2025 *Activity Report*

RESEARCH CENTRE: **Inria Centre at Université Côte d'Azur**
IN PARTNERSHIP WITH: **Université Côte d'Azur, CNRS**

Project-Team

CASTOR

Control for plAsma inSTability, Optimization and model Reduction

In collaboration with Laboratoire Jean-Alexandre Dieudonné (JAD)

Project-Team CASTOR

Creation of the Project-Team: 2024 December 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

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. – HPC for machine learning

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

Contents

1 Team members, visitors, external collaborators

Research Scientists

- Blaise Faugeras [CNRS, Senior Researcher]
- Hervé Guillard [INRIA, Emeritus]
- Florence Marcotte [INRIA, Researcher]

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- Francesca Rapetti-Gabellini [Team leader, UNIV COTE AZUR, Professor]
- Stephane Abide [UNIV COTE AZUR, Professor]
- Didier Auroux [UNIV COTE AZUR, Professor]
- Jacques Blum [UNIV COTE AZUR, Emeritus]
- Cédric Boulbe [UNIV COTE AZUR, Associate Professor]
- Didier Clamond [UNIV COTE AZUR, Professor]
- Boniface Nkonga [UNIV COTE AZUR, Professor]
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- Raphael Granger [CNRS, from Oct 2025]
- Guillaume Gros [UNIV COTE AZUR]
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- Sarah Ali [INRIA, Apprentice, from Sep 2025]
- Giorgio Appignanesi [INRIA, Intern, from Jun 2025]

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- Nathalie Nordmann [INRIA]

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- Mustapha Bahari [UNIV COTE AZUR, from Nov 2025]

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.

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 developed 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 [15]

4.2 MHD flows for liquid metal blankets

Participants: Herve Guillard, Boniface Nkonga, Stephane Abide, Praveen 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.

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. 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 Highlights of the year

Guillaume Gros defended his PhD on December 3, 2025. He has a three-month extension contract in the team until the end of March 2026 to work on the PDS (Plasma Discharge Simulator).

Aleksandar Stojcheski has reached the team (since 01/12) as PhD student supported by PEPR SupraFusion.

Sarah Ali has reached the team (since 01/09/2025) as “étudiante de MASTER 2 en alternance” supported by Inria for one year.

Mustapha Bahari has reached the team (since 01/11/2025) for six months as post-doc to work on moving meshes supported by Eurofusion.

Raphael Granger has reached the team (since 01/11/2025) as PhD student supported by Eurofusion to work on high-regularity Bezier finite elements.

7 Latest software developments, platforms, open data

The code NICE is now freely distributed under the GNU Lesser General Public License version 3.

The code TchebyCUBE is a massively parallel solver for the incompressible Navier-Stokes equations, based on Chebyshev-type spectral methods. It is used by the team to perfom specific tests [16].

7.1 Latest software developments

7.1.1 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

Participant: 4 anonymous participants

7.1.2 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

Participant: 3 anonymous participants

7.1.3 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

7.1.4 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: an anonymous participant

7.1.5 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

Participant: 4 anonymous participants

7.1.6 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

Participant: 4 anonymous participants

7.1.7 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

Participant: 5 anonymous participants

7.1.8 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

7.1.9 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

7.1.10 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

Participant: 3 anonymous participants

8 New results

8.1 Numerical simulation of Tokamak plasma equilibrium evolution

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

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 [7] for an X-point formation scenario in the WEST tokamak are presented as a first illustration of the efficiency of the developed numerical methods.

8.2 Development of a flight simulator for the WEST plasma and control system

Participants: Rémy Nouailletas *(IRFM-CEA Cadarache)*, Guillaume Gros, Blaise Faugeras, Jean-François Artaud *(IRFM-CEA Cadarache)*, Philippe Moreau *(IRFM-CEA Cadarache)*.

The ITER project should demonstrate in the next decades the technical feasibility of controlled fusion reactions in tokamaks. One of the critical issues reaching this purpose is the design of plasma scenarios and associated controllers in order to achieve the desired performance while satisfying the operational limits. To succeed, the non-linearity, the uncertainties, and the limited observability of the plasma presently require adjusting controllers and scenarios during commissioning sessions. This method is time-consuming and must be reduced to the strict minimum time. To address this issue, the community has developed for several years simulation tools to design both controllers and scenarios using numerical models of the plasma. From simple linear models of the vertical plasma instability to integrated modeling of both plasma transport and equilibrium, these codes are now efficient enough to predict the plasma behavior and be called "flight simulator". In this article, the flight simulator developed for WEST will be presented. One of the main features is the use as input of the same pulse schedule files and the same controllers as in the WEST Plasma Control System (PCS). Based on the free boundary equilibrium code NICE with flux diffusion equation and a 1D transport model, a consistent plasma time evolution can be computed and reduces the risk of failure due to numerical issues. To illustrate the abilities of the tool, a standard WEST X-point formation has been simulated and compared to the real data [9].

8.3 Turbulence and models for the edge region of tokamaks

Participants: Didier Auroux, Louis Lamerand, Francesca Rapetti.

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 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 k and ϵ estimated from two additional transport equations allow to introduce some non-locality in the transport model. This is illustrated in [3] 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 [12, 11]. 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 [4] and in [8].

8.4 Anisotropic diffusion

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

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 10^8 and the pollution by purely numerical errors can make the simulation of the heat transport in the perpendicular direction very difficult. 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 [6]).

8.5 On incompressible magnetohydrodynamic equations in terms of differential forms

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

Magnetohydrodynamic offers examples of non-scalar advection-diffusion problems which are relevant for applications. We consider its formulation in terms of differential forms, with the presence of operators such as the exterior derivative and Lie's derivative, being aware of the underneath analogy between electromagnetic dynamic and incompressible fluid dynamic. We analyze the intrinsic structure of the magnetic and fluid coupling, with a special attention to the Laplace's force. Taking the cue from Bossavit (2008), we focus on the density of virtual power associated with each of the involved force [13].

8.6 Interpretation of a Discrete de Rham method as a Finite Element System

Participants: Snorre Harald Christiansen *(Univ. of Oslo, Norway)*, Francesca Rapetti.

In [14] we adopt a new approach to show that the Discrete de Rham (DDR) method can be interpreted as defining a computable consistent discrete product on a conforming finite element system (FES) defined by PDEs. Without modifying the numerical method itself, this point of view provides an alternative approach to the analysis. The conformity and consistency properties we obtain are stronger than those previously shown, even in low dimensions. We can also recover some of the other results that have been proved about DDR, from those that have already been proved, in principle, in the general context of FES. We also bring the Virtual Element Method (VEM) into the discussion. The goal back then is to define a discrete de Rham finite element sequence on polytopal meshes that mimicked the lowest order mixed finite elements that correspond to Whitney forms. Indeed these were known only for simplices (and products of simplices handled by tensor product constructions).

8.7 MHD model applied to massive material injections

Participants: Boniface Nkonga, José Costa *(Univ. do Minho)*, Guido Huijsmans *(IRFM-CEA Cadarache)*, Stanislas Pamela *(CCFE - UKAEA Culham)*, Matthias Hoelzl *(IPP Garshing)*.

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 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 finite element method (FEM) in the computational framework of the nonlinear magnetohydrodynamics (MHD) code JOREK [5].

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 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) [1].

8.8 Treatment of grid singularities in the Hermite-Bézier approximations

Participants: Boniface Nkonga, Hervé Guillard, Meng Wu, Bernard Mourrain *(Inria)*.

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 [2].

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.

8.9 Isogeometric analysis for image registration and segmentation using optimal transport problem

Participants: Mustapha Bahari, Abderrahmane Habbal *(Inria)*, Ahmed Ratnani *(UM6P Marocco)*.

We present a fast and high order method for the problem of Image Registration, using Optimal Transport and the Isogeometric Analysis paradigm. Our method is based on the resolution of the Monge-Ampère equation and ensures the one-to-one property. In addition, the use of B-Splines allows to create a map that can be evaluated everywhere, and reduces the number of degrees of freedom needed to store the constructed (gradient) map, by using e.g. high order B-Splines functions [10]. This study is a preliminar step towards adapting the computational mesh to follow the magnetic surfaces' behavior.

8.10 Metal liquid flow under a strong magnetic field

Participants: Herve Guillard, Boniface Nkonga, Raphael Grangier, Praveen Chandrashekar *(TIFR, Bangalore)*, Devansh Sonigra *(TIFR, Bangalore)*.

The flow of liquid metal in a fusion device occurs under a strong external magnetic field. Due to the low magnetic Reynolds number, the induced magnetic field is negligible; thus, the total magnetic field can also be considered constant, and there is no need to solve for it. However, the induced currents can exert significant Lorentz forces on the flow and, hence, have to be time-evolved, leading to the inductionless model. This year, we begin the design of numerical strategies for the approximation of inductionless MHD. The first path investigates the use of the Raviart-Thomas finite element to derive a scheme that conserves total energy at the discrete level. We led to unsplit, fully discrete approximations that are provably energy-conservative or energy-dissipative. How to efficiently apply this strategy is the work to be undertaken with a new PhD student, Devansh Sonigra, located in Bangalore, who is co-advised by C. Praveen and B. Nkonga. The second path of investigation follows the Ck Hermite-Bezier (HB) finite element framework. We can now develop a hierarchical HB basis function for any prescribed order of continuity. The main advantage here is the possibility of having curved elements that can fit well with the magnetic field lines. Indeed, the anisotropic nature of flow dynamics makes mesh-aligned strategies particularly useful. The PhD R. Granger, starting in October 2025, will follow this path, under the co-advisement of H. Guillard and B. Nkonga. Preliminary results in stationary quasi-1D test cases are promising.

For the two PhDs, it is essential to develop numerical strategies to validate the physical requirements at the discrete level. Numerical simulations will aim to reproduce some available physical experiments and extend beyond them by providing new insights not accessible from the available diagnostics. Indeed, available diagnostics fail under extreme physical conditions (high temperatures, strong magnetic fields, skinny liquid films).

8.11 Compact schemes for MHD simulation of conductive flows

Participants: Hervé Guillard, Argyris Delis *(Tech. Univ. of Crete, Greece)*, Vassili Mandikas *(Tech. Univ. of Crete, Greece)*.

Compact schemes are often presented as an alternative to the more costly spectral methods as they combine low computational cost with high accuracy. In this work, we have begun to use these methods to compute conducting flows in pipes at high Hartmann numbers. These flows are characterized by the presence of a very thin boundary layer near the wall : The Hartmann layer. However in contrast to the boundary layers encountered in classical CFD (Computational Fluid Dynamics), electrical and magnetic phenomena occur in the Hartmann layer and these phenomena need to be accurately described. This makes the computation of these flows particularly challenging. This study is a preliminary step to investigate the relevance of compact schemes for these computations.

8.12 Spectral methods for fluid dynamics applications

Participants: Stephane Abide, Florence Marcotte, Clement Mariot, Sarah Ali.

The research on this topic lies at the intersection of scientific computing, computational fluid dynamics, and high-performance computing (HPC), with a particular focus on developing spectral methods and reference solvers for turbulent and multiphysics flows. The central challenge is to achieve high-fidelity numerical simulations while controlling the algorithmic and communication costs imposed by massively parallel architectures.

During this year, the activity reduces to almost exclusively the continued development of an HPC solver for incompressible fluid mechanics. The solver is built around spectral collocation methods in rectangular and cylindrical geometries, with parallelization based on pencil decomposition. The application frameworks used to validate the developments include, in particular, astrophysical flows, with the eventual integration of incompressible magnetohydrodynamics (MHD). The code is notably used to study the subcritical transition to turbulence in Keplerian stellar disks, using optimal control and adjoint methods aimed at identifying the minimal finite-amplitude perturbations that trigger a turbulent regime [16]. The first phase of the project has achieved a sufficient level of scientific and numerical maturity to enable reference 3D simulations; a second phase is now underway to prepare the open-source release of the code, in order to strengthen its dissemination and adoption within the community.

This solver is conceptually close to Fourier transform based approaches. Its parallelization therefore relies on large and costly collective communications, which severely limit scalability, particularly in view of the ongoing multi-GPU porting effort. This structural constraint is now one of the main bottlenecks of spectral methods for large-scale HPC simulations [20]. To partially circumvent this limitation, alternative discretizations based on compact schemes are being explored, with the goal of preserving high accuracy while reducing communication overhead. This approach has enabled simulations in astro-geophysical contexts, as illustrated by works such as [17, 18]. However, this strategy remains incomplete, since the elliptic solvers — especially for the Poisson equation — still rely on formulations similar to spectral methods, with the same communication volume bottleneck.

In this context, the work of Sarah Ali follows an exploratory direction aimed at developing a high-order Poisson solver with minimized communications. The chosen application framework is a reduced resistive axisymmetric MHD model designed to study tearing-type instabilities in tokamak plasmas (TOKAM2D code).

8.13 Minimal seeds of nonlinear transition: the case of the geodynamo benchmark

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 [21].

8.14 Nonlinear transitions in discs and stellar interiors

Participants: Stéphane Abide, Florence Marcotte, Clément Mariot, Yannick Ponty *(Observatoire de la Côte d'Azur)*, Nathanael Schaeffer *(ISTERRE)*.

We have differentiated the pseudo-spectral code SNOOPY (developed by G. Lesur at IPAG Grenoble, and widely used in the astrophysical community to model shear-periodic flows), implementing adjoint-based optimization techniques to efficiently identify critical initial perturbations for the baroclinic instability in Keplerian disks models. Using the in-house direct/adjoint spectral code TchebyCUBE, Clement Mariot's on-going PhD work focuses, using optimal control and transient growth analysis, on investigating the perturbations that are most likely to nonlinearly disrupt a Keplerian flow. For the purpose of studying nonlinear transitions in stellar interiors, on-going work is also focused on differentiating the pseudo-spectral code XSHELLS (developed by N. Schaeffer at ISTerre Grenoble).

8.15 Numerical simulations of magnetic field generation in radiative stellar layers

Participants: Giorgio Appignanesi *(Supaero / Politecnico di Torino)*, Lionel Bigot *(Observatoire de la Côte d'Azur)*, Florence Marcotte, Nathanael Schaeffer *(ISTERRE)*.

Angular momentum transport by magnetic fields in stellar radiative zones remains poorly understood. The first numerical model of the Tayler-Spruit dynamo [19] implemented Dirichlet boundary conditions for the velocity field, which may significantly influence dynamo saturation and, consequently, angular momentum transport. The focus of Giorgio Appignanesi's M2 internship was to modify these boundary conditions, replacing the existing framework with stress-free conditions combined with volume forcing to study the influence on dynamo saturation and angular momentum transport.

9 Bilateral contracts and grants with industry

9.1 ITER

Participants: Blaise Faugeras, Cédric Boulbe.

An 18 month contract (from 08/2024 to 04/2026) 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.

9.2 Participation to the Open Call for Technology Transfer Demonstrators

Participants: Blaise Faugeras, Francesca Rapetti.

A 12 month collaboration with GDTech S.A. (Liège) on the project MARS around the simulation of a Melting Alloy Release System for space applications with the code NICE, supported by EUROFusion - InExtenso - FUTTA III program 2025.

10 Partnerships and cooperations

10.1 European initiatives

10.1.1 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

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.

10.2 National initiatives

10.2.1 ANR HIPOTHEC

Participants: Francesca Rapetti.

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.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organization

Workshop CASTOR-CEA

To consolidate the partnership with the CEA, we have organized a one-day meeting with 7 seminars and round-table to exchange on the new perspectives about plasma fusion and astrophysics. We have also celebrated Pr.E. Jacques Blum for his work on the plasma control subject in occasion of his 75th birthday.

Member of the conference program committees

- Didier Auroux: Scientific board of PICOF 2025 (11th international conference Inverse Problems, Control and Shape Optimization), October 28-31 2025, Hammamet, Tunisia

11.1.2 Journal

Member of the editorial boards

- Didier Auroux: ESAIM Proceedings and Surveys
- Francesca Rapetti: SIAM J. Numer. Anal., Adv. COmput. Math. (Springer), Math. and Computers in Simulation (Elsevier)

Reviewer - reviewing activities

- Didier Auroux: Journal of Computational and Applied Mathematics; Applied Mathematics and Computation; ESAIM Proceedings and Surveys; Computational and Applied Mathematics

11.1.3 Invited talks

- Didier Auroux: Data science seminar, November 26 2025, IISER Pune, India

11.1.4 Scientific expertise

- Didier Auroux: Member of the CESAAR committee (Comité d'évaluation des agents de catégorie A ayant une activité de recherche), Ministère de la Transition écologique et de la Cohésion des territoires
- Francesca Rapetti: Member of the New E-TASC (EUROfusion Theory and Advanced Simulation Coordination) Scientific Board

11.1.5 Research administration

- Didier Auroux: Head of MSI (center of Modeling, Simulation and Interactions), Université Côte d'Azur

11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

11.2.1 Teaching

The team members associated with the Université Côte Azur have teaching duties (192h/year). They work actively within the Sciences, Engineering, Technologies and Environment (SITE) Portal, which offers Bachelor's degree programs in mathematics, computer science, MIAGE, physics, chemistry, electronics, Earth sciences, and geosciences. Some of the team members participate also in the Master's level, in the frame of the University Côte d'Azur's Graduate Schools SPECTRUM-Fundamental Sciences in Engineering.

11.2.2 Supervision

- Stephane Abide: Sarah Ali (Master), Clement Mariot (PhD)
- Didier Auroux: Theo Rolin (PhD)
- Cédric Boulbe: Guillaume Gros (PhD)
- Blaise Faugeras: Guillaume Gros (PhD), Aleksandar Stojcheski (PhD)

- Hervé Guillard: Raphael Granger (PhD)
- Florence Marcotte: Girogio Appignanesi (Master), Clement Mariot (PhD)
- Boniface Nkonga: Raphael Granger (PhD)
- Francesca Rapetti: Emil Hossjer (PhD in Montpellier, with D. Di Pietro)

11.2.3 Juries

- Francesca Rapetti: Member of the board for the concours CPJ, CEA Cadarache 2025

11.2.4 Educational and pedagogical outreach

- Cédric Boulbe: Coordinator from the Appl. Math. Dept. side of the Engng. Diploma at Polytech Nice Sophia
- Afeintou Sangam: Coordinator from the side “math” of the “Double Licence Math.-Informatique”' at the Université Côte d’Azur

12 Scientific production

12.1 Major publications

[1] 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. 16).

[2] 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. 16).

[3] 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. 14).

[4] L. Lamérand, D. Auroux and F. Rapetti. ‘Parameter identification for a reduced transport model in fusion plasma’. In: *International Journal for Numerical Methods in Engineering* 126.17 (2025). DOI: `10.1002/nme.70115`. URL: `https://univ-cotedazur.hal.science/hal-04846170` (cit. on p. 14).

[5] 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. 16).

12.2 Publications of the year

International journals

[6] B. Faugeras, H. Guillard, B. Nkonga and F. Rapetti. ‘On the behavior of two C1 finite elements versus anisotropic diffusion’. In: *International Journal for Numerical Methods in Fluids* (13th Aug. 2025). DOI: `10.1002/fld.70009`. URL: `https://univ-cotedazur.hal.science/hal-04703358` (cit. on p. 15).

[7] G. Gros, B. Faugeras, C. Boulbe, J. Artaud, R. Nouailletas and F. Rapetti. ‘Numerical simulation of tokamak plasma equilibrium evolution’. In: *Journal of Computational Physics* 529 (14th Feb. 2025), p. 113849. DOI: `10.1016/j.jcp.2025.113849`. URL: `https://inria.hal.science/hal-04589897` (cit. on p. 13).

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International peer-reviewed conferences

[10] M. Bahari, A. Habbal and A. Ratnani. ‘Isogeometric Analysis For Image Registration and Segmentation Using Optimal Transport Problem’. In: M3A 2024 - Mathematical Modeling with Modern Applications. Vol. 497. Springer Proceedings in Mathematics & Statistics. Istanbul, Turkey: Springer Nature Switzerland, 10th July 2025, pp. 131–150. DOI: `10.1007/978-3-031-89041-3_7`. URL: `https://inria.hal.science/hal-05399303` (cit. on p. 17).

Edition (books, proceedings, special issue of a journal)

[11] *Observers for Data Assimilation and Parameter Estimation*. CTIP 2023. Vol. Control Theory and Inverse Problems. Trends in Mathematics. Monastir, Tunisia: Birkhäuser, Cham, 7th Aug. 2025, pp. 59–79. DOI: `10.1007/978-3-031-68046-5_3`. URL: `https://inria.hal.science/hal-05464117` (cit. on p. 14).

[12] *Inverse problems and machine learning* 26.4 (24th Oct. 2025). DOI: `10.1007/s11081-025-10044-7`. URL: `https://inria.hal.science/hal-05464132` (cit. on p. 14).

Reports & preprints

[13] A. Alonso Rodríguez and F. Rapetti. *On incompressible magnetohydrodynamic equations in terms of differential forms*. Dec. 2025. URL: `https://hal.science/hal-05392678` (cit. on p. 15).

[14] S. Christiansen and F. Rapetti. *Interpretation of a Discrete de Rham method as a Finite Element System*. 2025. DOI: `10.48550/arXiv.2512.05912`. URL: `https://hal.science/hal-05446169` (cit. on p. 15).

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[15] 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. 8).

[16] C. Mariot, F. Marcotte and S. Abide. *High-order Poisson solvers for reduced MHD tokamak models*. in preparation. 2026 (cit. on pp. 10, 18).

[17] G. Meletti, S. Abide, U. Harlander, I. Raspo and S. Viazzo. ‘On the influence of the heat transfer at the free surface of a thermally driven rotating annulus’. In: *Physics of Fluids* 37.3 (2025) (cit. on p. 18).

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