7 New results

## 7.1 Numerical simulation of Tokamak plasma equilibrium evolution

**Participants:** Blaise Faugeras, Cédric Boulbe, Guillaume Gros, Francesca Rapetti-Gabellini.

This contribution focuses on the numerical methods recently developed in order to simulate the time evolution of a Tokamak plasma equilibrium at the resistive diffusion time scale. We develop on the method proposed by Heumann for the coupling of magnetic equilibrium and current diffusion. We introduce a new space discretization for the poloidal flux using C0 and C1 finite elements. This, together with the use of spline functions to represent the diamagnetic function in the resistive diffusion equation, enables to restrain numerical oscillations which can occur with the original method. We add to the model an evolution equation for electron temperature in the plasma. This enables us to compute consistently the plasma resistivity and the non-inductive current terms called bootstrap current needed in the resistive diffusion equation. It also enables us to evolve the pressure term in the simulation. These numerical methods are implemented in the plasma equilibrium code NICE. The code is coupled with a magnetic feedback controller through the MUSCLE3 library. This enables to simulate a prescribed plasma scenario. The results in [14] for an X-point formation scenario in the WEST tokamak are presented as a first illustration of the efficiency of the developed numerical methods.

## 7.2 Magnetic control of WEST plasmas through deep reinforcement learning

**Participants:** Samy Kerboua-Benlarbi, Remy Nouailletas, Blaise Faugeras, Eric Nardon *(IRFM,CEA)*, Philippe Moreau *(IRFM,CEA)*.

Tokamaks require magnetic control across a wide range of plasma scenarios. The coupled behavior of plasma dynamics makes deep learning a suitable candidate for efficient control in order to fulfil these high-dimensional and non-linear situations. For example, on the TCV tokamak, deep reinforcement learning has already been used for tracking of the plasma's magnetic equilibrium [3]. In this work, we apply such methods to the WEST tokamak, to address control of the plasma's shape, position, and current, in several relevant configurations. To this end, we developed a distributed framework to train an actor-critic agent on a C++ free boundary equilibrium code called NICE, in which resistive diffusion allows a more representative evolution of current profile throughout the simulation. The interface between components was done through UDS protocols for fast, asynchronous and reliable communication. The implemented tool handles feedback control of quantities of interest, with results showing flexibility of the method regarding the use of different training environments [11].

### 7.3 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 requires 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 k-epsilon model based on the turbulent kinetic energy k and its dissipation rate $\epsilon$ [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 $k$ and $\epsilon$ estimated from two additional transport equations allow to introduce some non-locality in the transport model. This is illustrated in [5] 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 minimization 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. New results on more reliable cases are presented in [6] and in [15].

### 7.4 Anisotropic diffusion

**Participants:** Blaise Faugeras, Hervé Guillard, Boniface Nkonga, Francesca Rapetti-Gabellini.

Heat transfer in magnetically confined plasmas is characterized by extremely high anisotropic diffusion phenomena. At the core of a magnetized plasma, the heat conductivity coefficients in the parallel and perpendicular directions of the induction field can be very different. Their ratio can exceed 1.e8 and the pollution by purely numerical errors can make very diffcult the simulation of the heat transport in the perpendicular direction. Standard numerical methods, generally used in the discretization of classical diffusion problems, are rather inefficient. The present paper analyzes a finite element approach for the solution of a highly anisotropic diffusion equation. Two families of finite elements of class C1, namely bi-cubic Hermite-Bézier and reduced cubic Hsieh-Clough-Tocher finite elements, are compared. Their performances are tested numerically, for various ratios of the diffusion coefficients, on different mesh configurations, even aligned with the induction field. The time stepping is realized by an implicit high-order Gear finite difference scheme. An example of reduced model is also provided in order to comment on some obtained results (see [13]).

### 7.5 High-order Whitney finite elements in electromagnetics modeling

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

A method classically used in the lower polynomial degree for the construction of a finite element basis of the space of divergence-free functions is extended in [12] to any polynomial degree for a bounded domain without topological restrictions. The method uses graphs associated with two differential operators: the gradient and the divergence, and selects the basis using a spanning tree of the first graph. It can be applied for the two main families of degrees of freedom, weights and moments, used to express finite element differential forms. See also [1].

### 7.6 MHD model applied to massive material injections

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

Massive material injection (MMI) experiments in tokamaks aim to inject 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 a recent work, under the assumption of coronal equilibrium, single fluid impurity transport modeling was 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 single-temperature full MHD model context 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. Second, high-order, high-resolution numerical methods produce high wave-number oscillations near shocks/discontinuities that adversely affect the numerical stability. Third, 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 associated with a SUPG-like numerical stabilization. The stabilization strategy aims to identify the contributions of the modeling that need smoothing and apply it locally in space according to fitting criteria. The result is a stabilized bi-cubic Hermite Bézier FEM in the computational framework of the nonlinear magnetohydrodynamics (MHD) code JOREK [7].

A collisional-radiative treatment for impurities using coronal equilibrium assumption was implemented, benchmarked, and applied to validate simulations of shattered pellet injection (SPI) in the JET tokamak. Deuterium and impurity/mixed SPI simulations for the JET tokamak reproduce critical experimental observations, e.g., regarding radiation, showing that plasmoid drifts play an essential role in material assimilation, radiation dynamics, and plasma evolution. SPI simulations for the AUG tokamak are ongoing and successively improved towards entirely realistic plasma parameters; they qualitatively reproduce experimentally observed double radiation peaks, suggesting that the first peak originates from the injection location and the second peak from the core. Numerical stabilization, axis singularity treatment, and shock-capturing methods are essential ingredients that allow the carrying out of highly nonlinear mitigated disruption studies with the full MHD and reduced-MHD models, which were previously impossible (with Jorek) [2].

### 7.7 Treatment of grid singularities in the Hermite-Bézier approximations

**Participants:** Ashish Bhole, Boniface Nkonga, Hervé Guillard, Meng Wu, Bernard Mourain.

JOREK uses high-order isoparametric bi-cubic Hermite-Bézier finite element method (FEM) to numerically approximate fusion plasma models. One 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 the polar grid center, where FEM is not well defined. These particular points may act as a source of numerical error, polluting the numerical solution. We have already proposed a numerical treatment for the geometric singularity at the polar grid center encountered in the application of the isoparametric bi-cubic Hermite 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 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 [4].

This year's studies go beyond the cases investigated in the past years and suggest a way to enforce regularity when using meshes containing singular points to interpolate smooth functions. The working context also extends the field of study to higher-order approximations by including bi-quintics interpolations. In practice, we use the fact that the meshing vectors differ for each neighbor element of a singular vertex. Therefore, the meshing vectors will now also contain the element's index. Consequently, the degrees of freedom can also differ for each neighbor element. Nevertheless, the physical state and gradient are shared to enforce the C1-regularity of the interpolations. For the C2-regularity, we also share the Hermitian matrix. This formal description, mathematically consistent, when included inside the Jorek platform, will further improve its use in practical and challenging simulations.

## 7.8 Numerical methods for shear shallow water model

**Participants:** Boniface Nkonga, Ashish Bhole, Praveen Chandrashekar *(TIFR, Bangalore)*, Arno Bhure *(TIFR, Bangalore)*.

A few years ago, we proposed a complete study of the Riemann problem for a genuinely non-conservative hyperbolic system derived from modeling reasonably turbulent thin flows. This model coincides with the ten-moment model derived from gas kinetics in the presence of a gravitational potential. Although the model is fundamentally non-conservative, the generalized jump conditions are compatible with the conservation of total energy. Consequently, the generalized jump conditions consistent with energy conservation are also independent of the path chosen. In this context, we show that the exact solution of the Riemann problem exists and is unique, except in the case of vacuum. This Riemann solver can work well within the numerical framework of Glim and Godunov but at a prohibitive computational cost. We also propose approximate solvers with two, three, or five waves of discontinuities: HLL, HLLC3, and HLLC5. These different solvers are compatible with the conservation of total energy. However, the averaging strategy included in each finite volume approach violates this fundamental conservation law. The main reason for this is that the square of an average quantity is generally not equal to averaging the square of the same amount. Moreover, some fundamental structures of the model also need to be preserved. For example, 1D solutions split into two sub-systems with a one-way coupling between a conservative and a non-conservative sub-systems.

This year's efforts on this subject have focused on strengthening the total energy conservation and the structure-preserving properties at the numerical level to ensure the numerical method converges to the exact solution of the Riemann problem. At least two such strategies have been published in recent years. One explicitly discretizes the conservation equation and uses it to adjust the numerical dissipation of non-conservative variables properly. However, this strategy takes advantage of the direction splitting and does not apply to unstructured meshes. The other approach uses a variable that ensures the symmetry of the stress tensor at the discrete level. It constructs the numerical dissipation coefficient in such a way as to verify the conservation of energy at the discrete level. We are developing a third approach applicable to unstructured meshes that can incorporate multi-wave Riemann solvers. This year, we have some encouraging preliminary results [9], but we still need to find an optimal solution to this challenging problem.

## 7.9 Sediment transport in the shear shallow water framework.

**Participants:** Boniface Nkonga, Ashish Bhole, Praveen Chandrashekar *(TIFR, Bangalore)*, Arno Roland Ndengna Ngatcha, Raphael Onguéné, Abdou Njifenjou.

gatcha, Ndengna Arno Roland, Nkonga, Boniface., Njifenjou, Abdou., Onguene, Raphael., Several shallow water (SW) based sediment transport models have come into the literature over the last decades. These classical averaged sediment transport models (STM) based on shallow water equations describe the hydromorphodynamic process, assuming that there is no shear velocity along the vertical direction. Mainly, these models do not feel the phase shift between the flow and the bed sediment's movement. The dynamic properties of the coastal flows for tropical rivers of interest are far from the SW assumptions. Our short- and medium-term objective is to revise sediment transport models to include the indispensable shear effects.

The classical models often combined the Exner strategy with the Grass approximations in the framework of the shallow water averaging. This year's work focuses on deriving suitable formulations for Shear Shallow Water (SSW) regimes. The derived model includes the distortion (fluctuation with great correlation lengths) that creates the turbulence. We consider the shift between fluid and sediment velocity (phase-lag) near the bed. The proposed theory significantly reduces the modeling errors observed in several sediment transport models based on nonhomogeneous shallow water equations. It has excellent potential to increase the predictive power of sediment transport models in rivers, lakes, coastal flows, and ocean basins. The proposed theory [16] improves several existing sediment transport theories recently developed in the literature, and we now have some confidence for future applications.

### 7.10 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. Firstly, 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 lets 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 optimization loop to minimize a cost functional measuring the distance between the computed and a target solution. Numerical experiments show that the optimization problem converges and allows to recover the value of the viscosity and resistivity corresponding to the target solution.

### 7.11 A robust, discrete-gradient procedure for optimisation with time-dependent PDE and norm constraints

**Participants:** Didier Auroux, Paul Mannix, Florence Marcotte, Calum Skene *(University of Leeds, UK)*.

Many physical questions in fluid dynamics can be recast in terms of norm-constrained optimization problems; which in-turn, can be further recast as unconstrained problems on spherical manifolds. Due to the nonlinearities of the governing PDEs, and the computational cost of performing optimal control on such systems, improving the numerical convergence of the optimization procedure is crucial. Borrowing tools from the optimization on manifolds community we outline a numerically consistent, discrete formulation of the direct-adjoint looping method accompanied by gradient descent and line-search algorithms with global convergence guarantees. We numerically demonstrate the robustness of this formulation on three example problems of relevance in fluid dynamics and provide an accompanying library SphereManOpt [18].

### 7.12 Tayler-Spruit dynamos in simulated radiative stellar layers

**Participants:** Florence Marcotte, Ludovic Petitdemange *(Observatoire de Paris)*, Christophe Gissinger *(Ecole Normale Supérieure)*, Florentin Daniel *(Ecole Normale Supérieure)*.

The Tayler-Spruit dynamo mechanism has been proposed two decades ago as a plausible mechanism to transport angular momentum in radiative stellar layers. Direct numerical simulations are still needed to understand its trigger conditions and the saturation mechanisms. The present study follows up on a previous paper by the same team [8], where we reported the first numerical simulations of a Tayler-Spruit dynamo cycle. Here we extend the explored parameter space to assess in particular the influence of stratification on the dynamo solutions. We also present numerical verification of theoretical assumptions made in (Spruit 2002), which are instrumental in deriving the classical prescription for angular momentum transport implemented in stellar evolution codes. A simplified radiative layer is modeled numerically by considering the dynamics of a stably-stratified, differentially rotating, magnetized fluid in a spherical shell. Our simulations display a diversity of magnetic field topologies and amplitudes depending on the flow parameters, including hemispherical solutions. The Tayler-Spruit dynamos reported here are found to satisfy magnetostrophic equilibrium and achieve efficient turbulent transport of angular momentum, following Spruit's heuristic prediction [19].

### 7.13 On nonlinear transitions, minimal seeds and exact solutions for the geodynamo

**Participants:** Florence Marcotte, Calum Skene *(University of Leeds, UK)*, Steven Tobias *(University of Leeds, UK)*.

Nearly fifty years ago, it was postulated that Earth's magnetic field, which is generated by turbulent motions of liquid metal in its outer core, likely results from a subcritical dynamo instability characterized by a dominant balance between Coriolis, pressure and Lorentz forces. Here we numerically explore the generation of subcritical geomagnetic fields using techniques from optimal control and dynamical systems theory to uncover the nonlinear dynamical landscape underlying dynamo action. Through nonlinear optimization, via direct-adjoint looping, we identify the minimal seed — the smallest magnetic field that attracts to a nonlinear dynamo solution. Additionally, using the Newton-hookstep algorithm, we converge stable and unstable travelling wave solutions to the governing equations. By combining these two techniques, complex nonlinear pathways between attracting states are revealed, providing insight into a potential subcritical origin of the geodynamo. This paper showcases these methods on the widely studied benchmark of Christensen et al. (2001), laying the foundations for future studies in more extreme and realistic parameter regimes. We show that the minimal seed reaches a nonlinear dynamo solution by first attracting to an unstable travelling wave solution, which acts as an edge state separating a hydrodynamic solution from a magnetohydrodynamic one. Furthermore, by carefully examining the choice of cost functional, we establish a robust optimization procedure that can systematically locate dynamo solutions on short time horizons with no prior knowledge of its structure [20].

## 8 Bilateral contracts and grants with industry

### 8.1 ITER

**Participants:** Blaise Faugeras, Cédric Boulbe.

An 18 month contract starting on August 2024 has been signed between ITER and a consortium IgnitionComputing-CEA-Université Côte d'Azur for the development of a PDS (Plasma Discharge Simulator) involving the code NICE.

### 8.2 France-Relance

**Participants:** Boniface Nkonga, Jeaniffer Vides.

As part of the Plan France Relance: financing agreement no. ANR-21-PRRD-0005-01 was signed between Agence Nationale de la Recherche (ANR) and Inria 15/06/2021. Then follows an associated contract between Inria, UCA, and CNRS on the one hand and the LEMMA company on the other. (287 K€). The goal was to explore new adaptive sliding methods for rotating machines. At the same time, the Establishments, the Company, and Ms. Jeaniffer VIDES HIGUEROS entered into, on 25/08/2022, an agreement for the provision of Ms. Jeaniffer VIDES HIGUEROS, an employee of the Company, to the CASTOR project team for 24 months

## 9 Partnerships and cooperations

### 9.1 European initiatives

#### 9.1.1 Horizon Europe

CIRCE project on cordis.europa.eu

**Title:** Control of Instabilities in Rotating flows Conducting Electricity: dynamo seeds and subcritical transition to MHD turbulence in stellar objects.

**Duration:** From January 1, 2024 to December 31, 2028

**Partners:**

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France

**Inria contact:** Florence Marcotte

**Coordinator:** Florence Marcotte

**Summary:** Modeling magnetic field generation by dynamo instability in stellar objects is a long-standing challenge with far-reaching implications for stellar evolution theory. Underlying motivations are exemplified by the need to understand stellar spin-down and accretion rates in protostellar discs, which are known to be dynamically impacted by magnetic fields. The interest sparked by recurring discrepancies between predictive evolution models and rapidly-progressing observations drives the current research into the characterization of dynamo mechanisms in stellar objects.

This important challenge cannot be solved analytically due to the strong nonlinearities of the magnetohydrodynamics (MHD) equations. Solving it therefore requires the development of innovative numerical approaches. In many astrophysical flows, infinitesimal magnetic seeds cannot be amplified by the flow, whereas finite-amplitude magnetic seeds with a favorable spatial structure can drive, through the Lorentz force nonlinear feedback, the very flow motions on which they subsequently feed by subcritical dynamo instability. This situation is particularly relevant for radiative stellar layers or for the innermost regions of protostellar discs, where the history of perturbations can thus define the magnetic fate of the object. Yet, classical stability methods fail to systematically characterize subcritical dynamo solutions and identify their critical dynamo seeds. The CIRCE project will tackle this theoretical obstacle by developing the recent mathematical tools of nonlinear stability analysis, based on adjoint-based optimal control, for MHD flows. The aim of CIRCE is to identify the least-energy perturbations that can trigger subcritical dynamos and transition to MHD turbulence in models of (a) radiative zones and (b) protostellar discs, and to predict how the resulting transitions determine rotational dynamics and accretion rates.

## 9.2 National initiatives

### 9.2.1 ANR Sistem

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

Member of the ANR SISTEM , Oct. 2019 - Feb. 2024 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-Gabellini

### 9.2.2 ANR HIPOTHEC

**Participants:** Francesca Rapetti-Gabellini.

Member of the ANR HIPOTHEC , Jan. 2024 - Sept. 2028 coordinated by the Inria Lille "HIgh-order POlyhedral meTHods for Eddy Current testing simulations" programme Modeles numeriques 2023, Contact : Francesca Rapetti-Gabellini

# 10 Dissemination

## 10.1 Promoting scientific activities

### 10.1.1 Scientific events: organisation

**Member of the organizing committees :**

Boniface Nkonga

- Responsible for the treasure and member of the Executive committee of Eccomas
- Member of the Managing Board and Scientific Council of FR-FCM

### 10.1.2 Journal

**Member of the editorial boards :**

Francesca Rapetti-Gabellini

- Advances in Computational Mathematics (Springer)
- SIAM J. Numerical Analysis (SIAM)

## 10.2 Research administration

Didier Auroux

- Responsible of the MSI at UniCA

Cedric Boulbe

- Director of the departement MAM (Mathématiques Appliquées et Modélisation) - Polytech Nice Sophia

Florence Marcotte

- Member of the scientific committee of the MSI at UniCA

## 10.3 Teaching - Supervision - Juries

### 10.3.1 Teaching responsibilities

Afeintou Sangam

- Coordinator of the “Double Licence Maths-Info”, at UniCA

- Cedric Boulbe
  - Coordinator of the third year and of year 5 of the INUM (Ingénierie Numérique) option of the Applied Math and modelization department.
  - Responsible of the “mineur” INUM of the master 2 "Ingénierie Mathématiques".

### 10.3.2 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, 70h, L2, Université Côte d’Azur
- Licence: F. Rapetti, Tp Analyse numérique, 10h, L2, Université Côte d’Azur
- Licence: F. Rapetti, TP Introduction au calcul scientifique, 12h, L3, 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, Approfondissements Mathématiques 1, 48 h, Semestre 1 de la Licence, Université Côte d’Azur, France
- Licence : A. Sangam, Fondements Mathématiques 2, 16 h, Semestre 2 de la Licence, Université Côte d’Azur, France
- Licence : A. Sangam, Fondements Mathématiques 3, 26 h, Semestre 3 de la Licence, Université Côte d’Azur, France

- Master : A. Sangam, Analyse de Fourier et Distributions, 36 h, Semestre 2 des Masters Mathématiques Fondamentales/Mathématiques Pures et Appliquées, Université Côte d'Azur, France
- Master : A. Sangam, Optimisation et Éléments Finis, 23 h, Semestre 2 des Masters Mathématiques Fondamentales/Mathématiques Pures et Appliquées, et Ingénierie Mathématique, Université Côte d'Azur, France
- Master : A. Sangam, Numerical Approximation of Hyperbolic Systems of Conservation Laws, 40 h, Semestre 3 du Master Mathématiques Pures et Appliquées, Université Côte d'Azur, France
- Master : A. Sangam, Stage, 5 h, Semestre 4 du Master Mathématiques Pures et Appliquées, 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

#### 10.3.3 Supervision

**PhD students**

**Louis Lamérand**, Oct 2020 - Dec 2024

'Data assimilation for the reduction and the calibration of turbulent transport models for magnetic confinement fusion'

**Guillaume Gros**, October 2022 - October 2025

'Numerical simulation of Tokamak plasma equilibrium evolution'

**Samy Kerboua-Benlarbi**, October 2021 - October 2024

'Intelligence artificielle et contrôle des plasmas de fusion: Application au tokamak WEST'

**Clément Mariot**, October 2024 - October 2027

'Sur la résolution d'écoulements soumis aux forces de Coriolis'

**Emil Hossjer**, November 2024 - November 2027

'Multigrid solvers for hybrid high order methods in electromagnetism'

**Post-doc students**

**Alexandre Vieira**, October 2022 - March 2024

**Master and pre-doc students**

**Anaïs Antonini**, May - July 2024

**Clément Mariot**, May - July 2024

**Toï Lucien Takouda**, April - October 2024

# 11 Scientific production

## 11.1 Major publications


[1] A. Alonso Rodríguez, J. Camaño, E. de Los Santos and F. Rapetti. *Weights for moments' geometrical localization: a canonical isomorphism.* 14th Oct. 2023. URL: https://hal.science/hal-04443059 (cit. on p. 12).

[2] 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'. In: *Computers & Mathematics with Applications* 142 (July 2023), pp. 225–256. DOI: 10.1016/j.camwa.2023.04.034. URL: https://hal.science/hal-03811224 (cit. on p. 12).

[3] 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 (cit. on p. 10).

[4] M. Hoelzl, G. T. A. Huijsmans, F. J. Artola, E. Nardon, M. Becoulet, S. Pamela, B. Nkonga, K. Aleynikova, V. Bandaru, H. Bergström, A. Bhole, T. Bogaarts, D. Bonfiglio, A. Cathey, T. Driessen, S. Futatani, G. Hao, F. Hindenlang, I. Holod, D. Hu, S. Hu, N. Isernia, H. Isliker, S. Kim, M. Kong, S. Korving, L. Kos, I. Krebs, S. Lee, L. Meier, V. Mitterauer, N. Nikulsin, R. Ramasamy, J. Reinking, G. Rubinacci, K. Särkimäki, N. Schwarz, C. Sommariva, R. Sparago, W. Tang, F. Vannini, S. Ventre, F. Villone, L. Wang, H.-H. Wang, F. Wieschollek and J. Zielinski. 'Non-linear MHD Modelling of Transients in Tokamaks: Recent Advances with the Jorek Code'. In: *IAEA Fusion Energy Conference.* FEC 2023 - 29th IAEA Fusion Energy Conference. London, United Kingdom, 16th Oct. 2023. URL: https://hal.science/hal-04403692 (cit. on p. 13).

[5] L. Lamérand, D. Auroux, P. Ghendrih, F. Rapetti and E. Serre. 'Inverse problem for determining free parameters of a reduced turbulent transport model for tokamak plasma'. In: *Advances in Computational Mathematics* 50.3 (2nd May 2024), p. 39. DOI: 10.1007/s10444-024-10135-6. URL: https://hal.science/hal-04569449 (cit. on p. 11).

[6] L. Lamérand, D. Auroux and F. Rapetti. *Parameter identification for a reduced transport model in fusion plasma.* 18th Dec. 2024. URL: https://univ-cotedazur.hal.science/hal-04846170 (cit. on p. 11).

[7] 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 (cit. on p. 12).

[8] L. Petitdemange, F. Marcotte and C. Gissinger. 'Spin-down by dynamo action in simulated radiative stellar layers'. In: *Science* 379.6629 (20th Jan. 2023), pp. 300–303. DOI: 10.1126/science.abk2169. URL: https://hal.science/hal-03948010 (cit. on p. 15).


## 11.2 Publications of the year

### International journals


[9] S. Gavrilyuk, B. Nkonga and K.-M. Shyue. 'The conduit equation : hyperbolic approximation and generalized Riemann problem'. In: *Journal of Computational Physics* 514 (4th Jan. 2024), p. 113232. DOI: 10.1016/j.jcp.2024.113232. URL: https://hal.science/hal-04377682 (cit. on p. 13).

[10] T. Goudon and S. Minjeaud. 'An explicit well-balanced scheme on staggered grids for barotropic Euler equations'. In: *ESAIM: Mathematical Modelling and Numerical Analysis* 58.4 (19th July 2024), pp. 1263–1299. DOI: 10.1051/m2an/2024035. URL: https://hal.science/hal-04294768.

[11] S. Kerboua-Benlarbi, R. Nouailletas, B. Faugeras, E. Nardon and P. Moreau. 'Magnetic control of WEST plasmas through deep reinforcement learning'. In: *IEEE Transactions on Plasma Science* (Sept. 2024). URL: https://hal.science/hal-04393963 (cit. on p. 11).

[12] A. A. Rodríguez, J. Camano, E. d. L. Santos and F. Rapetti. 'Basis for high order divergence-free finite element spaces'. In: *Results in Applied Mathematics* 23 (24th June 2024), p. 100469. DOI: 10.1016/j.rinam.2024.100469. URL: https://hal.science/hal-02429500 (cit. on p. 12).

**Reports & preprints**

[13] B. Faugeras, H. Guillard, B. Nkonga and F. Rapetti. *On the behavior of two C1 finite elements versus anisotropic diffusion*. 20th Sept. 2024. URL: https://univ-cotedazur.hal.science/hal-04703358 (cit. on p. 11).

[14] G. Gros, B. Faugeras, C. Boulbe, J. Artaud, R. Nouailletas and F. Rapetti. *Numerical simulation of tokamak plasma equilibrium evolution*. RR-9548. INRIA, May 2024. URL: https://inria.hal.science/hal-04589897 (cit. on p. 10).

[15] L. Lamérand, D. Auroux and F. Rapetti. *Parameter identification for a reduced transport model in fusion plasma*. 18th Dec. 2024. URL: https://univ-cotedazur.hal.science/hal-04846170 (cit. on p. 11).

[16] S. Tiwari, B. Nkonga, P. Chandrashekar and S. Gavrilyuk. *Finite volume approximations of shear shallow water model on unstructured grids*. 18th Jan. 2024. URL: https://hal.science/hal-04403870 (cit. on p. 14).

## 11.3 Cited publications

[17] 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] (cit. on p. 5).

[18] P. Mannix, C. Skene, D. Auroux and F. Marcotte. 'A robust, discrete-gradient procedure for optimisation with time-dependent PDE and norm constraints'. In: *SMAI Journal of Computational Mathematics* 10 (2024), pp. 1–28 (cit. on p. 15).

[19] L. Petitdemange, F. Marcotte, C. Gissinger and F. Daniel. 'Tayler-Spruit dynamos in simulated radiative stellar layers'. In: *Astronomy & Astrophysics* 681 (A75 2024) (cit. on p. 15).

[20] C. Skene, F. Marcotte and S. Tobias. 'On nonlinear transitions, minimal seeds and exact solutions for the geodynamo'. In: *arXiv:2411.05499* (2024), pp. 1–21 (cit. on p. 15).