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Activity Report 2017

Project-Team CASTOR

Control, Analysis and Simulations for TOkamak Research

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

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

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

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1. Personnel

Research Scientists

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Holger Heumann [Inria, Researcher]
Sebastian Minjeaud [CNRS, Researcher]
Richard Pasquetti [CNRS, Senior Researcher, HDR]

Faculty Members

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Cedric Boulbe [Université Côte d'Azur, Associate Professor]
Boniface Nkonga [Université Côte d'Azur, Professor]
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Ali Aboudou Elarif [Inria, from Oct 2017]
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Ayoub Belhachmi [Inria, from Aug 2017 until Sep 2017]

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Didier Auroux [Université Côte d'Azur]

2. Overall Objectives

2.1. Presentation

In order to fulfill the increasing demand, alternative energy sources have to be developed. Indeed, the current rate of fossil fuel usage and its serious adverse environmental impacts (pollution, greenhouse gas emissions, ...) lead to an energy crisis accompanied by potentially disastrous global climate changes.

Controlled fusion power is one of the most promising alternatives to the use of fossil resources, potentially with a unlimited source of fuel. France with the ITER (http://www.iter.org/default.aspx) and Laser Megajoule (http://www-lmj.cea.fr/) facilities is strongly involved in the development of these two parallel approaches to master fusion that are magnetic and inertial confinement. Although the principles of fusion reaction are well understood from nearly sixty years, (the design of tokamak dates back from studies done in the '50 by Igor Tamm and Andreï Sakharov in the former Soviet Union), the route to an industrial reactor is still long and the application of controlled fusion for energy production is beyond our present knowledge of related physical processes. In magnetic confinement, beside technological constraints involving for instance the design of plasma-facing component, one of the main difficulties in the building of a controlled fusion reactor is the poor confinement time reached so far. This confinement time is actually governed by turbulent transport that therefore determines the performance of fusion plasmas. The prediction of the level of turbulent transport in large machines such as ITER is therefore of paramount importance for the success of the researches on controlled magnetic fusion.

The other route for fusion plasma is inertial confinement. In this latter case, large scale hydrodynamical instabilities prevent a sufficiently large energy deposit and lower the return of the target. Therefore, for both magnetic and inertial confinement technologies, the success of the projects is deeply linked to the theoretical understanding of plasma turbulence and flow instabilities as well as to mathematical and numerical improvements enabling the development of predictive simulation tools.

CASTOR gathers the activities in numerical simulation of fusion plasmas with the activities in control and optimisation done in the laboratory Jean-Alexandre Dieudonné of the University of Nice. The main objective of the CASTOR team is to contribute to the development of innovative numerical tools to improve the computer simulations of complex turbulent or unstable flows in plasma physics and to develop methods allowing the real-time control of these flows or the optimisation of scenarios of plasma discharges in tokamaks. CASTOR is a common project between Inria (http://www.inria.fr/centre/sophia) and the University of Nice Sophia-Antipolis and CNRS through the laboratory Jean-Alexandre Dieudonné, UMR UNS-CNRS 7351, (http://math.unice.fr).

3. Research Program

3.1. Plasma Physics

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras, Hervé Guillard, Holger Heumann, Sebastian Minjeaud, Boniface Nkonga, Richard Pasquetti, Afeintou Sangam.

The main reseach topics are:

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

4. Application Domains

4.1. Magnetic confinment fusion

The main application domain is magnetic confined fusion. A part of the work is actually used on european Tokamaks like JET, WEST and ITER.

5. Highlights of the Year

5.1. Highlights

- Invited presentation at EPS Conference on Plasma Physics, 26 - 30 June 2017 Liu, F., Huijsmans, G.T., Alberto, L., Garofalo, A.M., Solomon, W.M., Nkonga, B., Hoelzl, M., Pamela, S., Becoulet, M., Orain, F. Non-linear MHD simulations of QH-mode and Type I ELMy H-mode DIII-D plasmas and implications for ITER high Q scenarios
- B. Nkonga, Elected member of the managing board, as treasurer, of the European Community on Computational Methods in Applied Sciences (ECCOMAS).

5.1.1. Awards

Jacques Blum has obtained the "Grand Prix de la ville de Nice" for 2017.

6. New Software and Platforms

6.1. CEDRES++

KEYWORDS: 2D - Magnetic fusion - Plasma physics
FUNCTIONAL DESCRIPTION: In Tokamaks, at the slow resistive diffusion time scale, the magnetic configuration in the plasma can be described by the MHD equilibirum equations inside the plasma and the Maxwell equations outside. Moreover, the magnetic field is often supposed not to depend on the azimutal angle.

Under this assumption of axisymmetric configuration, the equilibrium in the whole space reduces to solving a 2D problem in which the magnetic field in the plasma is described by the well known Grad Shafranov equation. The unknown of this problem is the poloidal magnetic flux. The P1 finite element code CEDRES++ solves this free boundary equilibrium problem in direct and inverse mode. The direct problem consists in the computation of the magnetic configuration and of the plasma boundary, given a plasma current density profile and the total current in each poloidal field coils (PF coils). The aim of the inverse problem is to find currents in the PF coils in order to best fit a given plasma shape.

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

6.2. Equinox

KEYWORDS: 2D - Problem inverse
FUNCTIONAL DESCRIPTION: EQUINOX is a code dedicated to the numerical reconstruction of the equilibrium of the plasma in a Tokamak. The problem solved consists in the identification of the plasma current density, a non-linear source in the 2D Grad-Shafranov equation which governs the axisymmetric equilibrium of a plasma in a Tokamak. The experimental measurements that enable this identification are the magnetics on the vacuum vessel, but also polarimetric and interferometric measures on several chords, as well as motional Stark effect measurements. The reconstruction can be obtained in real-time and the numerical method implemented involves a finite element method, a fixed-point algorithm and a least-square optimization procedure.

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

6.3. FBGKI

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

- Contact: Sebastian Minjeaud

6.4. FEEQS.M

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

FUNCTIONAL DESCRIPTION: FEEQS.M (Finite Element Equilibrium Solver in Matlab) is a MATLAB implementation of the numerical methods in [Heumann2015] to solve equilibrium problems for toroidal plasmas. Direct and inverse problems for both the static and transient formulations of plasma equilibrium can be solved. FEEQS.M exploits MATLAB's evolved sparse matrix methods and uses heavily the vectorization programming paradigm, which results in running times comparable to C/C++ implementations. FEEQS.M complements the production code CEDRES++ in being considered as fast prototyping test bed for computational methods for equilibrium problems. This includes aspects of numerics such as improved robustness of the Newton iterations or optimization algorithms for inverse problems. The latest developments aim at incorporating the resistive diffusion equation.

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

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

6.5. Fluidbox

FUNCTIONAL DESCRIPTION: FluidBox is a software dedicated to the simulation of inert or reactive flows. It is also able to simulate multiphase, multi-material and MDH flows. There exist 2D and 3D dimensional versions. The 2D version is used to test new ideas that are later implemented in 3D. Two classes of schemes are available : a classical finite volume scheme and the more recent residual distribution schemes. Several low Mach number preconditioning are also implemented. The code has been parallelized with and without domain overlapping.

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

6.6. Jorek-Inria

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

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

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

6.7. Plato

A platform for Tokamak simulation

FUNCTIONAL DESCRIPTION: PlaTo (A platform for Tokamak simulation) is a suite of data and softwares dedicated to the geometry and physics of Tokamaks. Plato offers interfaces for reading and handling distributed unstructured meshes, numerical templates for parallel discretizations, interfaces for distributed matrices and linear and non-linear equation solvers. Plato provides meshes and solutions corresponding to equilibrium solutions that can be used as initial data for more complex computations as well as tools for visualization using Visit or Paraview.

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

6.8. VacTH

KEYWORD: Problem inverse
FUNCTIONAL DESCRIPTION: VacTH implements a method based on the use of toroidal harmonics and on a modelization of the poloidal field coils and divertor coils to perform the 2D interpolation and extrapolation of discrete magnetic measurements in a tokamak and the identification of the plasma boundary. The method is generic and can be used to provide the Cauchy boundary conditions needed as input by a fixed domain equilibrium reconstruction code like EQUINOX. It can also be used to extrapolate the magnetic measurements in order to compute the plasma boundary itself. The method is foreseen to be used in the real-time plasma control loop on the WEST tokamak.

- Contact: Blaise Faugeras

6.9. NICE

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

- Contact: Blaise Faugeras

7. New Results

7.1. Mathematical theory of reduced MHD models

Participant: Hervé Guillard.

One of the fundamental model used for fusion plasma simulations is the magnetohydrodynamic (MHD) model. However, in practice, many theoretical and numerical works in this field use specific approximations of this model known as *reduced* MHD models. These models assume that in the presence of a strong magnetic field, the main dynamic reduces to incompressible motion in the plane perpendicular to the dominating magnetic field and to the propagation of Alfvén waves in the magnetic field direction. In the framework of the slab approximation for large aspect ratio tokamaks ($R/a >> 1$ where R and a are respectively the major and minor radius of the machine) we have studied last year the validity of this assumption using techniques coming from the asymptotic theory of hyperbolic equations with a large parameter. In particular, we have proved that the solutions of the full MHD system converge in a weak sense to the solutions of an appropriate reduced model even in the presence of ill-prepared initial data. This work continues with a tentative to relax the large aspect ratio assumption that is not verified in modern machines.

7.2. 2D C^1 triangular elements

Participants: Hervé Guillard, Ali Elarif.

In order to avoid some mesh singularities that arise when using quadrangular elements for complex geometries and flux aligned meshes, the use of triangular elements is a possible option that we have studied in the past years [30]. In particular, we have developped the geometric tools necessary for the construction of Powell-Sabin splines and have applied these methods for the approximation of some simple hyperbolic PDE systems (namely the Euler equation of fluid dynamics). The PhD thesis of Ali Elarif that has begun in october 2017 is devoted to the study of the applicability of these methods to more complex PDE models encountered in plasma physics and to an extension towards other triangular C^1 elements (Clough-Tocher elements).

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

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

We have studied numerically an extension designed for turbulent flows of the shallow water model. The model is able to describe the oscillatory nature of turbulent hydraulic jumps and as such correct the deficiency of the classical shallow water equations. The model equations, originally developed for horizontal flow or flows occurring over small constant slopes, are straightforwardly extended here for modeling flows over non-constant slopes and numerically solved by a second-order well-balanced finite volume scheme. Further, a new set of exact solutions to the extended model equations are derived and several numerical tests are performed to validate the numerical scheme and its ability to predict the oscillatory nature of hydraulic jumps under different conditions. The comparisons with experiments performed at Tainan University are very satisfactory given the simplicity of the model [27].

7.4. Block-structured meshes

Participants: Hervé Guillard, Alexis Loyer, Adrien Loseille [Gamma3 team, Inria Saclay], Jalal Lakhlili [IPP Garching], Ahmed Ratnani [IPP Garching].

Due to the highly anisotropic character of strongly magnetized plasmas, a crucial point for numerical simulations is the construction of meshes that are aligned on the magnetic flux surfaces computed by Grad-Shafranov equilibrium solvers. In this work, we study an original method for the construction of flux aligned grids that respect the magnetic equilibrium topology and that can be applied to block-structured meshes using C^1 finite element methods (Hermite-Bézier/Cubic spline). This method relies on the analysis of the singularities of the magnetic flux function and the construction of the Reeb graph that allows the segmentation of the physical domain into sub-domains that can be mapped to a reference square domain. Once this domain decomposition has been done, the mapping of the sub-domain to reference patches can be done using integration along the streamlines of the flux function[23], [34]. This work is performed in the framework of the EoCoE European project (see section 8.2.1.2).

7.5. FEM-BEM coupling methods for Tokamak plasma axisymmetric free-boundary equilibrium computations in unbounded domains

Participants: Blaise Faugeras, Holger Heumann.

Incorporating boundary conditions at infinity into simulations on bounded computational domains is a repeatedly occurring problem in scientific computing. The combination of finite element methods (FEM) and boundary element methods (BEM) is the obvious instrument, and we adapt here for the first time the two standard FEM-BEM coupling approaches to the free-boundary equilibrium problem: the Johnson–Nédélec coupling and the Bielak–MacCamy coupling. We recall also the classical approach for fusion applications, dubbed according to its first appearance von-Hagenow–Lackner coupling and present the less used alternative introduced by Albanese, Blum and de Barbieri. We show that the von-Hagenow–Lackner coupling suffers from undesirable non-optimal convergence properties, that suggest that other coupling schemes, in particular Johnson–Nédélec or Albanese–Blum–de Barbieri are more appropriate for non-linear equilibrium problems. Moreover, we show that any of such coupling methods requires Newton-like iteration schemes for solving the corresponding non-linear discrete algebraic systems.

7.6. Optimal control of a coupled partial and ordinary differential equations system for the assimilation of polarimetry Stokes vector measurements in tokamak free-boundary equilibrium reconstruction with application to ITER

Participant: Blaise Faugeras.

The modelization of polarimetry Faraday rotation measurements commonly used in tokamak plasma equilibrium reconstruction codes is an approximation to the Stokes model. This approximation is not valid for the foreseen ITER scenarios where high current and electron density plasma regimes are expected. In this work a method enabling the consistent resolution of the inverse equilibrium reconstruction problem in the framework of non-linear free-boundary equilibrium coupled to the Stokes model equation for polarimetry is provided. Using optimal control theory we derive the optimality system for this inverse problem. A sequential quadratic programming (SQP) method is proposed for its numerical resolution. Numerical experiments with noisy synthetic measurements in the ITER tokamak configuration for two test cases, the second of which is an H-mode plasma, show that the method is efficient and that the accuracy of the identification of the unknown profile functions is improved compared to the use of classical Faraday measurements.
In the framework of JET Task T17-15, the method has been implemented in the new code NICE and equilibrium reconstruction studies using real JET measurements are currently being performed.

7.7. Equilibrium reconstruction with Equinox at JET

Participant: Blaise Faugeras.

Within the framework of JET Task T17-02 an update of the real-time equilibrium reconstruction code Equinox at JET in view of its coupling with the transport code Raptor has been performed. Mainly the computation of all the averaged geometric quantities which enter the transport equation have been added.

7.8. Equilibrium reconstruction within the framework of the European Integrated Tokamak Modelling WPCD project

Participants: Blaise Faugeras, Cédric Boulbe.

We have been involved in a benchmark study between the equilibrium reconstruction codes VACTH-EQUINOX, EQUAL and LIUQE on TCV equilibriums [EPS paper R. Coelho et al] The benchmark study lead us to include new functionalities to VACTH-EQUINOX such as the possibility to have an upper X-point. The adaptation of VACTH-EQUINOX to IMAS (Integrated Modelling & Analysis Suite), the ITER standard using IDS (Interface Data Structure) as data type, has been carried on. Equilibrium reconstructions using IMAS have been performed on real JET measurements and on the first recently available WEST measurements.

7.9. Coupling free boundary equilibrium code and magnetic controller on IMAS

Participants: Cedric Boulbe, Jakub Urban.

During the previous years, the free boundary equilibrium code CEDRES++ has been coupled to the transport solver ETS and a magnetic simulink controler using the Integrated Tokamak Modelling infrastructure (Project Eurofusion WPCD - Work Package Code Development). In 2017, we have started to port this tool on IMAS which is the integrated modelling infrastructure developped by ITER. CEDRES++ has been adapted to IMAS and has been coupled to a magnetic controller in the framework of the Eurofusion WPCD project. This activity has been a pilot project to test the C++ tools provided on IMAS.

7.10. An Automated Approach to Plasma Breakdown Design

Participants: Holger Heumann, Eric Nardon.

Plasma breakdown in a tokamak requires a large toroidal electric field E_ϕ and a low poloidal magnetic field B_p, i.e. a so-called *field null region*. The latter should remain as extended as possible for a sufficient duration (typically a few tens of ms), all the more if one operates at low E_ϕ (e.g. in ITER where $E_\phi = 0.3V/m$). Finding appropriate settings (i.e. premagnetization coils currents and voltage waveforms) to produce and maintain a good field null region is not a trivial task, in particular in the presence of highly conducting passive structures which make the problem dynamic. WEST is a good example of this situation, due to two toroidally continuous copper plates which have been added for vertical stabilization: indeed, the current in the plates ramps up fast when E_ϕ is applied, which tends to degrade the field null region.

Our automated approach to determining appropriate breakdown settings relies on a precise electromagnetic model of the machine (including the iron core) and solves a constrained optimization problem, where the objective function to be minimized quantifies the design goal: the averaged magnitude of B_p. After discretization we end up with *finite dimensional* convex constrained optimization problem, that can be solved efficiently with Sequential Quadratic Programming. The approach follows the lines of optimal control methods for plasma equilibria in [35] and [36].

The automated approach was already beneficial for obtaining first breakdowns in WEST during the initial launch in December 2016. The data collected during these breakdowns allowed for improving the electromagnetic model and the simulations reproduce now very well magnetic measurements and the shapes observed on the fast camera during the experiments.

7.11. A high order method for the approximation of integrals over simplicity defined hypersurfaces

Participants: Lukas Drescher, Holger Heumann, Kersten Schmidt.

We introduced a novel method to compute approximations of integrals over implicitly defined hypersurfaces. The new method is based on a weak formulation in L2(0,1) that uses the coarea formula to circumvent an explicit integration over the hypersurfaces. As such it is possible to use standard quadrature rules in the spirit of hp/spectral finite element methods, and the expensive computation of explicit hypersurface parametrizations is avoided. We derived error estimates showing that high order convergence can be achieved provided the integrand and the hypersurface defining function are sufficiently smooth.

7.12. FEMs on Composite Meshes for Tuning Plasma Equilibria in Tokamaks

Participants: Holger Heumann, Francesca Rapetti, Xiao Song.

We rely on a combination of different finite element methods on composite meshes, for the simulation of axisymmetric plasma equilibria in tokamaks. One mesh with Cartesian quadrilaterals covers the burning chamber and one mesh with triangles discretizes the region outside the chamber. The two meshes overlap in a narrow region around the chamber. This approach gives the flexibility to achieve easily and at low cost higher order regularity for the approximation of the flux function in the area that is covered by the plasma, while preserving accurate meshing of the geometric details in the exterior. The continuity of the numerical solution across the boundary of each subdomain is enforced by a mortar-like projection. Higher order regularity is very beneficial to improve computational tools for tokamak research. In [13], we showed that the numerical calculation of free boundary plasma equilibria highly benefits from approximating the poloidal flux through some higher regular FE functions in the interior of the limiter. In the present work we show how the composite meshes and higher regular finite element functions allow to single out snowflake configurations, that play an important role to mitigate heat load in divertors. Implementations and numerical test were carried out in FEEQS.M

7.13. Automating the design of tokamak experiment scenarios

Participants: Jacques Blum, Holger Heumann, Xiao Song.

The real-time control of plasma position, shape and current in a tokamak has to be ensured by the Poloidal Field (PF) system. A standard strategy is to feedback-control the currents in the PF coils in order to match reference currents, the latter being a combination of FeedForward (FF) and FeedBack (FB) terms. While the FB part allows a precise control, it can work only near the target and therefore the FF part is essential to "guide" the system, i.e. to approximately reach the target while remaining clear from hardware limits. An essential part of tokamak scenario design is therefore the construction of these FF waveforms. A tool for automatic FF waveforms optimisation (the inverse evolutive mode of the Free-Boundary Equilibrium [FBE] solver FEEQS.M) has been developed recently in the frame of a collaboration with IRFM, CEA. This tool reduces drastically the amount of human work needed to design optimized scenarios compatible with hardware limits. Xiao Song has performed first applications and validations of this tool on present and future machines such as WEST and ITER. This preliminary work focused on the choice of the cost-function and compared different choices for the same type of discharge. A second key aspect of this work was the treatment of inequality constraints via penalisation terms.

7.14. Higher order FEM for Free-Boundary Equilibrium in FEEQS

Participant: Holger Heumann.

We extended FEEQS.M to work with higher order finite element functions (polynomials of degree 1, ... 11, or Powell-Sabin spline finite element functions). This feature is currently available only for the static modes. The free-boundary aspect is addressed by a subdivision approach, that needs to be improved in the future, to increase the accuracy.

7.15. The two temperature MHD model

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

The dynamics of plasma charged particles can be described by a two-fluid MHD model. This description considers a plasma as a mixture of ions fluid and electrons flow that are coupled by exchanged terms such as momentum transfer terms, ion and electron heating terms due to collisions, supplemented by the Maxwell's equations. This system is quite intricate so that it is usually reduced to more tractable models. We first derive the two-temperature model, the ideal and resistive MHD equations from the two-fluid MHD system, and show that they correspond to asymptotic regimes for weakly and strongly magnetized plasmas. We then propose a finite volume approximation to compute the solutions of these models in unstructured tessellations used to appropriate mesh the toroidal geometry of the tokamak, where flows the plasma. The formulation of the magnetic field as Euler potential ensures the divergence free constraint in cheap manner, while a relaxation scheme for the two temperature allows an accurate computation of the electron and ion temperatures.

7.16. Spectral element schemes for dispersive equations

Participants: Sebastian Minjeaud, Richard Pasquetti.

S. Minjeaud and R. Pasquetti have addressed the Korteweg-de Vries equation as an interesting model of high order PDE, in order to show that it is possible to develop reliable and effective schemes, in terms of accuracy, computational efficiency, simplicity of implementation and, if required, conservation of the lower invariants, on the basis of a (only) H^1-conformal Galerkin approximation, namely the Spectral Element Method (SEM). The proposed approach relies on the introduction of additional variables that can be trivially eliminated, because the SEM mass matrix is diagonal, thus allowing to define discrete high order differentiation operators. Highly accurate RK IMEX schemes are used in time, with implicit treatment of the third order term and explicit treatment of the convective one. While the conservation of the mass invariant is natural, the conservation of the energy invariant is enforced by interpolation between embedded IMEX schemes, with preservation of the time discretization accuracy. Applications to several test problems have shown the robustness and accuracy of the proposed method, that is *a priori* easily extensible to other PDEs and to multidimensional problems (See [38]).

7.17. Cubature nodes for spectral element methods on symplicial meshes

Participants: Richard Pasquetti, Francesca Rapetti.

In a recent JCP paper (see [37]), a higher order triangular spectral element method (TSEM) is proposed to address seismic wave field modeling. The main interest of this TSEM is that the mass matrix is diagonal, so that an explicit time marching becomes very cheap. In [16], R. Pasquetti and F. Rapetti have compared this cubature points based method to the Fekete-Gauss one, that makes use of Fekete points for interpolation and of Gauss points for quadrature. Moreover, they have proposed an extension of this cubature TSEM to address elliptic PDEs with non homogeneous Neumann or Robin boundary conditions. More recently, the cubature TSEM has been experimented with isoparametric mappings to consider the case of non polygonal computational domains. In any cases it turns out that the cubature TSEM compares well with the Fekete-Gauss one.

7.18. Validation of the Full MHD with Bohm Boundary conditions

Participants: Boniface Nkonga, Guido Huijsmans, Ashish Bhole.

We have implemented Bohm mach condition using penalty boundary integral over open field lines. We have added temperature dependent viscosity and parallel conductivity, Bohm condition on energy flux. The JET configuration has been considered with success to reach the equilibrium with Bohm conditions on the divertor. However, the solution needs to be improved at the separatrix close to the boundary by a proper numerical stabilization. These structures disappear with constant resistivity. First n=10 ballooning mode in JET has been considered and need to be compared to the reduced MHD results. In order to proceed to these comparisons, a model for the reduced model has been derived including modeling of the viscosity. Validations on circular geometries are on going.

7.19. Non-linear MHD simulations of QH-mode DIII-D plasmas : ITER high Q scenarios

Participants: Feng Liu, Guido Huijsmans, Alberto Loarte, Boniface Nkonga.

In nonlinear MHD simulations of DIII-D QH-mode plasmas it has been found that low n kink/peeling modes (KPMs) are unstable and grow to a saturated kink-peeling mode. The features of the dominant saturated KPMs, which are localized toroidally by non-linear coupling of harmonics, such as mode frequencies, density fluctuations and their effect on pedestal particle and energy transport, are in good agreement with the observations of the Edge Harmonic Oscillation (EHO) typically present in DIII-D QH-mode experiments. The non-linear evolution of MHD modes including both kink-peeling modes and ballooning modes, is investigated through MHD simulations by varying the pedestal current and pressure relative to the initial conditions of DIII-D QH-mode plasma. The edge current and pressure at the pedestal are key parameters for the plasma either saturating to a QH-mode regime or a ballooning mode dominant regime. The influence of E×B flow and its shear on the QH-mode plasma has been investigated. E×B flow shear has a strong stabilization effect on the medium to high-n modes but is destabilizing for the n=2 mode. The QH-mode extrapolation results of an ITER Q=10 plasma show that the pedestal currents are large enough to destabilize n=1-5 kink/peeling modes, leading to a stationary saturated kink-peeling mode.

7.20. Sharpening diffuse interfaces with compressible fluids on unstructured meshes

Participants: Alexandre Chiapolino, Richard Saurel, Boniface Nkonga.

Diffuse interface methods with compressible fluids, considered through hyperbolic multiphase flow models, have demonstrated their capability to solve a wide range of complex flow situations in severe conditions (both high and low speeds). These formulations can deal with the presence of shock waves, chemical and physical transformations, such as cavitation and detonation. Compared to existing approaches able to consider compressible materials and interfaces, these methods are conservative with respect to mixture mass, momentum, energy and are entropy preserving. Thanks to these properties they are very robust. However, in many situations, typically in low transient conditions, numerical diffusion at material interfaces is excessive. Several approaches have been developed to lower this weakness. In the present contribution, a specific flux limiter is proposed and inserted into conventional MUSCL type schemes, in the frame of the diffuse interface formulation of Saurel et al. (2009). With this limiter, interfaces are captured with almost two mesh points at any time, showing significant improvement in interface representation. The method works on both structured and unstructured meshes and its implementation in existing codes is simple. Computational examples showing method capabilities and accuracy are presented.

8. Partnerships and Cooperations

8.1. National Initiatives

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

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

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

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

Contact : Hervé Guillard

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. EuroFusion Consortium

CASTOR participates to the following EuroFusion consortium projects :

- CfP-WP14-ER-01/Swiss Confederation-01. École Polytechnique Fédérale de Lausanne (PI: Paolo Ricci) "Synergetic numerical-experimental approach to fundamental aspects of turbulent transport in the tokamak edge"
- CfP-WP14-ER-01/CEA-01. CEA (PI: Matthias Hoelzl IPP) "JOREK, BOUT++ non-linear MHD modelling of MHD instabilities and their control in existing tokamaks and ITER"
- Enabling research contract 2014-2018. (B. Nkonga, H. Guillard, A. Sangam) CfP-WP15-ENR-01/IPP-05, Grant agreement No 633053. «Global non-linear MHD modeling in toroidal X-point geometry of disruptions, edge localized modes, and techniques for their mitigation and suppression »
- EUROfusion WPCD (Working Package Code Development)
  - ACT1: Extended equilibrium and stability chain (participation)
  - ACT2: Free boundary equilibrium and control (participation and coordination)

8.2.1.2. EoCoE

Title: Energy oriented Centre of Excellence for computer applications

Programm: H2020

Duration: October 2015 - October 2018

Coordinator: CEA

Inria contact: Michel Kern

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

8.3. International Initiatives

8.3.1. Inria International Partners

The team collaborates with TUC (Technical University of Crete, Prof. Argyris Delis) on extension of the shallow water model to turbulent flows. These common works overlap with the collaboration with Taiwan in the framework of the former AMOSS associate team. [27]

8.3.2. Participation in Other International Programs

ITER Contracts (B. Nkonga):

- ITER IO/17/CT/4300001505 : 2017-2019, "Non-linear MHD simulations for ITER QH-mode plasma with & without 3D magnetic field perturbations from in-vessel ELM control coils". (150KE)
- ITER IO/15/PR/11410/MCI: 2015-2017, "Modeling of plasma instabilities in ITER" (120KE)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Conference Program Committees

Jacques Blum is member of the scientific commmittee of PICOF 18 (Inverse Problem, Control and Shape Optimization) which will take place in Beirut in 2018.

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

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

9.1.2.2. Reviewer - Reviewing Activities

- Hervé Guillard have been reviewer fo the Journal of Computational physics, Computers and Fluids and Internationa l Journal for Numerical methods in Fluids.
- R. Pasquetti has been reviewer for several journals, including the journal of Computational Physics and Computers and Fluids.

9.1.3. Invited Talks

- Hervé Guillard, “Fast waves and incompressible models”, School of Aerospace, Mechanical and Mechatronic Engine ering The University of Sydney, NSW 2006
- Hervé Guillard, “Fast waves and incompressible models”, Plasma Theory and Modelling, Centre for Plasmas and Fluids, Research School of Physics and Engineering, Australian National University, Canberra ACT 0200, AUS TRALIA
- Hervé Guillard, Workshop "Schémas numériques pour les écoulements à faible nombre de Mach", November 20-22 2017
- R. Pasquetti, Spectral element schemes for the Korteweg-de Vries and Saint-Venant equations, Rencontres Mathématiques - Mécanique du CFM 2017, Lille, August 28 - September 1, 2017

9.1.4. Leadership within the Scientific Community

- J. Blum is:
  - a member of the scientific committee of Academy 1 of UCA-IDEX JEDI: «Networks, Information and Digital society»,
  - member of the "bureau" and the director committee of the Fédération FR-FCM (Fédération de Recherche Fusion par Confinement Magnétique - ITER).
- H. Guillard is coordinator of the topic "Turbulence and transport of edge plasma" within the Fédération FR-FCM
- C. Boulbe is task coordinator of the ACT2: Free boundary equilibrium and Control within the Eurofusion WPCD workpackage.
- Responsabilities of Boniface Nkonga
  - Treasure of ECCOMAS, member of the Managing Board : 2017-2021. ECCOMAS : European Community on Computational Methods in Applied Sciences.
  - Scientific committee of EoCoe : 2016-2020.
  - Manager of the ITER contract IO/17/CT/4300001505 : 2017-2019.
  - Manager of the ITER contract IO/15/PR/11410/MCI: 2015-2017.
  - Manager of the Enabling research contract CfP-WP15-ENR-01/IPP-05 : 2014-2018
- Didier Auroux is president of the "Computer Science, Algorithms and Mathematics" committee of GENCI (HPC and numerical simulations)

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

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

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

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

Master: J. Blum, Optimisation, 36h, M1, Université de Nice Sophia Antipolis, France

Ecole d’ingénieur: C. Boulbe, Analyse Numérique, 71.5h, L3, Polytech Nice Sophia Antipolis, France

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

Ecole d’ingenieur: C. Boulbe, Projet, 35h, L3, Polytech Nice Sophia Antipolis, France

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

Master: S. Minjeaud, module Méthodes numériques en EDP, 36 h, M1, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, module Analyse et simulations numériques pour les EDP, 20 h, M2, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, module Simulations numériques des problèmes d'évolution, 20 h, M2, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, Méthodes numériques en EDP, 18 h, M1, Université de Nice Sophia Antipolis, France.

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

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

Ecole d'ingénieur/Master: B. Nkonga, Eléments finis mixtes, 24h, M2, Polytech Nice Sophia, France

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

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

Licence: A. Sangam, Méthodes Numériques et Formelles, 40h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse Numérique, 68h, L3, Université de Nice Sophia Antipolis, France

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

9.2.2. Supervision

PhD : Estibals, Elise,MHD modeling and numerical simulation with finite volume-type methods. Application to fusion plasma, Université Côte d'Azur, 2017 May 2nd, PhD Supervisors : Hervé Guillard, Afeintou Sangam. [6]

PhD in progress : X. Song, "Model based control oriented scenario construction in Tokamak", since October 2016, Blaise Faugeras, Holger Heumann.

PhD in progress : J. Llobell, "Schémas numériques sur grilles décalées pour la dynamique des gaz", since October 2015, T. Goudon, S. Minjeaud.

9.2.3. Juries

Boniface Nkonga

- Phd Reports and Jury: E. Itam, Univ de Montpellier, H. Gidey, Univ. of Pretoria (Sud Africa).
- Jury HDR, Jacek Narski, Univ. de Toulouse, 2017.

10. Bibliography

Major publications by the team in recent years

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[2] B. Faugeras, J. Blum, C. Boulbe, P. Moreau, E. Nardon. *2D interpolation and extrapolation of discrete magnetic measurements with toroidal harmonics for equilibrium reconstruction in a Tokamak*, in "Plasma Phys. Control Fusion", 2014, vol. 56

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[5] J. VIDES, B. NKONGA, E. AUDIT. *A Simple Two-Dimensional Extension of the HLL Riemann Solver for Hyperbolic Systems of Conservation Laws*, in "Journal of Computational Physics", January 2015, vol. 280, pp. 643-675 [*DOI :* 10.1016/J.JCP.2014.10.013], https://hal.inria.fr/hal-01103529

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Doctoral Dissertations and Habilitation Theses

[6] E. ESTIBALS. *MHD Modeling and Numerical Simulation with Finite Volume-type Methods. Application to Fusion Plasmas*, Université Nice Côte d'Azur, May 2017, https://hal.inria.fr/tel-01551701

Articles in International Peer-Reviewed Journals

[7] D. S. BALSARA, B. NKONGA. *Multidimensional Riemann problem with self-similar internal structure–Part III–A multidimensional analogue of the HLLI Riemann solver for conservative hyperbolic systems*, in "Journal of Computational Physics", October 2017, vol. 346, pp. 25-48, https://hal.inria.fr/hal-01589114

[8] A. CHIAPOLINO, R. SAUREL, B. NKONGA. *Sharpening diffuse interfaces with compressible fluids on unstructured meshes*, in "Journal of Computational Physics", July 2017, vol. 340, pp. 389-417, https://hal.inria.fr/hal-01589124

[9] L. DRESCHER, H. HEUMANN, K. SCHMIDT. *A High Order Method for the Approximation of Integrals Over Implicitly Defined Hypersurfaces*, in "SIAM Journal on Numerical Analysis", November 2017, vol. 55, n^{o} 6, pp. 2592 - 2615 [*DOI :* 10.1137/16M1102227], https://hal.archives-ouvertes.fr/hal-01637946

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[23] A. LOSEILLE, A. LOYER, H. GUILLARD. *Coupling Grad-Shafranov equilibrium solvers and grid generation to study plasma confinement properties in nuclear fusion devices*, in "Coupled Problems 2017 - VII International Conference on Coupled Problems in Science and Engineering", Rhodes, Greece, June 2017, vol. 31, 190103 p. , https://hal.inria.fr/hal-01644328

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