Activity Report 2015

Team TONUS

TOkamaks and NUmerical Simulations

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Nancy - Grand Est

THEME
Earth, Environmental and Energy Sciences

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Team TONUS

Creation of the Team: 2012 January 01

Keywords:

Computer Science and Digital Science:

6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization

Other Research Topics and Application Domains:

4.1.3. - Fusion
5.2.3. - Aviation
6.1.1. - Software engineering

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2. Overall Objectives

2.1. Overall Objectives

TONUS started in January 2014. It is a team of the Inria Nancy-Grand Est center. It is located in the mathematics institute (IRMA) of the university of Strasbourg.

The International Thermonuclear Experimental Reactor (ITER) is a large-scale scientific experiment that aims to demonstrate that it is possible to produce energy from fusion, by confining a very hot hydrogen plasma inside a toroidal chamber, called tokamak. In addition to physics and technology research, tokamak design also requires mathematical modeling and numerical simulations on supercomputers.

The objective of the TONUS project is to deal with such mathematical and computing issues. We are mainly interested in kinetic and gyrokinetic simulations of collisionless plasmas. In the TONUS project-team we are working on the development of new numerical methods devoted to such simulations. We investigate several classical plasma models, study new reduced models and new numerical schemes adapted to these models. We implement our methods in two software projects: Selalib [1] and SCHNAPS [2] adapted to new computer architectures. We intend to run challenging simulations on high performance computers with thousands of nodes.

We have strong relations with the CEA-IRFM team and participate to the development of their gyrokinetic simulation software GYSELA. We are involved into two Inria Project Labs, respectively devoted to tokamak mathematical modeling and high performance computing on future exascale super-computers. We also collaborate with a small company in Strasbourg specialized in numerical software for applied electromagnetics.

Finally, our subjects of interest are at the interaction between mathematics, computer science, High Performance Computing, physics and practical applications.

3. Research Program

3.1. Kinetic models for plasmas

The fundamental model for plasma physics is the coupled Vlasov-Maxwell kinetic model: the Vlasov equation describes the distribution function of particles (ions and electrons), while the Maxwell equations describe the electromagnetic field. In some applications, it may be necessary to take into account relativistic particles, which lead to consider the relativistic Vlasov equation, but generally, tokamak plasmas are supposed to be non relativistic. The particles distribution function depends on seven variables (three for space, three for velocity and one for time), which yields a huge amount of computations.

To these equations we must add several types of source terms and boundary conditions for representing the walls of the tokamak, the applied electromagnetic field that confines the plasma, fuel injection, collision effects, etc.

Tokamak plasmas possess particular features, which require developing specialized theoretical and numerical tools.

Because the magnetic field is strong, the particle trajectories have a very fast rotation around the magnetic field lines. A full resolution would require prohibitive amount of calculations. It is then necessary to develop models where the cyclotron frequency tends to infinity in order to obtain tractable calculations. The resulting model is called a gyrokinetic model. It allows us to reduce the dimensionality of the problem. Such models are implemented in GYSELA and Selalib. Those models require averaging of the acting fields during a rotation period along the trajectories of the particles. This averaging is called the gyroaverage and requires specific discretizations.

[1] http://selalib.gforge.inria.fr/
[2] http://schnaps.gforge.inria.fr

The tokamak and its magnetics fields present a very particular geometry. Some authors have proposed to return to the intrinsic geometrical versions of the Vlasov-Maxwell system in order to build better gyrokinetic models and adapted numerical schemes. This implies the use of sophisticated tools of differential geometry: differential forms, symplectic manifolds, and hamiltonian geometry.

In addition to theoretical modeling tools, it is necessary to develop numerical schemes adapted to kinetic and gyrokinetic models. Three kinds of methods are studied in TONUS: Particle-In-Cell (PIC) methods, semi-Lagrangian and fully Eulerian approaches.

3.1.1. Gyrokinetic models: theory and approximation

In most phenomena where oscillations are present, we can establish a three-model hierarchy: (i) the model parameterized by the oscillation period, (ii) the limit model and (iii) the Two-Scale model, possibly with its corrector. In a context where one wishes to simulate such a phenomenon where the oscillation period is small and where the oscillation amplitude is not small, it is important to have numerical methods based on an approximation of the Two-Scale model. If the oscillation period varies significantly over the domain of simulation, it is important to have numerical methods that approximate properly and effectively the model parameterized by the oscillation period and the Two-Scale model. Implemented Two-Scale Numerical Methods (for instance by Frénod et al. [30]) are based on the numerical approximation of the Two-Scale model. These are called of order 0. A Two-Scale Numerical Method is called of order 1 if it incorporates information from the corrector and from the equation to which this corrector is a solution. If the oscillation period varies between very small values and values of order 1, it is necessary to have new types of numerical schemes (Two-Scale Asymptotic Preserving Schemes of order 1 or TSAPS) with the property of being able to preserve the asymptotics between the model parameterized by the oscillation period and the Two-Scale model with its corrector. A first work in this direction has been initiated by Crouseilles et al. [28].

3.1.2. Semi-Lagrangian schemes

The Strasbourg team has a long and recognized experience in numerical methods of Vlasov-type equations. We are specialized in both particle and phase space solvers for the Vlasov equation: Particle-in-Cell (PIC) methods and semi-Lagrangian methods. We also have a longstanding collaboration with the CEA of Cadarache for the development of the GYSELA software for gyrokinetic tokamak plasmas.

The Vlasov and the gyrokinetic models are partial differential equations that express the transport of the distribution function in the phase space. In the original Vlasov case, the phase space is the six-dimension position-velocity space. For the gyrokinetic model, the phase space is five-dimensional because we consider only the parallel velocity in the direction of the magnetic field and the gyrokinetic angular velocity instead of three velocity components.

A few years ago, Eric Sonnendrücker and his collaborators introduce a new family of methods for solving transport equations in the phase space. This family of methods are the semi-Lagrangian methods. The principle of these methods is to solve the equation on a grid of the phase space. The grid points are transported with the flow of the transport equation for a time step and interpolated back periodically onto the initial grid. The method is then a mix of particle Lagrangian methods and eulerian methods. The characteristics can be solved forward or backward in time leading to the Forward Semi-Lagrangian (FSL) or Backward Semi-Lagrangian (BSL) schemes. Conservative schemes based on this idea can be developed and are called Conservative Semi-Lagrangian (CSL).

GYSELA is a 5D full gyrokinetic code based on a classical backward semi-Lagrangian scheme (BSL) [38] for the simulation of core turbulence that has been developed at CEA Cadarache in collaboration with our team [31]. Although GYSELA was carefully developed to be conservative at lowest order, it is not exactly conservative, which might be an issue when the simulation is under-resolved, which always happens in turbulence simulations due to the formation of vortices which roll up.

3.1.3. PIC methods

Historically PIC methods have been very popular for solving the Vlasov equations. They allow solving the equations in the phase space at a relatively low cost. The main disadvantage of the method is that, due to its random aspect, it produces an important numerical noise that has to be controlled in some way, for instance by regularizations of the particles, or by divergence correction techniques in the Maxwell solver. We have a longstanding experience in PIC methods and we started implement them in Selalib. An important aspect is to adapt the method to new multicore computers. See the work by Crestetto and Helluy [27].

3.2. Reduced kinetic models for plasmas

As already said, kinetic plasmas computer simulations are very intensive, because of the gyrokinetic turbulence. In some situations, it is possible to make assumptions on the shape of the distribution function that simplify the model. We obtain in this way a family of fluid or reduced models.

Assuming that the distribution function has a Maxwellian shape, for instance, we obtain the MagnetoHydroDynamic (MHD) model. It is physically valid only in some parts of the tokamak (at the edges for instance). The fluid model is generally obtained from the hypothesis that the collisions between particles are strong. Fine collision models are mainly investigated by other partners of the IPL (Inria Project Lab) FRATRES. In our approach we do not assume that the collisions are strong, but rather try to adapt the representation of the distribution function according to its shape, keeping the kinetic effects. The reduction is not necessarily a consequence of collisional effects. Indeed, even without collisions, the plasma may still relax to an equilibrium state over sufficiently long time scales (Landau damping effect). Recently, a team at the Plasma Physics Institut (IPP) in Garching has carried out a statistical analysis of the 5D distribution functions obtained from gyrokinetic tokamak simulations [32]. They discovered that the fluctuations are much higher in the space directions than in the velocity directions (see Figure 1).

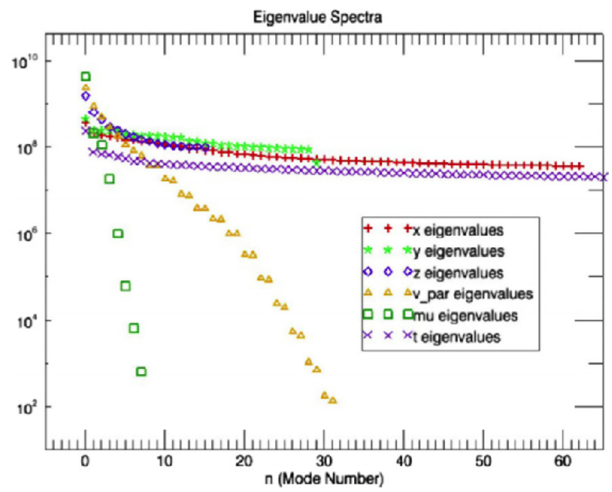

Figure 1. Space and velocity fluctuations spectra (from [32])

This indicates that the approximation of the distribution function could require fewer data while still achieving a good representation, even in the collisionless regime.

Our approach is different from the fluid approximation. In what follows we call this the “reduced model” approach. A reduced model is a model where the explicit dependency on the velocity variable is removed. In a more mathematical way, we consider that in some regions of the plasma, it is possible to exhibit a (preferably small) set of parameters α that allows us to describe the main properties of the plasma with a generalized “Maxwellian” M. Then

$$f(x, v, t) = M(\alpha(x, t), v).$$

In this case it is sufficient to solve for $\alpha(x, t)$. Generally, the vector α is solution of a first order hyperbolic system.

Several approaches are possible: waterbag approximations, velocity space transforms, *etc.*

3.2.1. Velocity space transformations

An experiment made in the 60's [35] exhibits in a spectacular way the reversible nature of the Vlasov equations. When two perturbations are applied to a plasma at different times, at first the plasma seems to damp and reach an equilibrium. But the information of the perturbations is still here and "hidden" in the high frequency microscopic oscillations of the distribution function. At a later time a resonance occurs and the plasma produces an echo. The time at which the echo occurs can be computed (see Villani [3], page 74). The fine mathematical study of this phenomenon allowed C. Villani and C. Mouhot to prove their famous result on the rigorous nonlinear Landau damping [37].

More practically, this experiment and its theoretical framework show that it is interesting to represent the distribution function by an expansion on an orthonormal basis of oscillating functions in the velocity variables. This representation allows a better control of the energy transfer between the low frequencies and the high frequencies in the velocity direction, and thus provides more relevant numerical methods. This kind of approach is studied for instance by Eliasson in [29] with the Fourier expansion.

In long time scales, filamentation phenomena result in high frequency oscillations in velocity space that numerical schemes cannot resolve. For stability purposes, most numerical schemes contain dissipation mechanisms that may affect the precision of the finest oscillations that could be resolved.

3.2.2. Adaptive modeling

Another trend in scientific computing is to optimize the computation time through adaptive modeling. This approach consists in applying the more efficient model locally, in the computational domain, according to an error indicator. In tokamak simulations, this kind of approach could be very efficient, if we are able to choose locally the best intermediate kinetic-fluid model as the computation runs. This field of research is very promising. It requires developing a clever hierarchy of models, rigorous error indicators, versatile software architecture, and algorithms adapted to new multicore computers.

3.2.3. Numerical schemes

As previously indicated, an efficient method for solving the reduced models is the Discontinuous Galerkin (DG) approach. It is possible to make it of arbitrary order. It requires limiters when it is applied to nonlinear PDEs occurring for instance in fluid mechanics. But the reduced models that we intent to write are essentially linear. The nonlinearity is concentrated in a few coupling source terms.

In addition, this method, when written in a special set of variables, called the entropy variables, has nice properties concerning the entropy dissipation of the model. It opens the door to constructing numerical schemes with good conservation properties and no entropy dissipation, as already used for other systems of PDEs [39], [25], [34], [33].

3.3. Electromagnetic solvers

A precise resolution of the electromagnetic fields is essential for proper plasma simulation. Thus it is important to use efficient solvers for the Maxwell systems and its asymptotics: Poisson equation and magnetostatics.

The proper coupling of the electromagnetic solver with the Vlasov solver is also crucial for ensuring conservation properties and stability of the simulation.

[3] Landau damping. CEMRACS 2010 lectures. http://smai.emath.fr/cemracs/cemracs10/PROJ/Villani-lectures.pdf

Finally plasma physics implies very different time scales. It is thus very important to develop implicit Maxwell solvers and Asymptotic Preserving (AP) schemes in order to obtain good behavior on long time scales.

3.3.1. Coupling

The coupling of the Maxwell equations to the Vlasov solver requires some precautions. The most important is to control the charge conservation errors, which are related to the divergence conditions on the electric and magnetic fields. We will generally use divergence correction tools for hyperbolic systems presented for instance in [22] (and included references).

3.3.2. Implicit solvers

As already pointed out, in a tokamak, the plasma presents several different space and time scales. It is not possible in practice to solve the initial Vlasov-Maxwell model. It is first necessary to establish asymptotic models by letting some parameters (such as the Larmor frequency or the speed of light) tend to infinity. This is the case for the electromagnetic solver and this requires implementing implicit time solvers in order to efficiently capture the stationary state, the solution of the magnetic induction equation or the Poisson equation.

4. Application Domains

4.1. Controlled fusion and ITER

The search for alternative energy sources is a major issue for the future. Among others, controlled thermonuclear fusion in a hot hydrogen plasma is a promising possibility. The principle is to confine the plasma in a toroidal chamber, called a tokamak, and to attain the necessary temperatures to sustain nuclear fusion reactions. The International Thermonuclear Experimental Reactor (ITER) is a tokamak being constructed in Cadarache, France. This was the result of a joint decision by an international consortium made of the European Union, Canada, USA, Japan, Russia, South Korea, India and China. ITER is a huge project. As of today, the budget is estimated at 20 billion euros. The first plasma shot is planned for 2020 and the first deuterium-tritium operation for 2027.

Many technical and conceptual difficulties have to be overcome before the actual exploitation of fusion energy. Consequently, much research has been carried out around magnetically confined fusion. Among these studies, it is important to carry out computer simulations of the burning plasma. Thus, mathematicians and computer scientists are also needed in the design of ITER. The reliability and the precision of numerical simulations allow a better understanding of the physical phenomena and thus would lead to better designs. TONUS's main involvement is in such research.

The required temperatures to attain fusion are very high, of the order of a hundred million degrees. Thus it is imperative to prevent the plasma from touching the tokamak inner walls. This confinement is obtained thanks to intense magnetic fields. The magnetic field is created by poloidal coils, which generate the toroidal component of the field. The toroidal plasma current also induces a poloidal component of the magnetic field that twists the magnetic field lines. The twisting is very important for the stability of the plasma. The idea goes back to research by Tamm and Sakharov, two Russian physicists, in the 50's. Other devices are essential for the proper operation of the tokamak: divertor for collecting the escaping particles, microwave heating for reaching higher temperatures, fuel injector for sustaining the fusion reactions, toroidal coils for controlling instabilities, etc.

4.2. Other applications

The software and numerical methods that we develop can also be applied to other fields of physics or of engineering.

- For instance, we have a collaboration with the company AxesSim in Strasbourg for the development of efficient Discontinuous Galerkin (DG) solvers on hybrid computers. The applications is electromagnetic simulations for the conception of antenna, electronic devices or aircraft electromagnetic compatibility.
- The acoustic conception of large rooms requires huge numerical simulations. It is not always possible to solve the full wave equation and many reduced acoustic models have been developed. A popular model consists in considering "acoustic" particles moving at the speed of sound. The resulting Partial Differential Equation (PDE) is very similar to the Vlasov equation. The same modeling is used in radiation theory. We have started to work on the reduction of the acoustic particles model and realized that our reduction approach perfectly applies to this situation. A new PhD with CEREMA (Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement) has started in October 2015 (thesis of Pierre Gerhard). The objective is to investigate the model reduction and to implement the resulting acoustic model in our DG solver.

5. Highlights of the Year

5.1. Highlights of the Year

We have launched the SCHNAPS project: http://schnaps.gforge.inria.fr/. Its goal is to develop a high performance software for plasma simulations. It is based on the runtime tool StarPU developed at Inria Bordeaux. The objective is to perform asynchronous hybrid CPU/GPU computations on HPC computers.

6. New Software and Platforms

6.1. SCHNAPS

Participants: Emmanuel Franck, Pierre Gerhard, Philippe Helluy [correspondent], Michel Massaro, Malcolm Roberts, Bruno Weber.

Solveur pour les lois de Conservation Hyperboliques Non-linéaires Appliqué aux PlasmaS
SCIENTIFIC DESCRIPTION

It is clear now that future computers will be made of a collection of thousands of interconnected multicore processors. Globally, it appears as a classical distributed memory MIMD machine. But at a lower level, each of the multicore processors is itself made of a shared memory MIMD unit (a few classical CPU cores) and a SIMD unit (a GPU). When designing new algorithms, it is important to adapt them to this kind of architecture. Our philosophy will be to program our algorithms in such a way that they can be run efficiently on this kind of computers. Practically, we will use the MPI library for managing the coarse grain parallelism, while the OpenCL library will efficiently operate the fine grain parallelism.

We have invested for several years until now into scientific computing on GPUs, using the open standard OpenCL (Open Computing Language). We were recently awarded a prize in the international AMD OpenCL innovation challenge thanks to an OpenCL two-dimensional Vlasov-Maxwell solver that fully runs on a GPU. OpenCL is a very interesting tool because it is an open standard now available on almost all brands of multicore processors and GPUs. The same parallel program can run on a GPU or a multicore processor without modification. OpenCL programs are quite complicated to construct. For instance it is difficult to distribute efficiently the computation or memory operations on the different available accelerators. StarPU http://starpu.gforge.inria.fr/ is a runtime system developed at Inria Bordeaux that simplifies the distribution of tasks on heterogeneous compute units. We have started to use this software tool in SCHNAPS.

Because of the envisaged applications, which may be either academic or commercial, it is necessary to conceive a modular framework. The heart of the library is made of generic parallel algorithms for solving conservation laws. The parallelism can be both fine-grained (oriented towards GPUs and multicore processors) and coarse-grained (oriented towards GPU clusters). The separate modules allow managing the meshes and some specific applications. With our partner AxesSim, we also develop a C++ specific version of SCHNAPS for electromagnetic applications.

FUNCTIONAL DESCRIPTION

SCHNAPS is a generic Discontinuous Galerkin solver, written in C, based on the OpenCL, MPI and StarPU frameworks.

- Partner: AxesSim
- Contact: Philippe Helluy
- URL: http://schnaps.gforge.inria.fr/

6.2. Selalib

Participants: Sever Adrian Hirstoaga, Michel Mehrenberger [correspondent], Pierre Navaro, Laurent Navoret, Thi Trang Nhung Pham, Christophe Steiner.

SEmi-LAgrangian LIBrary

KEYWORDS: Plasma physics - Semi-Lagrangian method - PIC - Parallel computing - Plasma turbulence

SCIENTIFIC DESCRIPTION

The objective of the Selalib project (SEmi-LAgrangian LIBrary) is to develop a well-designed, organized and documented library implementing several numerical methods for kinetic models of plasma physics. Its ultimate goal is to produce gyrokinetic simulations.

Another objective of the library is to provide to physicists easy-to-use gyrokinetic solvers, based on the semi-Lagrangian techniques developed by Eric Sonnendrücker and his collaborators in the past CALVI project. The new models and schemes from TONUS are also intended to be incorporated into Selalib.

FUNCTIONAL DESCRIPTION

Selalib is a collection of modules conceived to aid in the development of plasma physics simulations, particularly in the study of turbulence in fusion plasmas. Selalib offers basic capabilities from general and mathematical utilities and modules to aid in parallelization, up to pre-packaged simulations.

- Partners: Max Planck Institute - Garching - IRMA, Université de Strasbourg - IRMAR, Université Rennes 1 - LJLL, Université Paris 6
- Contact: Michel Mehrenberger
- URL: http://selalib.gforge.inria.fr/

6.3. Django

Participants: Emmanuel Franck [correspondent], Boniface Nkonga, Ahmed Ratnani.

- Scientific description:
  The JOREK code is one of the most important MHD codes in Europe. This code written 15 years ago allows to simulate the MHD instabilities which appear in the TOKAMAK. Using this code the physicist has obtained some important results. However to run larger and more complex test cases it is necessary to evolve the numerical methods used.
  In 2014, the DJANGO code has been created, the aim of this code is double: have a numerical library to implement, test and validate new numerical methods for MHD, fluid mechanics and Electromagnetic equations in the finite element context and prepare the future new JOREK code. This code is a 2D-3D code based on implicit time schemes and IsoGeometric (B-Splines, Bezier curves) for the spatial discretization.
- Functional description:

DJANGO is a finite element implicit solver written in Fortran 2003 with a Basic MPI framework. The code is coupled with the PETSC library for the linear solvers and the code CAID (A. Ratnani) for the mesh.

- Authors:
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- Contributors:
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- Year 2015:
The year 2015 is an important year for the JOREK code. Indeed, after the year 2014 where the IsoParametric (Bezier curves) finite element approach in 2D have been implemented for basic elliptic equations, in 2015 we have extended the code for more complex problems. Now the code can treat some hyperbolic, parabolic and elliptic models with different approaches (IsoParametric/IsoGeometric approach, Splines for triangle) in 2D and 3D by tensor product. The compilation of the code is more stable and some regression test cases have been added. To finish, two realistic MHD models (which come from to the JOREK code) have been implemented and must be validated. The Year 2016 will be the year of the first physical and realistic results.

7. New Results

7.1. Particle-in-cell simulations for highly oscillatory Vlasov-Poisson systems

Participants: Edwin Chacon Golcher, Sever Adrian Hirstoaga [correspondent], Mathieu Lutz.

The aim of the following works is to study the dynamics of charged particles under the influence of a strong magnetic field by numerically solving in an efficient way the Vlasov-Poisson and guiding center models.

First, we work on the development of the time-stepping method introduced in [7], [8] in two directions: improve the accuracy of the algorithm and adapt the algorithm for general configuration of magnetic field.

Second, by using appropriate data structures, we implement an efficient (from the memory access point of view) Particle-In-Cell method which enables simulations with a large number of particles. Thus, we present in [13] numerical results for classical one-dimensional Landau damping and two-dimensional Kelvin-Helmholtz test cases. The implementation also relies on a standard hybrid MPI/OpenMP parallelization. Code performance is assessed by the observed speedup and attained memory bandwidth. A convergence result is also illustrated by comparing the numerical solution of a four-dimensional Vlasov-Poisson system against the one for the guiding center model.

7.2. Eulerian simulations of parallel transport in the SOL

Participants: David Coulette, Sever Adrian Hirstoaga [correspondent], Giovanni Manfredi.

We continue to investigate kinetic models for simulating the heat load on the divertor plates during transient events as edge-localised modes (ELMs). Our previous work [36] deals with Vlasov-Poisson equations for two particle species for the dynamics of their transport parallel to the magnetic field. We started to improve this model by adding an equation for the evolution in time of the perpendicular temperatures. These equations take also into account the collisions between species which may play a role over long times. The first numerical results are encouraging, showing different features with respect to the older (simpler) model when computing total particles and energy fluxes on the divertor plates.

7.3. Quasi-neutrality equation in a polar mesh

Participants: Christophe Steiner [correspondent], Michel Mehrenberger, Nicolas Crouseilles, Philippe Helluy.

In this work [21], we are concerned with the numerical resolution of the quasi-neutrality equation arising in plasma physics. A classic method is based on a Padé approximation. Two other methods are proposed in this paper: a high order Padé approximation and a direct method in the space configuration which consists in integrating on the gyrocircles using an interpolation operator. Numerical comparisons are performed with analytical solutions and considering the 4D drift-kinetic model with one Larmor radius. This is a preliminary study; further study in GYSELA is envisioned.

7.4. The Semi-Lagrangian method on curvilinear grids

Participants: Aurore Back, Adnane Hamiaz, Michel Mehrenberger [correspondent], Pierre Navaro, Hocine Sellama, Eric Sonnendrücker.

We study the semi-Lagrangian method on curvilinear grids [18], [9]. The classical backward semi-Lagrangian method preserves constant states but is not mass conservative. Natural reconstruction of the field permits nevertheless to have at least first order in time conservation of mass, even if the spatial error is large. Interpolation is performed with classical cubic splines and also cubic Hermite interpolation with arbitrary reconstruction order of the derivatives. High odd order reconstruction of the derivatives is shown to be a good ersatz of cubic splines which do not behave very well as time step tends to zero. A conservative semi-Lagrangian scheme is then described; here conservation of mass is automatically satisfied and constant states are shown to be preserved up to first order in time.

Semi-Lagrangian guiding center simulations are performed on sinusoidal perturbations of cartesian grids, and on deformed polar grids with different boundary conditions. Key ingredients are: the use of a B-spline finite element solver for the Poisson equation and the classical backward semi-Lagrangian method (BSL) for the advection. We are able to reproduce standard Kelvin-Helmholtz and diocotron instability tests on such grids. When the perturbation leads to a strong distorted mesh, we observe that the solution differs if one takes standard numerical parameters that are used in the cartesian reference case. We can recover good results together with correct mass conservation, by diminishing the time step.

7.5. Solving the Guiding-Center model on a regular hexagonal mesh

Participants: Michel Mehrenberger [correspondent], Laura Mendoza, Charles Prouveur, Eric Sonnendrücker.

This work [11] introduces a Semi-Lagrangian solver for the Vlasov-Poisson equations on a uniform hexagonal mesh. The latter is composed of equilateral triangles, thus it doesn't contain any singularities, unlike polar meshes. We focus on the guiding-center model, for which we need to develop a Poisson solver for the hexagonal mesh in addition to the Vlasov solver. For the interpolation step of the Semi-Lagrangian scheme, a comparison is made between the use of box-splines and of Hermite finite elements. The code will be adapted to more complex models and geometries in the future.

7.6. High-order Hamiltonian splitting for Vlasov-Poisson equations

Participants: Fernando Casas, Nicolas Crouseilles, Erwan Faou, Michel Mehrenberger [correspondent].

In this work [12], we consider the Vlasov-Poisson equation in a Hamiltonian framework and derive new time splitting methods based on the decomposition of the Hamiltonian functional between the kinetic and electric energy. Assuming smoothness of the solutions, we study the order conditions of such methods. It appears that these conditions are of Runge-Kutta-Nyström type. In the one dimensional case, the order conditions can be further simplified, and efficient methods of order 6 with a reduced number of stages can be constructed. In the general case, high-order methods can also be constructed using explicit computations of commutators. Numerical results are performed and show the benefit of using high-order splitting schemes in that context. Complete and self-contained proofs of convergence results and rigorous error estimates are also given.

7.7. Velocity space transformations: collisional case

Participants: Emmanuel Franck, Philippe Helluy [correspondent], Laurent Navoret.

The method of "velocity space transformations" allows to obtain an interesting discretization of the Kinetic equations like Vlasov-Poisson or Vlasov Maxwell equations as has been proved in the works of P. Helluy, L. Navoret and N. Pham. During this year, we have begun to extend this method to the collisional case using the entropy variable to write a general collisional operator. To treat all the regimes (small or large collisional regime), asymptotic preserving schemes (stability and convergence independent of the collisional frequency) have been designed. However, this method admits some numerical difficulties if we use the physical entropy to construct the collisional operator. Now we propose to use modified entropy, which has good numerical properties and gives limit regime close to the real one in the low Mach context. If this new approach gives interesting results, we will study the adaptivity of the velocity discrete basis which would allow to treat the collisional and non-collisional regimes with the same method.

7.8. Preconditioning and implicit solvers

Participants: Emmanuel Franck [correspondent], Philippe Helluy, Matthias Hoelzl, Ahmed Ratnani, Malcolm Roberts, Eric Sonnendrücker, Stefano Serra-Capizzano.

The Viscous-resistive MHD model used to simulate the instabilities is a multi-scale models with fast waves. In this context, it is not possible to use full explicit time schemes. However the classical implicit schemes are not usable directly since the matrices are ill-conditioned. For this reason it is necessary to use a preconditioning method. During this year we have studied a method called "physic based preconditioning" for the wave equations which consists to approximate the solution by suitable smaller and simpler systems. The results are very good. After this, we have extended this method to the Linearized Euler equation. During this new study, we have found additional difficulties which appear in some regimes. Two methods to treat this problem will be tested in 2016. We have also implemented a version of this preconditioning for the reduced MHD models of JOREK. The first results are positive. To finish, we have begun a collaboration with S. Serra-Capizzano to study at the theoretical level the physic based preconditioning and propose new preconditioning for each sub-systems of the Physic-Based PC efficient in all the physics regimes and for an arbitrary order.
We have also developed an implicit solver for the transport equation based on the upwind nature of the DG numerical flux. This solver will be used for solving Vlasov models or fluid models thanks to the Lattice-Boltzmann methodology. We have obtained recently a SPPEXA support (http://www.sppexa.de) in a joint french-german-japanese project.

7.9. Finite element for full-MHD problems

Participants: Emmanuel Franck [correspondent], Eric Sonnendrücker.

This work have begun at the end of 2015. It is organized around a PhD: Mustafa Gaja supervised by E. Sonnendrücker, A. Ratnani and E. Franck at the Max-Planck Institute of Plasma Physic. The aim of this work is to design and study compatible finite element method (finite element method which preserve the DeRham sequence and the inclusion between the functional space) for B-Splines. This method will allow to discretize efficiently the Maxwell equations, the MHD model and some operators as curl-curl or grad-div vectorial operators which appear in the physic-based PC. For now, we have begun to study the finite element discretization of vectorial operators which appears in the linearized Euler equations and in the physic-based PC associated.

7.10. Lagrangian averaged gyrokinetic-waterbag continuum

Participant: Nicolas Besse [correspondent].

In this paper [26], we first present the derivation of the anisotropic Lagrangian averaged gyrowaterbag continuum (LAGWBC-α) equations. The gyrowaterbag (nickname for gyrokinetic-waterbag) continuum can be viewed as a special class of exact weak solution of the gyrokinetic-Vlasov equation, allowing to reduce this latter into an infinite dimensional set of hydrodynamic equations while keeping its kinetic features such as Landau damping. In order to obtain the LAGWBC-α equations from the gyrowaterbag continuum we use an Eulerian variational principle and Lagrangian averaging techniques introduced by Holm, Marsden, Ratiu and Shkoller for the mean motion of ideal incompressible flows, extended to barotropic compressible flows by Bhat and co-workers and some supplementary approximations for the electrical potential fluctuations. Regarding to the original gyrowaterbag continuum, the LAGWBC-α equations show some additional properties and several advantages from the mathematical and physical viewpoints, which make this model a good candidate for describing accurately gyrokinetic turbulence in magnetically confined plasma. In the second part of this paper we prove local-in-time well-posedness of an approximate version of the anisotropic LAGWBC-α equations, that we call the “isotropic” LAGWBC-α equations, by using quasilinear PDE type methods and elliptic regularity estimates for several operators.

7.11. Hamiltonian structure, fluid representation, stability for the Vlasov-Dirac-Benney equation

Participants: Claude Bardos, Nicolas Besse [correspondent].

This contribution [23] is an element of a research program devoted to the analysis of a variant of the Vlasov$-$Poisson equation that we dubbed the Vlasov$-$Dirac$-$Benney equation or in short V$-$D$-$B equation. As such it contains both new results and efforts to synthesize previous observations. One of main links between the different issues is the use of the energy of the system. In some cases, such energy becomes a convex functional and allows to extend to the present problem the methods used in the study of conservation laws. Such use of the energy is closely related to the Hamiltonian structure of the problem.

7.12. Semi-classical limit of an infinite dimensional system of nonlinear Schrödinger equations

Participants: Claude Bardos, Nicolas Besse [correspondent].

In this paper [24], we study the semi-classical limit of an infinite dimensional system of coupled nonlinear Schrödinger equations towards exact weak solutions of the Vlasov-Dirac-Benney equation, for initial data with analytical regularity in space. After specifying the right analytic extension of the problem and solutions, the proof relies on a suitable version of the Cauchy-Kowalewski Theorem and energy estimates in Hardy type spaces with convenient analytic norms.

7.13. Aligned interpolation for gyrokinetic Tokamak simulations

Participants: Guillaume Latu, Michel Mehrenberger [correspondent], Maurizio Ottaviani, Eric Sonnendrücker.

This work is devoted to study the aligned interpolation method in semi-Lagrangian codes. The scheme is presented and algorithms used implementing the scheme are given. A theoretical justification of the method is given with convergence estimates in the simplified context of 2D constant advection, assuming stability of the scheme. The stability is here studied numerically, letting the formal proof as an open problem. The solution is successfully applied in the gyrokinetic context: first in a simplified case in cylindrical geometry and then in toroidal geometry. In the first case, the solutions provided by simulations based on the scheme are in accordance with linear dispersion analysis; in the second case, numerical simulations produced by the Gysela code are presented, simulation based on the standard scheme are compared to those based on the new aligned scheme. This work will lead to a project of paper, which will be submitted in 2016.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

We are involved in a common project with the company AxesSim in Strasbourg. The objective is to help to the development of a commercial software for the numerical simulation of electromagnetic phenomena. The applications are directed towards antenna design and electromagnetic compatibility. This project was partly supported by DGA through "RAPID" (régime d'appui à l'innovation duale) funds. The CIFRE PhD of Thomas Strub is part of this project. Another CIFRE PhD has started in AxesSim on the same kind of subjects in March 2015 (Bruno Weber). The new project is devoted to the use of runtime system in order to optimize DG solvers applied to electromagnetism. The resulting software will be applied to the numerical simulation of connected devices for clothes or medicine. The project is supported by the "Banque Public d'Investissemnt" (BPI) and coordinated by the Thales company.

9. Partnerships and Cooperations

9.1. Regional Initiatives

The thesis of Pierre Gerhard devoted to numerical simulation of room acoustics is supported by the Alsace region. It is a joint project with CEREMA (Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement) in Strasbourg.

9.2. National Initiatives

9.2.1. ANR

- ANR project GYPSI (2010-2015), https://sites.google.com/site/anrgypsi/: coordinator Philippe Ghendrih (CEA Cadarache), other participants, University of Marseille, Universities of Strasbourg and Nancy (CALVI and then TONUS project-team). The aim is to understand the physics of turbulence in magnetically confined plasma using numerical simulation
  Participants: Philippe Helluy [local coordinator], Michel Mehrenberger.
- ANR project ”PEPPSI” in Programme Blanc SIMI 9 – Sciences de l'ingénierie (Edition 2012) started in 2013.
  Participants: Giovanni Manfredi [coordinator], Sever Adrian Hirstoaga.

9.2.2. IPL FRATRES

The TONUS project belongs to the IPL FRATRES and there was an annual meeting, on 15-16 October 2015, with talks of Emmanuel Franck, Philippe Helluy, Sever Adrian Hirstoaga, Michel Mehrenberger.

9.2.3. IPL C2S@exa

The TONUS and HIEPACS project have obtained the financial support of the PhD thesis of Nicolas Bouzat thanks to the IPL C2S@exa. Nicolas Bouzat works at CEA Cadarache and is supervised locally by Guillaume Latu; the PhD advisors are Michel Mehrenberger and Jean Roman.

9.2.4. Competitivity clusters

- GENCI projet : t2015067387 "Simulation numérique des plasmas par des méthodes semi-lagrangiennes et eulériennes adaptées" 800 000 scalar computing hours on CURIE_standard (January 2015-February 2016); use: 300 000 heures.
  Participants: Sever Adrian Hirstoaga, Guillaume Latu, Michel Mehrenberger [coordinator], Thi Nhung Pham, Christophe Steiner.
- GENCI projet : t2016067580 "Simulation numérique des plasmas par des méthodes semi-lagrangiennes et PIC adaptées" 450 000 scalar computing hours on CURIE_standard (January 2016-January 2017); coordinator: Michel Mehrenberger

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. EUROfusion 2015-2017

- Eurofusion Enabling Research Project ER15-IPP01 (1/2015-12/2017) "Verification and development of new algorithms for gyrokinetic codes" (Principal Investigator: Eric Sonnendrücker, Max-Planck Institute for Plasma Physics, Garching).
  Participants: Philippe Helluy, Sever Adrian Hirstoaga, Michel Mehrenberger.
- Eurofusion Enabling Research Project ER15-IPP05 (1/2015-12/2017) "Global non-linear MHD modeling in toroidal geometry of disruptions, edge localized modes, and techniques for their mitigation and suppression" (Principal Investigator: Matthias Hoelzl, Max-Planck Institute for Plasma Physics, Garching).
  Participant: Emmanuel Franck.

9.4. International Initiatives

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

Michel Mehrenberger has a collaboration with Bedros Afeyan (Pleasanton, USA) to work on KEEN wave simulations.

9.4.2. Participation In other International Programs

Participants: Emmanuel Franck, Philippe Helluy [local coordinator].

ANR/SPPEXA "EXAMAG" is a joint French-German-Japanese project. Its goal is to develop efficient parallel MHD solvers for future exascale architectures. With our partners we plan to apply highly paralelized and hybrid solvers for plasma physics. One of our objective is to develop Lattice-Boltzmann MHD solvers based on high-order implicit Discontinous Galerkin methods using SCHNAPS and runtime systems such as StarPU.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Journal

10.1.1.1. Member of the editorial boards

Philippe Helluy is member of the editorial board of IJFV http://ijfv.org/

10.1.1.2. Reviewer - Reviewing activities

Emmanuel Franck participates in reviewing for

- ENUMATH 2015 Proceedings
- Comptes Rendus Mathematique

Philippe Helluy participates in reviewing for

- Mathematical reviews
- ESAIM Procs
- Computers and fluids
- Computational physics paper
- International Journal for Numerical Methods in Fluids
- SINUM
- Computer Physics Communications
- Journal of Mechanical Science and Technology

Sever Adrian Hirstoaga participates in reviewing for

- Discrete and Continuous Dynamical Systems-Series S
- ESAIM Procs.

Michel Mehrenberger participates in reviewing for

- Electronic Journal of Qualitative Theory of Differential Equations (EJQTDE)
- ESAIM Procs
- SISC
- Zeitschrift fuer Angewandte Mathematik und Physik (ZAMP)
- Abstract and Applied Analysis (AAA)

Laurent Navoret participates in reviewing for

- ESAIM Procs
- J. Comp. Phys.

10.1.2. Invited talks

Emmanuel Franck was invited at

- Congrès SMAI 2015", Mini-symposium "Numerical method for Plasma physic", Karellis, June 2015.
- "Multi-scale Numerical Methods for the Vlasov Poisson system with strong magnetic field", http://www.ipp.mpg.de/3874888/Program, October, 26th 2015.
- " Workshop JOREK ", Garching, May 2015.
- Seminar Nantes, October 2015

Philippe Helluy was invited at:

- Numkin 2015, Max Planck Institute for Plasma Physics, Munich, Germany, October 2015, http://www.ipp.mpg.de/3874888/Program
- JLESC workshop, Barcelona, June 2015, http://jlesc.bsc.es/
- Forum ORAP, November 2015, http://orap.irisa.fr/?page_id=129

Sever Adrian Hirstoaga was invited at

- the workshop Modeling and Numerical Methods for Hot Plasmas II, Bordeaux, October 12-14, 2015
- the "Séminaire d'Analyse", IRMA Strasbourg, December 10, 2015.

Michel Mehrenberger was invited at

- IFIP Nice June 30, 2015, Mini Symposium "Oscillation, Degeneracy and Controllability".

Laurent Navoret was invited at

- Séminaire LAMA, Université de Savoie
- Séminaire Calcul Stochastique, IRMA, Université de Strasbourg
- Workshop "Collective dynamics of active particles, swimmers, motile cells", IMFT, Toulouse

10.1.3. Scientific expertise

Sever Adrian Hirstoaga, expertises for:

- computational project proposal at the Swiss National Supercomputing Centre

Philippe Helluy, expertises for:

- ANR
- U.S. Army Research Office
- Defence Institute of Advanced Technology (India)
- Energy research call CNRS (France).

10.1.4. Research administration

Michaël Gutnic is member of the National Commity for Scientific Research (from september 2012).

Philippe Helluy:

- head of the "Modélisation et Contrôle" research team at IRMA Strasbourg,
- chargé de mission calcul scientifique at CNRS.

Michel Mehrenberger is partly responsible of the seminar MOCO (MOdelisation et COntrôle, IRMA, Université de Strasbourg).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: Michaël Gutnic, Mathématiques pour les sciences du vivant, 84h eq. TD, L1 Sciences du Vivant, Université de Strasbourg, France

Licence: Michaël Gutnic, Statistiques pour les biologistes, 117h eq. TD, L2 Sciences du Vivant, Université de Strasbourg, France

Licence: Philippe Helluy, Calcul scientifique, 54h eq. TD, L2 Maths, Université de Strasbourg, France

Licence: Michel Mehrenberger, Fonctions de plusieurs variables et analyse vectorielle, 30 h eq. TD, L2, Université de Strasbourg, France

Licence: Laurent Navoret, Calcul scientifique, 65 h eq. TD, L3, Université de Strasbourg, France

Licence: Laurent Navoret, Optimisation Non-Linéaire, 54h eq. TD, Cours et TD, L3 Maths-Eco, Université de Strasbourg, France

Master: Michaël Gutnic, Probabilités et Statistiques, 30h eq. TD, Formation d'ingénieur en informatique en apprentissage, Institut des Techniques d'Ingénieur de l'Industrie, Centre de Formation d'Apprentis de l'Industrie, Conservatoire national des arts et métiers, France.

Master: Philippe Helluy, Recherche opérationnelle, 45h eq. TD, ENSIIE, Université de Strasbourg, France

Master: Philippe Helluy, Contrôle Optimal, 26h eq. TD, M2, Université de Strasbourg, France

Master: Philippe Helluy, Méthode des volumes finis, 26h eq. TD, M2, Université de Strasbourg, France

Master: Philippe Helluy, Calcul scientifique, 10h eq. TD, M2 Agrégation, Université de Strasbourg, France

Master: Michel Mehrenberger, Cours avancé math fonda, 20 h eq. TD, M1, Université de Strasbourg, France

Master: Michel Mehrenberger, PIP certification Python, 13 h eq. TD, M1, Université de Strasbourg, France

Master: Laurent Navoret, PIP : certification python, 13h eq. TD, M1 Mathématiques, Université de Strasbourg, France.

Master: Laurent Navoret, Calcul scientifique, 54 h eq. TD, M2 Agrégation, Université de Strasbourg, France.

Master: Laurent Navoret, Correction de devoir, 26 h eq. TD, M2 Agrégation, Université de Strasbourg, France.

Master: Laurent Navoret, Basics in Maths, 24h eq. TD, Cours, M2 Cell Physics, Université de Strasbourg, France.

10.2.2. Supervision

PhD : Thomas Strub, "Résolution des équations de Maxwell tridimensionnelles instationnaires sur architecture massivement multicoeur", Université de Strasbourg, March 2015, Advisor: Philippe Helluy.

PhD in progress: Thi Trang Nhung Pham, "Méthodes numériques pour Vlasov", October 2012, Advisors: Philippe Helluy, Laurent Navoret.

PhD in progress: Pierre Gerhard, "Résolution des modèles cinétiques. Application à l'acoustique du bâtiment.", October 2015, Advisor: Philippe Helluy, Laurent Navoret.

PhD in progress: Bruno Weber, "Optimisation de code Galerkin Discontinu sur ordinateur hybride. Application à la simulation numérique en électromagnétisme", March 2015, Advisor: Philippe Helluy.

PhD in progress: Nicolas Bouzat, "Fine grain algorithms and deployment methods for exascale codes", October 2015, Advisor: Michel Mehrenberger, Jean Roman, Guillaume Latu.

PhD in progress: Michel Massaro, "Méthodes numériques pour les plasmas sur architectures multi-cœurs", December 2012, Advisor: Philippe Helluy.

10.2.3. Juries

Michel Mehrenberger was invited member of the jury of the PhD of Fabien Rozar (CEA Cadarache).

Philippe Helluy, PhD defence of: Lauriane Schneider (Strasbourg), Rémi Chauvin (Toulouse).

10.3. Popularization

Philippe Helluy participated to the redaction of an ONISEP brochure about the jobs related to Mathematics or computer sciences http://www.onisep.fr/Toute-l-actualite-nationale/Decouvrir-les-metiers/Mars-2015/Zoom-sur-les-metiers-des-mathematiques-et-de-l-informatique

Michel Mehrenberger is in the IREM ("Instituts de recherche sur l?enseignement des mathématiques") team "Modélisation" for the year 2015-2016.

11. Bibliography

Major publications by the team in recent years

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[2] N. CROUSEILLES, P. GLANC, S. A. HIRSTOAGA, E. MADAULE, M. MEHRENBERGER, J. PÉTRI. *A new fully two-dimensional conservative semi-Lagrangian method: applications on polar grids, from diocotron instability to ITG turbulence*, in "The European Physical Journal D", 2014, vol. 68, n^o 9, pp. 1–10

[3] E. FRENOD, S. A. HIRSTOAGA, M. LUTZ, E. SONNENDRÜCKER. *Long time behaviour of an exponential integrator for a Vlasov-Poisson system with strong magnetic field*, in "Communications in Computational Physics", August 2015, vol. 18, n^o 2, pp. 263–296 [*DOI :* 10.4208/CICP.070214.160115A], https://hal.archives-ouvertes.fr/hal-00974028

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[6] T. STRUB. *Resolution of tridimensional instationary Maxwell's equations on massively multicore architecture*, Université de strasbourg, March 2015, https://tel.archives-ouvertes.fr/tel-01132856

Articles in International Peer-Reviewed Journals

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Research Reports

[11] M. MEHRENBERGER, L. S. MENDOZA, C. PROUVEUR, E. SONNENDRÜCKER. *Solving the guiding-center model on a regular hexagonal mesh*, Institut Camille Jordan, Université Claude Bernard Lyon 1, France ; equipe projet KALIIFFE, 2015, pp. 1 - 28, https://hal.archives-ouvertes.fr/hal-01117196

Other Publications

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