Acronyme / Acronym	**ANEMOS**		
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Proposal title	Schémas numériques avancées pour les ELMs: Modélisation et stratégies de résolution optimisées.		
Axe(s) thématique(s) / theme(s)	X1 ☐ 2 ☐ 3 ☐ 4 ☐ 5		
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1. EXECUTIVE SUMMARY

The main goal of the project is to make a significant progress in understanding of largely unknown at present physics of active control methods of plasma edge MHD instabilities Edge Localized Modes (ELMs) wich represent particular danger with respect to heat and particle loads for Plasma Facing Components (PFC) in ITER. Project is focused in particular on the numerical modelling study of such ELM control methods as Resonant Magnetic Perturbations (RMPs) and pellet ELM pacing both foreseen in ITER. The goals of the project are to improve understanding of the related physics and propose possible new strategies to improve effectiveness of ELM control techniques. The tool for the non-linear MHD modeling is code JOREK which was essentially developed within previous ANR project ASTER (2006-2009). JOREK will be largerly developed within the present project to include corresponding new physical models in conjunction with new developments in mathematics and computer science strategy. The present project will put the non-linear MHD modeling of ELMs and ELM control on the solid ground theoretically, computationally, and applications-wise in order to progress in urgently needed solutions for ITER. The proposed work scope is organized in six main tasks:

1. Nonlinear MHD modeling of ELM s control by Resonant Magnetic Perturbations (RMPs) including self-consistent rotating plasma response.
2. Modeling of pellets ELMs pacing.
3. Development of new numerical algorithms and strategies of optimization and parallel scaling in JOREK needed for modeling of large (up to ITER-size) tokamaks at realistic experimental large magnetic Reynolds numbers (10^9).
4. Development and implementation of higher-order-of-continuity advanced meshing in JOREK to treat realistic tokamak geometry.
5. Development of new variational multi-scale stabilization methods for compressible non-linear MHD models to improve code stability.
6. Improvement and development of new methods of visualization, data management and JOREK code integration.

Through this proposed work scope, we will develop new numerical strategies and improve existing software tools and physical modeling for compressible non-linear MHD in order to obtain predictive simulations of the global dynamics of Type I ELMs control in fusion experiment. Therefore, the project will play an important role in the scientific foundations for existing tokamaks (JET, AUG, DIII-D, MAST etc) and as a final goal for ITER-size machine. The progress in physics and numerical analysis obtained within the project will be largely

available and applicable not only in tokamak physics but in much larger non-linear MHD community involving fluid dynamics in general.

2. CONTEXT, POSITION AND OBJECTIVES OF THE PROPOSAL

2.1. CONTEXT, SOCIAL AND ECONOMIC ISSUES

The next step large-scale tokamak ITER device (International Thermonuclear Experimental Reactor), which is under construction in Cadarache in France, has the main goal to study physics of burning D-T plasma magnetically confined in tokamak device. ITER should prove that exploitation of controlled fusion energy as a resource of electrical power is conceivable and that fusion power plants could be achievable before the end of the 21st century. If ITER reaches its goals and demonstrates that fusion may be used to produce economically exploitable energy, then next step DEMO will be the first prototype of what could later be a fusion reactor. The conditions needed for a reactor to reach ignition (Lawson Criterion), are strongly related to the maximum achievable plasma confinement time which determines fusion plasma performance. In fact, an empirical scaling law has demonstrated that the confinement time is nearly proportional to the square of major radius R, which explains why next step tokamaks have larger and larger sizes (R=3m for JET, R=6m for ITER and R=9m for DEMO). Central plasma temperature in present day tokamaks already reaches 200 million degrees (more then ten times hotter compared to surface temperature of the Sun), hence plasma column is magnetically confined within closed magnetic flux surfaces to avoid interaction with the wall, maintained at ~200°C. Two regions are formed in typical tokamak: the plasma core, with closed imbedded torus magnetic flux surfaces, and the Scrape-Off - Layer (SOL), where magnetic lines are open onto the so-called Plasma-Facing Components (PFC). These two regions are separated by the last closed flux surface, called the separatrix, or plasma boundary. The magnetic configuration foreseen for ITER is the divertor or X-point configuration where an additional axisymmetric coil is introduced near the plasma so that the poloidal magnetic field vanishes at a chosen radial position to form an X-point. In this particular configuration, the German tokamak ASDEX discovered in the early 1980's that when the additional heating power is raised above a certain threshold, the turbulent transport is suppressed in the narrow (few cm) region at the plasma edge, leading to an Edge Transport Barrier (ETB) formation. In H-mode, density and temperature profiles take specific form with so-called "pedestal" due to ETB near boundary plasma. Plasma confinement in H-mode is considerably improved ("H" for high confinement) compared to a low confinement L-mode plasma typically observed below L/H transition power threshold. H-mode is one of the main baseline ITER scenarios, where in particular a fusion power gain Q=10 can be achieved [PIPB2007] (where Q is the ratio between the fusion power and the applied additional heating power).

Note also that the maximum fusion plasma performance in terms of maximum plasma current, normalised plasma pressure ("beta") and pressure gradient is limited in many cases by large-scale MHD instabilities [PIPB2007]. Hence the achievable fusion power

gain in ITER (and future fusion reactor DEMO) even in H-mode will depend on these operational limits ruled by MHD activity. A large edge pressure gradient accompanied by a large edge current density (so-called "bootstrap" current) are the typical conditions met in an H-mode, and are particular prone to MHD activity. The pressure gradient and the current density are the two driving forces of the so-called Edge Localized Modes (ELMs), resulting from a coupling between kink (or peeling) modes driven by current and ballooning MHD modes driven by pressure gradient. During their non-linear evolution, ELMs evacuate very rapidly energy and particles through the separatrix, so that the pressure gradient decreases and ballooning/peeling modes become stable again [Huysmans2005]. After the fast (~200μs) ELM crash, the edge pressure gradient builds up again until the MHD stability limit is achieved leading to the following ELM crash and, hence, to the quasi-periodic nature of ELM relaxations. Usually ELMy scenario prevents from impurities (coming from the edge) accumulation in the central plasma. However the main concern is that PFCs suffer under heat fluxes due to large ELMs, since up to 20% of pedestal energy can be lost in ELM. The resulting damages on PFCs due to large (Type I) ELMs can be significant even in present day machines like JET. The extrapolation of present day experiments for ITER predicts that big type-I ELMs in ITER could release up to 20MJ on the tungsten ITER divertor [PIPB2007]. According to present day materials and ELM physics knowledge [Loarte 2006], ITER divertor target plates cannot face more than 1MJ ELMs. Larger ELMs will lead to the rapid overall material erosion and even melting of the divertor and hence a reduction of the ITER divertor lifetime after only few full power ELMy H-mode shots [Loarte2006].

In last decade of intensive experimental and related material studies the consensus was reached that ELMs need to be actively controlled in ITER, otherwise ITER can not operate and the program goal will not be reached. Experimental observations, theoretical predictions and numerical simulations bring an important amount of information concerning ELMs process, so that a consequent understanding of the instability has been achieved in recent years [Huysmans2010]. This has lead to the design of strategies for ELMs control in tokamaks [Hawryluk2009]: the application of resonant magnetic fields- perturbations (RMPs) (see recent overview [Fenstemacher2010]), the injection of hydrogen ice ("pellets") [Lang2008] and the induction of oscillations ("kicks") of the plasma vertical position [delaLuna2009]. The effects of these ELM control techniques varies from total ELM suppression (using RMPs) to more frequent and, hence, much smaller (mitigated) ELMs triggering (by pellets and kicks). The management of these strategies for operational reactor as ITER is still challenging and in many aspects underlying physics is not totally understood for reliable predictions for ITER.

With this respect the non-linear MHD theory can provide further physical and numerical improvements to refine knowledge of basic ELM dynamics and related ELM control techniques. In view of particular complexity of the problem the numerical simulations provide a key component of this effort, since computations are performed at a tiny fraction of the cost of an experiment. To be effective, simulations are combined with a well-focused, well-diagnosed experimental physics program to guide model development, and to assure the validity of numerical results. Recent developments in plasma theory,

computational physics, and computer science, along with anticipated advances in computer hardware performance, combine to make this simulation capability of non-linear MHD codes a very attractive option to study ELM physics [Huysmans 2009-10].

Developing and deploying this capability for non-linear MHD simulation of ELMs and ELM control will be the focus of the present proposal. We plan to progress in related physics understanding using new numerical and mathematical developments in JOREK code focusing in particular on active ELMs control physics which still remains essential and in most aspects unsolved issue for ITER. The expected result is to contribute in possible optimization and the ELM control methods in ITER, in the design details of the corresponding systems, which hopefully provide real economical gain for the present tokamaks and ITER project. At the same time the progress in MHD theory and numerical methods adapted for strongly non-linear problems expected within the project will be available and applicable in several tokamak frame and different domains, for example in astrophysics and other magnetized fluid dynamics problems.

2.2. POSITION OF THE PROJECT

In this project we plan to concentrate our efforts on the non-linear MHD modeling of the active control of Type I ELMs representing (if uncontrolled) a particular danger for PFC and divertor materials in ITER due to fast (~0.2ms) transient release of energy (up to 20MJ in ITER) in ELM crash. ELMs occur in the high energy confinement regime, H-mode that will be the standard operating regime in ITER. This regime is characterized by an extremely large pressure gradient (up to hundreds of kPa/m) at the localized edge plasma region with a width of ~2-5 cm. In the last ten years, significant progress in the characterization of ELMs physics and corresponding to transient heat and particle loads experiments has taken place [Becoulet2003, Loarte2006, Huysmans2009]. Understanding of ELM physics progresses also due to non-linear MHD modeling and its continuous benchmarking against experimental observations [Huysmans2005-2010a].

The progress in ELMs physics studies and their particular danger for ITER gave birth to some new active methods of ELMs control, which are the subject of intensive experimental and theoretical studies. The promising active mean of ELMs control by Resonant Magnetic Perturbations (RMPs) produced by specific coils permitted total Type I ELM suppression on DIII-D [Evans2008] or strong mitigation of the ELM size [Liang2008] on JET. RMPs are studied at present on many tokamaks which are developing new facilities (coils) for RMP generation (DIII-D, JET, MAST, TEXTOR, NSTX, AUG) [Fenstermacher2010], but underlying physics of ELM suppression is not understood for reliable predictions for ITER. The present RMP system in ITER is essentially designed on the semi-empirical and vacuum (without plasma response) modeling background [Becoulet2008], [Hawryluk2009], which not always gives satisfactory result on the experiment. For example, on MAST ELMs were not suppressed by especially designed coils on the bases of vacuum modeling without plasma response [Fenstermacher2010], hence, the reliability of the designed already RMP coils for ITER using the same vacuum modeling principle [Fenstermacher2010], [Hawryluk2009]

remains questionable, motivating theory and modeling of plasma response on RMPs. Thus understanding of RMP physics and interaction with ELMs being the particular focus of this ANR project will help in present day experiments with a final goal to do predictions for ITER.

Two other methods of ELM mitigation are based on actively increasing the ELM frequency by injection of small pellets or forced fast vertical displacements of plasma (vertical "kicks"), which were proven experimentally to trigger ELMs up to a certain frequency, reducing their size. ELM triggering and frequency control by pellet pacing is a robust and reproducible effect, observed in all major tokamaks [Lang2008]. But at present the underlying ELM trigger physics is on the initial stage in spite of the recent significant progress in qualitative understanding based on non-linear MHD modeling [Huysmans 2009]. We are still lacking knowledge of what minimum pellet size and penetration depth are required to trigger an ELM for a given set of pedestal parameters and especially in ITER.

Even less known is physics of triggering of ELMs by vertical kicks, produced by the changing current in the vertical stability control system of tokamaks like JET, TCV, AUG [delaLuna2009]. "Kicks" ELM control method uses vertical plasma stability control system of tokamak and is closely related to the issue of the global vertical stability control. This issue will not be treated in the present project, however the new developments in JOREK proposed here will be used in the future.

The modeling of ELMs and their control is quite challenging both from physics and numerical sides, since it deals with strongly non-linear problems in complex realistic geometry and with large range of the characteristic time scales starting from few to millions of Alfven times [Huysmans2007-2010a]. To resolve very fine filamentary structure of ELMs at relevant experimental values of the magnetic Reynolds number ($S=10^9$) is numerically extremely challenging, hence very high spatial resolution is needed. Highly non-linear nature of the ELM, complexity of the tokomak's geometry, different time scales , very fine mesh that are required, all this leads to prohibitive memory requirements even for most performing parallel computers. Thus, the development of new numerical methods based on high level of parallelization is necessary for these kinds of non-linear MHD problems.

At present the theory and modeling of ELMs is in the initial stage in the world and it is based mainly on the resistive non-linear MHD description [Huysmans2006-2010], [Sovinec2003], [Strauss2009], [Sugiyama2010]. ELM control modeling is even less developed. In most of the calculations in realistic geometry the experimentally relevant plasma parameters with respect to the high realistic magnetic Reynolds numbers are not reached.

In Europe, there is only one well-established code (apart from JOREK) for non-linear simulations of MHD instabilities in tokamak plasmas. The XTOR (XTOR-2F) developed at "Ecole Polytechnique Paris" [Lutjens 2008] is a highly advanced code but is adapted towards instabilities in the centre of the tokamak. This code uses either semi-implicit or a nonlinearly implicit preconditioned Newton-Krylov method, using spectral representation in both the poloidal and toroidal angles considered plasma region with close magnetic flux surfaces., since it does not treat outside separatrix region (SOL) and X-point and hence is not suitable for the simulation of ELMs. With respect to current project ANR "**ANIKA"** aiming further

development of the 3D full MHD numerical code XTOR at CPhT, "Ecole Polytechnique" and the present project for JOREK code are totally independent.

In the **USA**, there are **three non-linear MHD simulation codes** which are under development in parallel with JOREK code in EU (France). These US codes can be also applied to modelling of ELM and ELM control by RMPs and pellet penetration physics [Jardin2007]: NIMROD [Sovinec2003, Izzo2008], BOUT++ [Xu2010] and M3D-C1 [Jardin 2007, Strauss2009, Sugiyama2010]. The **NIMROD** code [Sovinec2003] is reduced MHD code uses high-order finite elements in the poloidal plane and a spectral representation in the toroidal angle similar to JOREK. The **M3D-C1** code also use split linearly implicit schemes, magnetic divergence free constraint is achieved by the use of vector potential vector (full MHD code). The M3D and NIMROD code developers are in periodic collaborative contact with our team and they are also progressing in ELM and RMP physics, however new physics we propose to study in this project related to the pellet ELM pacing, the neoclassical and diamagnetic effects in RMP interaction with plasma at relevant S numbers were not taken into account yet in M3D and NIMROD physics models. Both NIMROD and M3D (at least in recent publications) are limited by rather low numbers $S\sim10^7$ compared to realistic values $S=10^8$-10^9.

Another non-linear code **BOUT++** [Xu2010] code uses a potential vector formulation and a curvilinear (field aligned) finite difference approximation in the poloidal plane and the toroidal direction, realistic geometry with SOL. Initial biggest success of BOUT ++ is mainly electrostatic turbulence modeling. However, the MHD instabilities and in particular ELMs simulations published by BOUT++ team did not go beyond the early non-linear stage or circular cross section , possibly due to the numerical problems. The multi cycle of ELMy regime modeling has not yet been achieved by anyone. The new developments concerning diamagnetic two fluid effects in JOREK proposed here possibly will open the way to multi ELM modeling.

This situation with respect to urgent ITER issues of ELM control motivated the present proposal, which is the logic but even more challenging continuation of the previous **ANR projects ASTER** (2006-2009) (http://aster.gforge.inria.fr/index.html), where the non-linear MHD ELM modeling started using code JOREK. [Huysmans2010,2010,2010a]. The JOREK code uses a fully implicit time evolution scheme which is essential due to the large variety of time scales and strong non-linearity of the problem. The important progress in physics was done due to the essential and important corresponding specific numerical tools developed in strong collaboration between the « Institut de Recherche sur la Fusion Magnétique " (IRFM, CEA/Cadarache), the "Laboratoire Bordelais de Recherche en Informatique" (LaBRI) and "Laboratoire Mathématiques Appliquées de Bordeaux" (MAB) at the University of Bordeaux I. JOREK is in conjunction with the PaStiX sparse matrix library (Parallel Sparse matriX package, //pastix.gforge.inria.fr), which was also under continuous improvement within the previous project permitting large improvement in parallelization of the solution of the large sparse matrixes using direct and hybrid numerical methods. The progress in physics understanding achieved within ASTER project was rather outstanding and unique in the world, since it went up to the point where high resolution simulations of ELM have become feasible for experimental discharges for the

numerically extremely challenging relevant experimental values of the magnetic Reynolds number ($S=10^9$) [S Pamela2010]. Note also that the significant discoveries in physics of ELMs were made within the project where for the first time the theoretical basis of the energy losses in ELMs and pellet triggered ELMs were explained [Huysmans2009-10]. Even if quite significant progress was achieved, it is only the first steps in the solution of many complex problems related to ELMs and in particular to ITER.

With this respect the progress in modeling and understanding in still unknown underlying physics of relevant for ITER active ELM control schemes such as RMPs and pellets motivated us to propose this new project, which challenges new theoretical and numerical implementation of new physics in JOREK code. In this purpose we plan to do significant changes in numerical schemes and parallelization methods to reach particularly high spacial and time resolution needed to meet ITER relevant parameters. With respect to new physics of the project related to ELM control modeling, note the importance of plasma flows including diamagnetic and neoclassical effects, which are of particular importance in the edge region of large pressure gradients typical for H-mode ELMy regimes [Becoulet2010]. This is urgent issue for ITER since the design of RMP coils for ITER should be fixed in 1-2 years time, motivating strongly the proposal of this subject in this new ANR project.

Many aspects of pellet ELM pacing are also not understood and in particular needed pellet monitor frequency for pacing, minimum ELM size and its penetration into the plasma limiting predictions for ITER pellet pacing system. The main difficulty in MHD modeling of small pellets is a description of highly toroidaly localized objects within Fourier description implemented at present in JOREK leading rapidly to numerical limits for smaller pellets and larger machines, the issue we are going to treat in this project implementing 3D approach and adaptive mesh techniques.

The JOREK code is mainly composed of numerical computations on 3D data. The toroidal dimension of the tokamak is treated in Fourier space, while the poloidal plane is decomposed in Bezier patches [Czarny2008]. The numerical scheme used involves a direct solver on a large sparse matrix as a main computation of one time step. Two main costs are clearly identified: the assembly of the sparse matrix, and the direct factorization and solve of the system that includes communications between all processors. The efficient parallelization of JOREK is one of our main goals, to do so we will reconsider: data distribution, computation distribution or GMRES implementation. The quality of the sparse solver is also crucial, both in term of performance and accuracy. In the current release of JOREK, the memory scaling is not satisfactory to solve problems listed above , since at present as one increases the number of processes for a given problem size, the memory footprint on each process does not reduce as much as one can expect. In order to access finer meshes on available supercomputers, memory savings have to be done in the whole code. Another key point for improving parallelization is to carefully profile the application to understand the regions of the code that do not scale well. Depending on the timings obtained, strategies to diminish communication overheads will be evaluated and schemes that improve load balancing will be initiated. JOREK uses PaStiX sparse matrix library for matrix inversion.

However, large number of toroidal harmonics and particular thin structures to resolve for realistic plasma parameters and ITER machine size still require more aggressive optimisation in numeric dealing with numerical stability, adaptive meshes etc. However many possible applications of JOREK code we proposed here which represent urgent ITER relevant issues related to ELM control by RMPs and pellets remain to be solved.

The second current **ANR-E2T2** leading by University of Marseille contains a subject of RMP studies [Leconte2009]. Some of the participants of present project (M. Becoulet , G. Latu) are involved at minimum rate (<4%) in ANR-E2T2 mainly as consulters then developers, since the proposed in ANR-E2T2 modelling using code EMEDGE3D mainly aims the micro turbulence interaction with RMPs in the external transport barrier (ETB) and not MHD issues. Some physics of magnetic islands interaction with intrinsic resistive ballooning turbulence will be treated. However, the self-consistent treatment of plasma equilibrium with flows and equilibrium electric field, interaction of RMPs and Type I ELMs, ELM triggering by pellets, proposed in our new project, can not and will not be treated within the E2T2 project. Note that the present situation of separation between fluid micro-turbulence and MHD description of plasma is temporary and is dictated by computer science limits. In the future these two descriptions (MHD and turbulence) hopefully will converge progressively in to one global self-consistent model. With this respect ANRs E2T2 and proposed ANEMOS can be considered as complimentary and will serve to prepare further more ambitious steps in self-consistent electromagnetic turbulence modelling with flows in realistic geometry including naturally global MHD instabilities at the same time, but for the moment this goal is limited by existing computers performance.

To summarise, general goal of this new ANR project is to achieve significant progress in understanding of the many unknown aspects of the underlying physics of ELMs control schemes such as ELM suppression/mitigation by RMPs and ELMs triggering by small pellets. New physics related to the ELM control modelling by RMPs, including diamagnetic and neoclassical effects, which are of particular importance in RMP screening in pedestal region [Becoulet2010], will be implemented. Interaction ELMs and RMPs will be studied including plasma flows important both for ELM stabilization and RMP screening by plasma. ELM pellet pacing modelling will progress within the project to the new stage of high spatial resolution of small highly localized toroidally pellets in large ITER-like size machine, which is very challenging. For realization of these physics tasks the corresponding numerical developments will be done aiming implementation of higher-order-of-continuity advanced meshing in JOREK to treat realistic tokamak geometry and highly localized small pellets, development new numerical algorithms and strategies of optimization and parallel scaling in JOREK needed for modelling of fine structures in large (up to ITER-size) tokamaks at realistic experimental large magnetic Reynolds numbers (10^9) and development of new variational multi-scale stabilization methods for compressible non-linear MHD models used in JOREK. Finally the development of new methods of visualization, data management and JOREK code integration is foreseen. The proposed new non-linear MHD JOREK code developments will be of interest to the wider community of fluid and MHD simulations.

This proposal is mainly associated to the ANR theme "Modélisation de systèmes complexes" with associated key-words : Modeling, Simulation, multi-scale, multi-physic and high performance computing. The consortium composition will enforce the "applied mathematic" culture within some CEA departments of plasma physic and develop synergy between INRIA, CNRS and CEA.

2.3. STATE OF ART

As it was mentioned before, one of the major difficulties in the numerical simulations of MHD instabilities in tokamak plasmas is the multi-scale time in the system. Typical values of the linear growth of ELM instability is of the order of 0.05ms and non-linear stage of ELM crash about 0.2ms [Becoulet2003]. However the typical time scale of RMP penetration into pedestal plasma is related to the resistive time scale, which is usually largest time scale in tokamaks. For low ITER relevant resistivity (~10^{-9}, corresponding to S~10^9) could reach 10^6 Alfven times (~0.1s). [Becoulet2009]. Multi ELM cycles typically involve confinement time scale (~1s) needed for re-heating after the ELM crash. Additional complications in the simulations of MHD instabilities in tokamaks result from the very high magnetic Reynolds numbers (S~10^6-10^9) leading to the very thin current layers and structures and the large anisotropy of the directions parallel and perpendicular to the magnetic field. For example the typical ratio of parallel and perpendicular energy conductivities: $\mathbf{k}_{//}/\mathbf{k}_{\wedge}$~$10^8$-$10^{10}$.

At present only few initial modeling of ELMs and RMPs exist in US which used available non-linear MHD codes such as NIMROD [Izzo2008] and M3D [Strauss2009] which are limited by maximum S=10^6-10^7 being far from relevant parameters. The important factor of plasma response to RMPs is plasma flows. In particular radial electric field produces ExB poloidal rotation which is important in RMP screening. Radial electric field itself depend on toroidal and poloidal rotation and pressure gradient, tending to establish new equilibrium force balance in the presence of RMPs. This physics is not well known and should be treated self-consistently in non-linear MHD picture with all plasma flows, which is proposed in the project. With this respect diamagnetic electron and ion rotation is also important in the zone of strong pressure gradient typical for pedestal region. Note that the important physics of RMP screening due to the poloidal flows and diamagnetic effects proposed in this ANR project in the pedestal region are not included in the existing NIMROD and M3D modeling of RMPs. The ideal zero resistivity plasma response to RMPs was modeled by VIMEC code [JK Park2010]. Magnetic islands can not be formed in this kind of modeling since all elects of finite resistivity and rotation are out of the frame of the model, which corresponds more to the limit case of very low resistivity where all islands are screened, limiting also realism of the plasma response modeling. Kinetic modeling using code XGC0 [GPark2010] showed relevant results on heat and particles transport with RMPs, it takes many elements from neoclassical physics and two fluid effects, however magnetic topology with RMPs is given a priory and based on the supposed a priory screening of RMPs . Very simplified initial modeling of RMPs with JOREK code was done and reported in [Nardon2007], but at that

time it was also limited by low S-numbers (~10^7) and without self-consistent plasma flows which are of the particular importance for RMP screening by rotating plasma. RMPs physics is studied in EU using electrostatic turbulence codes [Reiser2009], [Laconte2009]. Some important results were obtained on the influence of stochastisity produced by RMPs on turbulent convective cells, which are shown to be reduced. However many simplifications of this modeling and in particular not self-consistent magnetic flux evolution, circular geometry, absence of open field lines region (SOL) , no plasma flows, equilibrium electric field, still makes these results far from being complete picture of RMP interaction with plasma. Type I ELMs are not treated by these codes.

Recent significant progress in qualitative understanding of pellet triggered ELMs was done using present version of JOREK [Huysmans 2009]. Pellet was modeled by toroidaly localized initially static density perturbation introduced in marginally MHD stable plasma. The resulting pellet generated plasmoid heated by parallel heat conductivity resulting in destabilization of large number of the ballooning modes with different toroidal numbers forming density filament was observed in JOREK modeling [Huysmans 2010] and was discovered later in dedicated JET experiments [Winnenger 2010]. In spite of significant progress in pellet triggered ELMs modeling many issues remained with respect to numerical stability for the smaller pellets bigger machines and realistic S numbers which can not be modeled because of numerical limits in present JOREK version and further numerical methods developments are planed in this project to meet ELM control physics problems requirements.

JOREK uses the PaStiX sparse matrix library (Parallel Sparse matriX package, //pastix.gforge.inria.fr), which was under continuous improvement within respect to the parallelization of the solution using direct and hybrid numerical methods. However solving large sparse matrix systems is clearly a bottleneck in numerical simulations with JOREK, hence we need to improve full parallel and scalable preprocessing steps (ordering and symbolic factorization of matrix), efficient algorithmic coupling of direct and iterative methods that allow a powerful management of the different levels of parallelism, adapt scheduling of computation tasks to take advantage of the runtime that operates on mixed architectures with multi-cores and GPUs. This new developments still are to be done in JOREK to progress in physics study, but they also improve the parallelization of PaStiX library itself which can be then used in other domains of physics dealing with large sparse matrix inversion.

Other important issue of the proposed modeling is to represent the complex magnetic and material geometry of tokamak, necessary for the simulation of ELMs and their control by pellets and RMPs. With this respect finite elements are a common choice for the discretization of the 2 non-period directions of a torus (used in MHD codes NIMROD, M3D, JOREK). The geometric approximation inherent in the mesh can lead to inaccuracy problems. Recently, the use of B-splines as shape functions for a Finite Element-like simulation has been studied [Hughes2005]. The main objective is clear: B-splines are the standard for CAD systems, and they reproduce the geometry of the domain exactly, which is not the case in Finite Element models. The use of the same approximation for both the construction of the

geometry and the approximation of the essential field of the problem obviously "simplifies" the burdensome mesh generation process. In JOREK, isoparametric formulation is achieved with cubic finite element using Bezier patches. The Bezier elements allow a refinement of the size of the element either in two or in four smaller elements. The efficiency of these new elements and their refinement has been tested on model problems in 2D geometry. A gain up to an order of magnitude has been demonstrated in both the required number of degrees of freedom and in the total computing time for the non-linear MHD test case in 2D. However, meshing in JOREK still need to be improved for topological complexity of ITER tokamak.
This difficulty can be overcome by T-splines (defined by some piecewise polynomial functions) that allow T-joints in the grid of control vertices. However, T-splines have several drawbacks: the domains where these functions are polynomial do not match with the cells of the T-subdivision and are not necessarily linearly independent. Moreover, the partition of unity property, which is important in CAD, is not directly available in this space. The T-spline construction is fairly complex and poses challenges in practical use. An alternative approach is the C1 cubic PHT (Polynomial Hierarchical T-splines) [Deng2006]. These splines are piecewise polynomial functions over recursive T-subdivisions of a certain type. The construction of a basis is described for bicubic C1 spline spaces in terms of the coefficients of the polynomials in the Bernstein basis attached to a cell. Several improvements are, however, possible to decrease the degree of the polynomial for a given regularity, to increase the flexibility of the subdivision scheme, and to reduce the complexity of constructing, representing and evaluating the basis functions [Galigo2008, Mourrain2010]. We will create a class of volume parameterizations to make a separate mesh generation process unnecessary, and demonstrate that they are suitable for the isoparametric approach.

The main physical models used in JOREK arising from reduced MHD and therefore, compressible fast waves are not taken into account [Huysmans2009]. The result is that numerically the need for stabilization is less demanding and for the moment JOREK stabilization is simply based on numerical resistivity and / or viscosity tensor. Nevertheless, this stabilization depends on parameters that are strongly linked to physical problem solved and in some cases are unsatisfactory. Furthermore, with the development of more sophisticated MHD models, it becomes urgent to improve stabilization robustness and performance, allowing producing and ensuring predictive results. Some well established codes as XTOR NIMROD and M3D, use stabilization techniques based on Taylor-Galerkin methods introduced in [Donea1984]. This is a family of high-order time-stepping schemes with stabilization of convective term by the means of intrinsic streamline diffusion. Taylor-Galerkin formulation is a class of more general sub grid scale concept introduced in [Hughes1995]. This strategy has been widely developed (our contribution [Nkonga2010,2010b]) and recently applied for incompressible MHD in [Codina2000, 2008]. The main idea is to split the continuous solution of the problem in two components, the weak solution at a given scale and the *subscales* or *subgrid scales*, which are the part of the solution that cannot be captured by the discretization. In this situation, the problem is reduced to obtain a good approximation for the *subscales*. Many of these stabilizations

depend on arbitrary algorithmic parameters, which need some tuning in order to achieve the best accuracy possible. In this proposal, and according to result obtained on turbulence models [Nkonga2010b] we can achieve, by multi scale analysis, the development of parameter free stabilization methods.
Numerical solutions that will be produced have more accuracy and continuity properties than what are used for visualization software. Another improvement will be to develop visualization tools that can take into account the high order resolution of developed numerical strategies.

2.4. ORIGINALITY AND NOVELTY OF THE PROJECT

This project represent a large collaborative effort to achieve maximum synergy between physics, mathematics and computer science in solving urgent ITER relevant issues related to active control of ELMs . The main goals of the current proposal are:

A) Make a significant progress in understanding of still unknown physics of the active Type I ELM control methods foreseen for ITER such as Resonant Magnetic Perturbations (RMPs) and ELM pacing by pellets.
B) To meet physics requirements proposed in project a significant challenging computer science and applied mathematics tasks will be accomplished in order to achieve maximum optimization of JOREK in terms of memory and computer time aiming realistic plasma parameters and ITER-size machine.
C) Improve the construction of higher order of continuity shape functions in order to better take into account the complexities of both the geometry of the tokamak plasma chamber and the topology of the magnetic field, proper treatment of the boundary geometry.
D) Develop parameter free stabilization methods for MHD models based on multi-scale decomposition. Higher order of continuity shape functions also help to obtain more robustness of the stabilization as there is no more singularities on elements edges.
E) Successful simulation of macroscopic plasma behavior requires successful diagnosis of results for a better physical understanding.

The work described here is aimed at developing powerful macroscopic simulation codes and using these on the most advanced computers available to contribute to the science base underlying proposed burning plasma tokamak experiments such as ITER. Many of the developments will also have more general applications beyond confined plasmas. The work scope also includes further developing and testing of the underlying MHD model, formulating this in a way that can be used to perform practical computations, and applying this to the most critical burning plasma global stability problems. Through this proposed work scope, we want to play an important role in the scientific foundations for existing tokamaks (JET, AUG, DIII-D, MAST etc) and as a final goal for ITER-size machine. The progress in physics and numeric achieved within the project will be largely available for the European community of JOREK users.

3. SCIENTIFIC AND TECHNICAL PROGRAM, PROJECT ORGANIZATION

3.1. SCIENTIFIC PROGRAM, PROJECT STRUCTURE

The main tool use for modeling is the non-linear MHD code JOREK that will be largerly evolved including new essential physics and corresponding new terms in the basic equations of the model. The equilibrium ExB flows and diamagnetic two fluid effects shown to be of particular importance for RMP screening [Becoulet2010] in the pedestal region of the large pressure gradients will be included in the model. This development is also relevant for ELM physics itself, since growths rate of peeling-ballooning mode could be largerly affected by poloidal flows including diamagnetic effects. The RMP physics will be studied using realistic pareameters present day experiments (DIII-D,MAST,JET etc) aiming to progress versus particular nummerically challenging ITER relevant parameters. Pellet pacing modelling will be done for particular challenging small pellets sizes and large up to ITER size machines. This objectives are of high importance for sucsess of ITER , since uncontrolled ELMs will be highly damaging for ITER divertor life time. However, considerably numerical developements are need to properly achieve pellet fuelling. Then ELMs control will be split into tow tasks devoted to RMP and Pellets :

- The RMP physics and modelisation will be investigated by using more and more efficient and stable numerical methods that can provide analysis with relevant physical parameters.
- For pellet injection, there is a need for local refinement in the toroidal direction. This cannot be achieved by the Fourier representation especially for small pellets compared to the machine size. Then B-Splines representation in the toroidal direction will be developed.

The spatial and temporal stiffness of models describing macroscopic plasma behavior defies straightforward numerical implementation, irrespective of any conceivable level of computing power. Numerical difficulties to be addressed in this proposal are of several kinds:

- The geometrical representation of the chamber boundary and the important components of the plasma flow. This will be achieved, from the experience gained on the CAD, by the construction of B-splines shape functions on T-subdivisions and triangular subdivisions. An alternative will be the use of the reduced quintic triangular finite elements.
- The numerical stability of finite element approximation of convection dominated flow. We will achieve the development of parameter free stabilization methods [Nkonga2010b] for MHD models based on multi-scale decomposition. The aim is to propose the best self-consistent stabilization strategy for different MHD models in order to preserve the global accuracy of the initial Galerkin formulation and enforce physical properties as monocity and positivity. This is a crucial step in order to obtain predictive simulations with full and extended MHD models.

- The memory consumption and efficiency on today's supercomputers. Indeed, in order to consider more and more realistic physical parameters and geometries for numerical simulations of edge plasma in tokamaks, some algorithmic improvements of JOREK are needed. The proposal will investigate some optimizations related to: memory footprint, load balance, memory requirement by using explicit-implicit schemes and alternative methods for the resolution of linear systems.

The visualization and data management component of this proposal will seek to extract, from the numerical simulations, the maximum amount of information possible and to provide a convenient means for data access, storage for both simulations and experiments.

3.2. PROJECT MANAGEMENT

This project team is the extension of the pre-existing team of ASTER ANR. The management of ASTER team, involving group meetings and conference calls, has proven to be effective. Moreover, there already exists a very strong connection between partners JAD (Nice) and IRFM(CEA-Caradache) through the associated laboratory (LRC-CEA) and by regular exchanges in particular in the context of the MHD working group. This organization will be preserved and additionally, collaborative activities will be plan for the global team. Partners JAD and IRFM will interact to insure effectiveness, with respect to target applications, of advance meshing tools and VMS stabilization strategies. The partners IRFM and INRIA/Bacchus will continue to collaborate on numerical optimizations and alternative linear solvers. Partner IFRM and IRFU will collaborate on code integration and the design of appropriate visualization and diagnostics tools that are suitable to extract in the numerical results data for comparison with physical experiments. All the team will participate to regular technical meetings and follow-up communications for information exchange. One main component of the technical meeting is a depth analysis of the further developments with regard to performance, modeling and optimization. A development plan will then be upgrade and any deviation from the baseline plan has to be discussed and approved by the team members via an email and/or meeting call discussion.

3.3. DESCRIPTION BY TASK

3.3.1 ELMS CONTROL BY RESONANT MAGNETIC PERTURBATIONS (RMP) .

Manager	M. Becoulet (IRFM)
Contributors	V. Grandgirard, G. Latu, C. Passeron, B. Nkonga, P. Ramet + 1 **PhD + 1 PostDoc (IRFM)**
Partners	CEA/IRFM, INRIA/Bacchus, Nice University
Main Goal	Non-linear MHD modeling and simulation of RMP interaction with plasma and ELMs

Duration	48 months

Program: New physical features essential for plasma response to RMPs and in particular screening of RMPs by rotating plasma will be introduced. The neoclassical viscous tensor will be implemented in equations for vorticity and parallel velocity. Source of toroidal rotation and two fluid diamagnetic effects also will be taken into account in the model. The initial study of plasma equilibrium with resulting poloidal and parallel equilibrium flows will be produced by JOREK code. As test cases the circular plasma will be modeled first and later on the realistic geometry with X-point. The equilibrium toroidal and poloidal flows and hence radial electric field are of particular importance for RMP penetration in plasma. RMP physics will be introduced in the model via given vacuum solution on the boundary of the computational domain. Vacuum code ERGOS developed for calculation of the magnetic perturbation generated by realistic coils on the present day tokamaks and ITER [Becoulet2008] will be used to generate these boundary conditions. RMP penetration or screening will be studied in different parameters scans: rotation, density, temperature, resistivity etc. Relevant results of RMP amplification versus screening are expected. Corresponding to RMP penetration convective ExB density transport will be studied in MHD approximation. Possible RMP coupling with intrinsic ELMs will be studied in multi-harmonics version of JOREK. Final goal of the project is to approach as much as possible ITER plasma parameters especially with respect to low resistivity and plasma size. Within this Task initially neoclassical equilibrium flows will be implemented and modeled starting with circular plasma and then X-point configuration. RMP model will be implemented and physics studied on smaller machines (DIII-D and JET) at modest magnetic Reynolds numbers (10^6-10^7). Later on (>2^{nd} year) when new numerical developments (in particular stabilization, adaptive meshes and memory and parallelization optimization in JOREK) permit, more realistic modeling of RMP physics will be done for larger S(=$10^{9)}$ numbers and ITER-size machine.

Milestones

- Theoretical formulation of ion neoclassical poloidal viscosity tensor in equations of motion in JOREK (t+3months). Implementation of the developed model of poloidal neoclassical viscosity into reduced MHD version of JOREK code. First tests cases to obtain magnetic equilibrium (harmonic n=0) and equilibrium poloidal and toroidal flows with source of toroidal rotation, diamagnetic two fluid effects and neoclassical poloidal viscosity included in JOREK. For simplicity first tests on establishment of equilibrium will be done on the circular plasma cross section, JET-size machine and plasma profiles with strong pedestal gradients will be used, since diamagnetic and neoclassical effects are important in pressure gradient zone. Implementation of module of calculation of neoclassical viscosity coefficients in the code. Relevant plasma parameters scan (pressure gradient, temperature, resistivity, etc). (t+9months)
- Establishment of magnetic equilibrium with toroidal and poloidal neoclassical flows with H-mode like profiles (with pedestal) in X-point geometry for JET size machine. Relevant plasma parameters scan. Use of stabilised version, since typically

diamagnetic effects are particular sensitive to numerical instabilities in the centre (Task N°3.3.5) of JOREK. Use optimised version of JOREK which includes developments of the Task N°3.3.3 (t0+15months).

- Implementation of RMP in the code and on the computational boundary. For this task vacuum code for RMP calculations ERGOS developed in IRFM will be used together with EFIT equilibrium code for realistic discharges of DIII-D (or/and JET). First test cases of RMP penetration/screening with neoclassical equilibrium electric field and diamagnetic effects in the marginally stable plasma for main n of applied RMP. Relevant parameters scan, going if possible to relevant resistivity (S=10^8) On this stage only one toroidal harmonic of RMP will be taken into account. Test if plasma remains stable or couples with intrinsic MHD. This is in conjunction with Tasks 3.3.3 (JOREK optimisation); 3.3.4 (to represent realistic geometry of divertor); 3.3.5 (stabilisation, needed for particular high beta plasmas). (t0+24months)
- Starting from test ELM modelling (for example in DIII-D) with one most unstable toroidal harmonic include RMP with n=3 (for DIII-D) at relevant S numbers. Test if ELM is stabilized by RMP. This is in conjunction with Tasks 3.3.3; 3.3.4; 3.3.5. Test multi-n non-linear simulations for ELMs together with RMPs. (t0+30months).
- Using obtained results in all numerical tasks results try first test cases of RMP penetration for ITER-size machine and realistic RMP coils and equilibrium (EFIT). Then simulations for ELMs together with RMPs for ITER size machine. (t0+48months)

3.3.2 MODELING OF PELLETS ELMS PACING.

Manager	B. Nkonga (JAD) and M. Becoulet (IRFM)
Contributors	H. Guillard, A. Sangam., E. Audit, **+ Post-Doc (JAD/IRFM) + Post-Doc (MdS) .**
Partners	CEA/IRFM, JAD, MdS
Main Goal	Develop and improve numerical tools for efficient numerical simulations of pellets ELMs Pacing.
Duration	48 months

Program :

Upstream of this application, there are a number of important changes to be implemented in the current version of JOREK, including graph profiles, parallel structure, linear solver interfaces and variables storage. Indeed, pellet ELMs facing is driven by the injection of very small ice of neutral matter. The size of these pellets is the local characteristic size that the mesh must have in the toroidal and poloidal directions around the injection site. Using Fourier representation in the toroidal direction we need a global refinement of more than O(100) Fourier modes. In this context, Computational CPU time need by the current version

of JOREK is out of computational resources that can be at our disposal in few years. The current task is devoted to the development of a new version of JOREK with B-splines representation in the toroidal direction so that local 3D mesh refinement can be possible.
The switch from Fourier transform to B-splines in the toroidal direction as well as the need to build a highly scalable code on hybrid machines make necessary to rethink the all code structure. This approach is probably more time efficient in the long term. We will therefore design a new code architecture and data structure. This will be done to have the best compromise between performances on massively multi-cores and/or GPU systems, easy coupling to existing tools for linear algebra or partitioning (PasTiX, Scotch, Metis,…) and versatility to add new physics. This task will lead by expert in software engineering in close collaboration with plasmas physicists and applied mathematicians.
In this first step, 3D mesh will be defined as a tensor product of a 1D curved (toroidal) and a 2D (poloidal) adapted meshes. Resulting finite element formulations have additional numerical sparsity in the toroidal direction. The Bacchus team (INRIA Bordeaux) has developed a general programming interface for mesh handling, data communication and exchange, remeshing, and data redistribution (PaMPA). This will be used as a base module for this task. This objective is also a part of our ongoing project PlaTo (A platform for Tokamak simulation) (http://www-sop.inria.fr/pumas/plato.php). Then, components of this new code version are already under development and the finalized version will probably be available in the year 3 of this proposal. At the same time, some pellet ELMs facing simulations will be performed with the actual version of JOREK by the means of local mass source terms. The last year will be devoted to numerical simulations with the latter version of the code to take into account the local dynamic of pellets injections.

Milestones

- Development of numerical tools for 3D curvilinear Beziers patches: graphs constructions, matrix structure, partitioning.
- Numerical implementation of the code version using 3D curvilinear Beziers patches formulation with an isentropic Reduced MHD model and VMS stabilization.
- Application to pellet injection by mass source: Comparative analysis with numerical simulations achieved by finite element/Fourier version of Jorek.
- Extension to non-isentropic Reduced and Full MHD models.
- Numerical implementation of a simple model for pellet dynamics and validation with refined mesh in the poloidal direction.
- Design of the new code architecture.
- Implementation and test of this new platform.

3.3.3 NUMERICAL ALGORITHM OPTIMIZATIONS AND PARALLEL SCALING.

Manager	P. Ramet
Contributors	V. Grandgirard, G. Latu, C. Passeron, P. Ramet , P. Kestener, **+ 1 PhD (INRIA) + 1stage(IRFM)+1stage(INRIA)**
Partners	CEA/IRFM, INRIA/Bacchus, MdS.

Main Goal	*Improve numerical algorithms and optimize memory usage to perform large physical cases on parallel machines.*
Duration	42 months

Program:

Several improvements can be done in JOREK in order to be able to consider bigger physical case and larger meshes of the spatial domain. The complexity of the tokamak's geometry and the fine mesh that is required leads presently to prohibitive memory requirements. The proposed task aims at improving JOREK in reducing **memory consumption** and **speeding up** the code. The following proposals will solve the problem of dealing with bigger physical case on today's supercomputer. This task will be subdivided into three subtasks described hereafter:

- **Reduce memory footprint:** In the current release of JOREK, the memory scaling is not satisfactory: as one increases the number of processes for a given problem size, the memory footprint on each process does not reduce as much as one can expect. So, the memory consumption is a serious problem in JOREK. Taking a large mesh in input, it exists a lower bound on the number of processors to use in order to fit all required data into main memory. There are several benefits in actually reducing memory waste. One of the most important at the present time is to be able to deal with bigger meshes than we use now, while running on reasonable numbers of processors. Otherwise, ITER type ELM's simulations would not be possible. A memory usage analysis has revealed three main memory consumers in the code. First, the large input matrix storing the whole system to be inverted represents a lot of memory. Compression techniques can be foreseen to reduce the footprint of this matrix without having to pay large computation expenses. Second, the representation of the factorized preconditioning matrix stored inside the direct solver takes also a large amount of memory. The Bacchus team has developed a general programming interface for sparse linear solvers. The goal is to normalize the API to sparse linear solvers and to provide some very simple ways of doing some fastidious tasks such as the parallel matrix assembly for instance. Thus, a generic API specifications called **MURGE** (http://murge.gforge.inria.fr) has been proposed. This interface has been coded in the two sparse solvers HIPS and PaStiX by Bacchus team. This interface needs to be extended to handle more complex schemes when the application is coupled with sophisticated hybrid solver. The MURGE interface and associated PaStiX routines that performs the matrix assembly and factorization will be upgraded and tuned in JOREK. We are looking for a fair distribution of data over the parallel processes and to reduce at best memory consumption. The effective parallelization of this assembly step is one of the main bottlenecks up to now, as far as memory usage is concerned. The GMRES driver is the third biggest consumer in terms of memory. We plan to consider up-to-date parallel implementation of **GMRES** in order to better parallelize this step and to lower memory usage. Together with physicists, a list of

relevant test cases will be established. These tests will be organized in order to design a non-regression testing. This will be useful to evaluate afterwards the performance of the JOREK code once one will have performed some improvements and optimization. A complementary approach will be to investigate algorithms in which maximum allowed memory consumption is a priori fixed at code launch. Then, algorithms and schemes are designed to replace data that cannot be stored in memory because of memory restriction by extra workload whenever it is required.

- **Optimize & load balance:** The strategy prescribing the maximum amount of memory wanted has already been initiated in PaStiX software and will be continued and extended in JOREK. Hybrid programming, mixing MPI process and threads, is a way to reduce memory overhead due to parallel implementation in direct solvers. The rationale that motivates this hybrid implementation was that the communications within a node could be advantageously substituted by direct accesses to shared memory between the processors inside nodes using threads. In addition, the MPI communications between processes are grouped by node. We have shown that this approach allows a great reduction of the memory required for communications. Nevertheless, this programming model has a strong impact on the design of parallel code. Some parts of PaStiX and JOREK need to be rewritten/optimized to take care of shared data efficiently. The assembly of preconditioning matrix and global matrix can be revised in order to get better load balance and reduce the amount of communications on the parallel machines. Another topic would be the use of SIMD instructions available on modern processors to optimize several costly steps in JOREK.

    - **Improve time-stepping scheme:** We intend to investigate a mixed **explicit–implicit formulation** to split the time integration operator. The advantage would be to reduce the size of the matrix to factorize and therefore the cost of the solving stage using PaStiX software. The solution will be tried on specific test cases to validate this approach.

    - **Investigate alternative sparse solvers:** New supercomputers incorporate many processing units, which include themselves one or many computational cores. These new architectures induce strongly hierarchical topologies. On one hand, Bacchus team has introduced a dynamic scheduling designed for these **architectures in the PaStiX solver.** On the other hand, a parallel version of HIPS is available that provides full iterative methods as well as hybrid methods that mixes a direct factorization inside the domain and an iterative method in the Schur complement. The solving step is clearly a bottleneck in numerical simulations such as JOREK. We propose to work on a hybrid method that is able to bring performance and scalability enhancement. An important aim for this goal is the design and the implementation of a sparse linear solver that can exploit the power of these new supercomputers. We will look for solutions concerning the following problems:

- Full parallel and scalable pre-processing steps (ordering and symbolic factorization);
- Efficient algorithmic coupling of direct and iterative methods that allow a powerful management of the different levels of parallelism;
- Adapted scheduling of computation tasks to take advantage of the runtime that operates on mixed architectures with multi-cores and/or eventually GPGPUs.

All developments foreseen within this task will be added dynamically during this project both to the JOREK code and to the Bacchus sparse solvers. All users of the JOREK code will benefit incrementally from these improvements. Strong collaborations between INRIA-Bacchus and CEA-IRFM will be needed in order to improve simultaneously JOREK and the sparse solver.

3.3.4 HIGHER-ORDER-OF-CONTINUITY ADVANCED MESHING AND LOCAL REFINEMENT.

Manager	B. Mourrain
Contributors	A. Galligo, B. Nkonga, A. Dervieux. **+ CDD.**
Partners	JAD/INRIA-Galaad, JAD.
Main Goal	Improve the meshing for general geometry.
Duration	36 months

Program :

The Bezier patches finite elements approach for the poloidal representation is now the standard in JOREK. For a given resolution, significant gain in both the number of degrees of freedom and computing time has been achieved using the Bezier patches as compared to the Lagrange finite elements. B-splines are piecewise polynomials that offer great flexibility and precision for a large class of modeling applications. They are built from a linear combination of basis functions that span a corresponding B-spline space. These shape functions are locally supported and higher order continuity is easily controlled. Continuity of derivatives is an important ingredient of the strategy for enhancing numerical stress divergence, to have a weak formulation of higher order differential operators (<= 4) consistently, to have an accurate representation of the alignment with the magnetic field, reducing the overall number of unknowns. Bezier patches used in JOREK are defined on quadrilateral elements as tensor product of 1D cubic splines. Continuity of derivatives of basic functions is obtained only in areas where the mesh nodes are at the intersection of exactly four neighbors' elements. It is a very strong constraint for the mesh generation such as accurate representation of complex geometries as ITER may be impossible.

One of our aims is to improve the construction of higher order of continuity shape functions in order to better take into account the complexities of both the geometry of the tokamak plasma chamber and the topology of the magnetic field. Indeed, proper treatment of the boundary geometry and field aligned mesh are mandatory to get accurate results in a very efficient way. This will be achieved, from the experience gained on the CAD, by the

construction of B-splines shape functions on T-subdivisions and triangular subdivisions. The present task will include classes of stable elements, quadrature rules, and ad hoc solvers, for splines discretizations. A posteriori error estimation will be addressed and combined with automatic refinement strategies. An alternative to this ambitious strategy will be the use of the reduced quintic triangular finite element that is already used in M3D-C1 code [Jardin].

Milestones

- Global analysis of the problem (meshing and construction of bases of functions to deal with the geometry encountered in a tokamak) and synthesis of the algorithmic strategies adopted in JOREK and other important existing computer programs.
- Strategy to address geometric questions in ITER, based on automatic generation of general rectangular meshes together with parameterization and adapted bases of splines functions (not necessarily positive but allowing partitions of unity). This will be illustrated by experiments computed with prototype software implementing our algorithms.
- Approximation techniques to fit the tokamak equilibrium field by a family of splines. An algorithm will provide automatically a mesh aligned on the field lines, together with a re-parameterization and adapted bases of splines functions.
- Strategy for refining the previous meshes, based on an improvement of the so-called T-splines and PHT-splines techniques. The number of independent basis functions at each node will be constant in order to ease further manipulations in the optimization process.
- A report presenting an extension of our previous strategies and algorithms to triangular meshes. This will extend techniques and ideas developed with quintic functions and with simplex-splines.
- In order to test our algorithms we will consider the computation of the equilibrium (a scalar equation) and the "current hole" problem (a system of equations), since there are some known analytic solutions for these problems.

3.3.5 VARIATIONAL MULTI SCALE STABILIZATION FOR COMPRESSIBLE MHD.

Manager	B. Nkonga
Contributors	A. Dervieux, M. Martin, A. Sangam, E. Audit, **+ PhD student + stages.**
Partners	JAD/Nice-University, CEA/IRFM, MdS
Main Goal	Develop parameter free stabilization for MHD models in the context of multi-scale analysis.
Duration	36 months

Program.

In order to obtain predictive simulations with reduced, full and extended MHD models, it is crucial to design a numerical strategies face some difficulties related to the use of the classical

Galerkin methods for convection dominated flows. To achieve this, some well established codes as XTOR NIMROD and M3D, use stabilization techniques based on Taylor-Galerkin methods introduced in [Donea1984]. Taylor-Galerkin formulation is a class of more general sub grid scale concept of multi scale stabilization introduced in [Hughes1995]. None of these modern stabilizations are available in the actual version of Jorek. This task has the objective of filling the gap by using the must advance stabilization strategy for different MHD model in order to preserved the global accuracy of the initial Galerkin formulation and enforce physical properties as monotony and positivity. This approach has a justified mathematical framework when the hyperbolic part of the system can be formulated in a symmetric form with a complete set of left and right eigenvectors. For the MHD equations, the ideal MHD is the main hyperbolic component and, using the Powell modification, we can be achieved the request. Therefore, stabilization will be reformulated as an additional contribution to the original set of equations. The important point is that this stabilization is defined locally and parameter free. This last property is obtained by using the local spectral properties of the hyperbolic component to define the stabilization parameter. This is the main step of this task and will be achieved in the first year. The stabilization of reduced models will be derived by the application of reduction operators on the stabilized set of equations. This strategy will be developed and improved, during this proposal, for all MHD models available in JOREK. Higher order of continuity shape functions also help to obtain more robustness of the stabilization has there is no more singularities on elements edges.

Milestones

- Mathematical formulation and analysis of the variational multi-scale stabilization for different MHD models: Reduced MHD, Full MHD and Extended MHD.
- Numerical implementation and validations using reduced MHD model. Finite element formulation using quadrangular Bezier patches in the poloidal plane (2D) and Fourier decomposition in the toroidal direction. Make this stabilized version available for ELMs control applications.
- Extensions to Full MHD model with the same finite element formulation as previous. Make this stabilized version available for ELMs control applications and also for algorithmic optimizations on large-scale parallel architectures.
- Numerical implementation and validations using C1 shapes functions designed for quadrangular meshes in the task 5. Make this stabilized version available for ELMs control applications.
- Numerical implementation and validations using C1 shapes functions designed for triangular meshes in the task (3.3.4). Make this VMS stabilized version available for ELMs control applications and also for algorithmic optimizations on large-scale parallel architectures

3.3.6 VISUALIZATION.

Manager	B. Thooris
Contributors	E. Audit, D. Pomarede + **CDD + stage**

Partners	MdS, CEA/IRFM
Main Goal	Explore in space and time the plasmas structure
Duration	48 months

With the power of supercomputers increasing exponentially, the simulation of complex systems at higher spatial and temporal resolution produces very large and complex datasets. The analysis, exploration and proper understanding of these datasets is a major issue. Visualization tools should transform complex datasets into readily understandable images; they should also allow easy exploration and the discovery of regions of particular physical interest. For this purpose, the stereoscopic display and multi-windowing facility available at the "Maison de la Simulation", which allow visualizing simultaneously several physical properties of the same region, is particularly useful.

This data analysis issue is particularly important in the context of this project because the physical processes happening around the divertor and during the ELM are very nonlinear and largely unknown. Therefore great insight of the physics understanding can be expected by advanced visualization techniques.

This work will be carried out in close collaboration with the Digiscope project (of which the "Maison de la Simulation" is a member). We will therefore benefit from the best available expertise in the field and to other outstanding visualization platform if necessary.

The visualization tools to be developed in this task should be able to handle very large datasets. It will be developed either based on an existing opensource software or build from a graphical library. This tool will foster scientific discovery by allowing visualizing simultaneously the spatial structures and the time evolution of the physical quantities relevant in Tokamak physics (magnetic field, pressure, temperature…). An added value is that these kinds of tools are also of great interest to debug large simulations where numerical instabilities or bugs can appear.

Milestones :

- Analysis of existing software and graphical libraries in order to choose the most appropriate development environments
- Implementation a stereoscopic visualization tool adapted to quadrangular and curvilinear meshes
- Development special visualization techniques for fields which are defined by localized scalar value and gradient
- Formation of the project members to the use of this visualization tools.
- Production of pictures and movies for public outreach.

3.3.7 PROJECT MANAGEMENT.

Manager	B. Nkonga
Contributors	M. Bécoulet, P. Ramet, E. Audit
Partners	

Main Goal	Managing the project.
Duration	48 months

The project management will take in charge: the organization annual and technical meeting, the evaluation of research advance compare to the baseline plan, the redaction of annual report and relations with the ANR staff, the organization a summer school during the proposal.

3.4. TASKS SCHEDULE, DELIVERABLES AND MILESTONES

<table>
<tr><th></th><th>Year 1</th><th>Year 2</th><th>Year 3</th><th>Year 4</th></tr>
<tr><td rowspan="2">Task 1
ELMs control by RMP.</td><td>Extended Fluid Models: neoclassical viscosity .</td><td colspan="2">Implementation of RPM physics and validations with more relevant parameters: JET size tokamak.</td><td>Final Report</td></tr>
<tr><td></td><td colspan="2">Neoclassical Equilibrium for JET and ITER size Tokamak.</td><td colspan="2">Nonlinear simulations of ELMs interactions with RMPs : ITER-size machine.</td></tr>
<tr><td rowspan="2">Task 2
Pellets ELMs Pacing.</td><td>Numerical tools for 3D curvilinear Beziers patches</td><td colspan="2">Numerical implementation of the code version using 3D curvilinear Beziers patches.</td><td>Final Report</td></tr>
<tr><td></td><td colspan="3">Applications to Pellets ELMs Pacing:by mass source term and latter by a simple model for pellet dynamic</td></tr>
<tr><td rowspan="3">Task 3
Numerical Optimizations and parallel scaling.</td><td colspan="2">Reduce memory footprint</td><td></td><td>Final Report</td></tr>
<tr><td colspan="2"></td><td colspan="2">Optimize & load balance
Improve time-stepping scheme</td></tr>
<tr><td colspan="4">Investigate alternative sparse solvers</td></tr>
<tr><td rowspan="2">Task 4
Higher order of continuity Advanced Meshing</td><td>Global analysis, strategies for the resolution.</td><td colspan="2">Implementations and Validations for MHD simulations.</td><td>Final Report.</td></tr>
<tr><td colspan="2">Development of automatic mesh aligned C1-Splines for general quadrangular subdivisions.</td><td colspan="2">Development of automatic C1-Splines for triangular meshes.</td></tr>
</table>

Task 5 Stabilization for MHD models.	Global analysis for MHD Models.	Code development for full MHD models: Improvement.	Final Report
	Code development for reduced MHD Numerical Validations.	Upgrade of VMS Stabilized Version of Jorek.	
Task 6 Visualization.	Analysis of existing software and graphical libraries	Formation to production of scientific pictures &movies.	Final Report
	Visualization tool for quadrangular and curvilinear meshes	Visualization techniques for high order resolution fields.	

Computing resource requirements

Essentially all the applications *will* be resource limited. The resources available determine the allowed resolution, which in turn determines what range of physical parameters can be realistically modeled. Computational resources will be sought from national centers (IDRIS, GENCI) and more widely to computing centers that accompany the ITER project.
The ANEMOS project will benefit of the use of the facilities installed at the Maison de la Simulation thanks to the Equip@meso and Digiscope Equipex project. The medium range computer from Equip@meso will allow developing, testing and optimizing the codes up to more than a thousand cores. The large 3D wall from Digiscope will be used to explore and analyze the data using the tools developed during this proposal.

4. DISSEMINATION AND EXPLOITATION OF RESULTS. INTELLECTUAL PROPERTY

Advances in this research program will be published without specific restrictions in international journals. The new algorithmic developments will be integrated in HIPS and PaStiX which are distributed under the CeCCIL-C license at : http://www.hips.gforge.inria.fr and http://www.pastix.gforge.inria.fr. Numerical tools, once validated, will be disseminated widely and available to the European users of Jorek.
We also plan to organize a summer school (CEMRACS or Porquerolles) on the topic of nonlinear MHD simulations. The objective here is to bring together different communities of

controlled fusion and astrophysics to take stock of the various researches in this field. Team JAD has extensive experience in organizing such events. Indeed we hold on average every two on the island of Porquerolles one-week conference on various themes. In 2009 the theme was "Numerical Models for Controlled Fusion http://www-sop.inria.fr/teams/pumas/NMCF09/. In addition, we have organized this summer in collaboration with our colleagues of Strasbourg and participation of IRFM, the CEMRACS on Numerical Models for the controlled fusion "http://smai.emath.fr/cemracs/cemracs10/"

5. CONSORTIUM DESCRIPTION

5.1. PARTNERS DESCRIPTION & RELEVANCE, COMPLEMENTARITY

Teams of the present proposal have productive collaborations for several years and in particular they have joint work in the ANR ASTER (06-10), ANR SINERGHY(06-10), ANR ESPOIR(09-12). Each consortium member has some experience on several themes of this program. This multidisciplinary approach goes beyond the scientific interests and concerns the programming structure and software engineering.

Partner IRFM was initially the main developer of the code JOREK during previous ANR ASTER project (2006-2009) . IRFM is a coordinator of JOREK users in EU. The IRFM team consists of internationally known specialists in non-linear MHD physics and modelling (M. Becoulet, V. Grandgirard, G. Latu, collaborating with G. Huysmans , the author of the code JOREK, presently at ITER Organisation). In particular, ELM control by RMP physics and modelling was under development in IRFM since 2003, which participated in RMP experiments on DIII-D(US), MAST, JET (UK) in modelling and design of most RMP experiments around the world (AUG-Germany, JT-60SA(Japan) ,MAST (UK), WEST-TS (France)) and finally in design of RMP coils for ITER. On the other hand the existing JOREK IRFM combines physics knowledge with numerical schemes optimisation skills with large experience of working with large codes on high performance parallel computers (V. Grandgirard, G. Latu, C. Passeron). IRFM team will provide expertise both for all physics applications of ELM control and numerical optimisation of JOREK.

Partner JAD is centred around the UMR 6621 J.-A. Dieudonné (JAD) and consists of two project joint teams with INRIA Sohia-Antipolis : Pumas and Galaad. The team Pumas is composed of specialist in numerical schemes, adaptive mesh generation and high-performance computing. This team has a long experiment on development of multi physic parallels numerical tools using finite element formulation. They have some achievement in the context of: aerodynamic, Lagrangian hydrodymic, Laser/plasma interaction, turbulence modelling, … The team Galaad develop method for effective and reliable representation of complex geometries and surfaces by set of appropriate shape functions.

Partner INRIA/Bacchus The purpose of the BACCHUS team is to analyze and solve efficiently scientific computation problems that arise in complex research and industrial applications and that involve scaling. Solving these kinds of problems requires a multidisciplinary approach involving both applied mathematics and computer science. One of the contributions of the BACCHUS team is the creation and implementation of optimized parallel algorithms and high-performance codes. This team is composed of experts in sparse direct solvers and preconditioners based on incomplete factorizations and the use of graph partitioning techniques in these methods. In collaboration with researchers at INRIA Bordeaux, they has implemented scalable parallel direct/incomplete factorization algorithms in the sparse linear solvers HIPS and PaStiX and the graph partitioning software Scotch and is parallel version PT-Scotch.

Maison de la Simulation. With the fast spreading of large computing centers at both the national and European levels, the French research community now has access to a world leading computing infrastructure. Such an infrastructure should foster major advances in both fundamental research and technology. Nevertheless, in order to meet these goals, it is necessary to develop applications software adapted to a very high degree of parallelism. These high-end applications can only be developed by gathering multidisciplinary teams, composed of HPC engineers, software and application specialists. For this reason, the Maison de la Simulation was created under the joint impulsion of CEA and CNRS. It is now a joint laboratory between CEA, CNRS, INRIA, University Paris-Sud and University of Versailles – St Quentin. Its main goal is to promote the efficient use by the scientific community of the available computing infrastructure. For that purpose, the Maison de la Simulation is developing along three main axes:

1) multidisciplinary research center dedicated to numerical simulation;
2) service and expertise center open to the scientific community;
3) nerve center for education and scientific animation.

The members of Maison de la Simulation have a long experience in high performance computing and scientific visualization. They have developed several massively parallel codes as well as high performance visualization tools, especially for stereoscopic vision.

5.2. QUALIFICATION OF THE PROJECT COORDINATOR

Boniface Nkonga is currently Professor at the University of Nice and permanent head of the project team PUMAS (Plasma, Turbulence, Modeling, Approximations and Simulations). He was member of the ANR Sinerghy and Aster. He has developed contribution that have give rise to scientific publications and computational tools. For two last years he worked actively in collaboration with IRFM on numerical methods for compressible MHD. This leads to regular participation in working groups of the IRFM on ELMs and MHD turbulence.
B. Nkonga is the principal manager of the platform FluidBox for computations in fluid mechanics (1D/2D/3D in F90, and Python). FluidBox offers a development environment for unstructured meshes with suitable integration (plug-in) of new physical models. FluidBox include automatically all the efforts made in data management, generation and management

of graphs, the construction of geometric parameters, checks in the data flow, structure and matrices filling, solving linear systems, methods of time integration, communications structures, compatibility with some external software (visualization, interactive computing, partitioning, linear solvers,...). FluidBox includes several physical models (compressible Navier-Stokes, RANS turbulence, multiphase incompressible MHD Flows with interfaces Compressible / incompressible, Lagrangian hydrodynamics,) and Numerical Strategies (Finite volume vertex centered and cell centered, stabilized finite elements, residual distribution P1, P2, Q1 and Q2). The developer community FluidBox consists of fifteen members (researchers, Post-Doctoral, PhD), FluidBox is deposited in the APA and is the subject of collaboration between INRIA and Glaizer innovation.

5.3. QUALIFICATION AND CONTRIBUTION OF EACH PARTNER

Partner 1: JAD	**Name**	**First name**	**Position**	**Work time**	**Contribution to the project**
Responsable	Nkonga	Boniface	Professor	32 months	VMS stabilization, Advanced Meshing, ELMs applications.
Other members	Dervieux	Alain	DR. INRIA	18 months	Field aligned mesh, scalable nonlinear solver, stabilization.
	Guillard	Hervé	DR. INRIA	18 months	Numerical tools for 3D curvilinear Finite Elements.ELMs applications.
	Sangam	Afeintou	Teacher & researcher	18 Months	Scientific computing,Simulations.
	Mourrain	Bernard	DR. INRIA	10 months	General unstructured adapted B-splines and associated tools.
	Galligo	André	Professor	24 months	General unstructured adapted B-splines and associated tools.

Partner 2 CEA/IRFM	**Name**	**First name**	**Position**	**Work time**	**Contribution to the project**
Responsible	Bécoulet	Marina	CEA researcher	24 months	Non-linear MHD of RMPs, ELMs , neoclassical and diamagnetic effects, physics of pellet triggering of ELMs
Other members	Latu	Guillaume	CEA researcher	15 months	JOREK optimisation, parallelisation, memory minimisation
	Grandgirard	Virginie	CEA researcher	15 months	Numerical scheme optimisation, JOREK optimisation
	Passeron	Chantal	CEA	15 Months	High level technical support on

			technical staff		supercomputers, documentation

Partner 3 INRIA/Bacchus	Name	First name	Position	Work time	Contribution to the project
Responsable	Ramet	Pierre	Teacher & researcher.	25 months	Sparse direct linear solvers and preconditioning.
Other members	Pellegrini	François	Teacher & researcher.	10 months	Graph partitioning and communication structures.

Partner 4	Name	First name	Position	Work time	Contribution to the project
Responsable	Edouard	Audit	CEA researcher.	6 months	Astrophysics, computers sciences
Other members	Kestener	Pierre	CEA	18 months	Code optimisation and scalability
	Pomarede	Daniele	CEA	12 months	Visualisation
	Thooris	Bruno	CEA	15 months	Visualisation

6. SCIENTIFIC JUSTIFICATION OF REQUESTED RESOURCES

6.1. PARTNER 1 : JAD/INRIA

Équipement / Equipment

Small equipment (workstations,…)	10KEuros
Total	**10 KEuros**

Personnel / Staff

Permanents Staff			**600 KEuros**
Teachers & researchers B. Nkonga, A. Sangam, A. Galligo	74 months	4257 Euros/month	315 KEuros
Researchers H. Guillard, A. Dervieux, B. Mourrain	46 months	6285 Euros/month	285 KEuros

Non-permanent Staff without ANR financing			
Research engineer	10 months	3150 Euros/month	31.5 KEuros
PhD's	10 months	2860 Euros/month	28.6 KEuros
Non-permanent Staff with ANR financing			**211 KEuros**
Post-Doc	24 months	4500 Euros/month	108 KEuros
PhD's	36 months	2860 Euros/month	103 KEuros

Post-Doc :

Title : Developments of general B-splines shape functions : hierarchical construction, refinement and mesh alignment.
Topics: Applied Mathematics, CAD, scientific computing, Plasma modeling.
Team-host : INRIA Sophia Antipolis.
Program for 24 months.

PhD thesis:

Title : Variational multiscale Stabilization with B-splines finite element for MHD models.
Topics: Applied Mathematics, numerical analysis, scientific computing, Plasma modeling.
Team-host : Laboratoire J.A. Dieudonné UMR CNRS.
Program for 36 months.

The aim of this PhD is to develop a global variational multi-scale strategy for the stabilization of reduced MHD models already implemented in JOREK code. Main effort will be to derive a parameter free stabilization that preserves the global finite element order of accuracy. To achieve this goal, the hyperbolic part of the system (Ideal MHD) should be reformulated in a symmetric form, by adding terms that are proportional to the magnetic field divergence (suppose to be zero, no magnetic monopole). In this form, it is possible to derive the spectral structure of the system and use it to define a parameter free stabilization. Then the stabilization of reduced models can be obtained using the same asymptotic expansion as the one use to derive these models from the full MHD, but in this context with the stabilized MHD system. Using B-splines shape functions will provide more robustness of the stabilization and, as B-splines shape functions constrained to enforce Ck continuity across element boundaries, will allow considering models involving higher order derivatives.
This more general approach will be compare to Taylor-Galerkin stabilization that is often used in numerical codes solving MHD equations in tokamaks. Validations will be performed for MHD instabilities (ELM's) and their control by RMP.

Missions / Travel

Travels in France : 7 travels, 11 days	4800 Euros
Participation to CEMRACS summer school	5000 Euros

International conferences : 1 travel + 7 days	3200 Euros
Total	**13 KEuros**

6.2. PARTNER 2 : CEA/IRFM.

Équipement / Equipment

Small equipment (workstations,…)	7KEuros
Total	**7 KEuros**

Personnel / Staff

Permanents Staff (IRFM)			**507,213KEuros**
Researcher -G. Latu	15month	7 223 €/month	108,345kEuros
Researcher -V. Grandgirard	15month	7 223 €/month	108,345kEuros
Researchers -Becoulet M	24month	8 697 €/month	208,728KEuros
Technical staff C. Passeron	15month	5 453 €/month	81,795 KEuros
Non-permanent Staff with ANR financing			**210,2KEuros**
Post-Doc	22month	4274 €/month	94,03KEuros
PhD	36 months	3051€/month	109,836 KEuros
stage	6month	1055Euros/month	6,3KEuros

Stage(non finance):

Title: Numerical algorithms optimization in JOREK.

Topics: Applied Mathematics, scientific &parallel computing.

Team-host :CEA/IRFM

Program for 6 months.

The non-linear MHD simulation code JOREK is used to study the evolution of the ELM instability inside a Tokamak. To simulate the complete cycle of an ELM instability, a large range of time and spatial scales need to be resolved simultaneously. A fully implicit time evolution scheme is used in the JOREK code in order to deal with this large spectrum of scales. To deal with the implicit scheme, a parallel direct solver, Pastix, is coupled with JOREK. Pastix solves the large matrix produced by JOREK at each time step. An hybrid thread/MPI programming model has been chosen both in JOREK and Pastix in order to improve the scalability on parallel platforms.

The large input matrix storing the whole system to be inverted represents a lot of memory. The first objective will be to consider several compression techniques in order to reduce the

footprint of this matrix, even if it induces some computation expenses. This large matrix is mainly used as input for the Pastix solver, and for the GMRES driver. The second objective will consist in improving the GMRES driver using up-to-date parallel implementation of GMRES in order to better parallelize computations and also to lower memory usage.

PhD thesis:

Title : Edge Localised Modes (ELM) control by Resonant Magnetic Perturbations (RMPs) in tokamaks.

Topics: Non-linear MHD tokamak plasma modeling.

Team-host :CEA/IRFM

Program for 36 months. In this thesis interaction of ELM with RMP physics will be studied and modelled using essentially non-linear MHD code JOREK. The main aim of the thesis is to progress in understanding of unknown mechanisms of interaction RMP with plasma and ELMs based on non-linear MHD theory and modelling of the rotating plasma response to RMPs . New developments in JOREK will be done to include RMP-ELMs-plasma interaction in self-consistent way in JOREK. In particular the role of the equilibrium electric field, neoclassical poloidal and toroidal viscosity, toroidal and poloidal plasma rotation on RMP screening and interaction of RMPs with ELMs will be studied. In the frame of this thesis modelling of the existing RMP experiments is envisaged on (DIII-D(US), JET(UK), MAST(UK) etc with the aim to compare theory predictions with experiments. PhD student will participate in some real experiments to collect data needed for modelling input (realistic geometry, equilibrium, plasma parameters, etc) and compare modelling results with observations. Once MHD modelling of RMPs physics will be tested on present experiments, the predictions for ITER are the final goal of this thesis aiming to give more reliable predictions for ITER RMP ELM control system.

Post-Doc :

Title: Modelling of RMP application in ITER-size machine using IsoGeometric Analysis (IGA).

Topics: Non-linear MHD tokamak plasma modeling.

Team-host :CEA/IRFM

Program for 22 months

The aim is to reach ITER relevant parameters in all ELM, RMP and pellet pacing modelling using JOREK code, which it is inaccessible for the moment with respect to realistic geometry, machine size and large Magnetic Reynolds numbers. For this we propose to implement in JOREK new kind of discretisation in poloidal plane using for IGA methods (such as NURBS, for example, use of higher order elements, refinement, multi-patches, etc) , which should be a natural generalisation of Bezier (C1) surfaces used at the moment. The Post-Doc work will be to find the most optimum way of IGA methods and their implementation in independent module ("black-box" type for user) for basic functions in JOREK in order to find a compromise between reasonable memory-time consumption, real geometry and possibility to resolve the particular finite structures of RMP response currents in plasma in large

tokamaks up to ITER-size. The application of new numerical discretisation to RMP in ITER is a final goal of Post-Doc.

Missions / Travel

Travels in France : 7 travels, 11 days	4800 Euros
Participation to CEMRACS summer school	4300 Euros
International conferences : 2 travels + 7 days	6400 Euros
Total	**15,5 KEuros**

6.3. PARTNER 3 : INRIA/BACCHUS.

Personnel / Staff

Permanents Staff (INRIA)			**149 KEuros**
Teachers & Researcher s P. Ramet, F. Pellegrini	35month	4257 Euros/month	149 KEuros
Non-permanent Staff with ANR financing			**120 KEuros**
stage	6month	2860 Euros/month	17 KEuros
PhD	36 months	2860 Euros/month	103 KEuros

Stage:
Title : Hybrid programming, to reduce memory overhead due to parallel implementation in direct solver PastiX.
Topics: Applied Mathematics, scientific &parallel computing.
Team-host : INRIA/Bacchus
Program for 6 months.

The non-linear MHD simulation code JOREK is used to study the evolution of the ELM instability inside a Tokamak. To simulate the complete cycle of an ELM instability, a large range of time and spatial scales need to be resolved simultaneously. A fully implicit time evolution scheme is used in the JOREK code in order to deal with this large spectrum of scales. To deal with the implicit scheme, a parallel direct solver, Pastix, is coupled with JOREK. Pastix solves the large matrix produced by JOREK at each time step. An hybrid thread/MPI programming model has been chosen both in JOREK and Pastix in order to improve the scalability on parallel platforms.
Hybrid programming, mixing MPI process and threads, is a way to reduce memory overhead due to parallel implementation in direct solvers. The rationale that motivates this hybrid implementation was that the communications within a node could be advantageously substituted by direct accesses to shared memory between the processors inside nodes using threads. In addition, the MPI communications between processes are grouped by node. We have shown that this approach allows a great reduction of the memory required for communications. Nevertheless, this programming model has a strong impact on the design of parallel code. Some parts of PaStiX and JOREK need to be rewritten/optimized to take care

of shared data efficiently. The assembly of preconditioning matrix and global matrix can be revised in order to get better load balance and to globally reduce the amount of communications on the parallel machine.

PhD thesis:
Title : scalable and robust hybrid solvers to reach numerical simulation challenges.
Topics : high-performance computing, sparse linear algebra, hybrid direct/iterative methods
Team-host : INRIA Bordeaux, BACCHUS
Program for 36 months :
New supercomputers incorporate many microprocessors which include themselves one or many computational cores. These new architectures induce strongly hierarchical topologies. On one hand, we have introduced a dynamic scheduling designed for these architectures in the PaStiX solver. On the other hand, we have a parallel version of HIPS that provides full iterative methods as well as hybrid methods that mixes a direct factorization inside the domain and an iterative method in the Schur complement. Moreover, graphs or meshes partitioners (Scotch software for instance) are able to deal with problems that have more than several billion of unknowns. Solving linear systems is clearly the limiting step to reach this challenge in numerical simulations. An important aim for this work is the design and the implementation of a sparse linear solver that can exploit the power of this new supercomputers. We will have to propose solutions for the following problems:

- full parallel and scalable pre-processing steps (ordering and symbolic factorization);
- efficient algorithmic coupling of direct and iterative methods that allow a powerful management of whole the levels of parallelism;
- adapted scheduling of computation tasks to take advantage of the runtime that operates on mixed architectures with multi-cores and GPUs.

6.4. PARTNER 4 : MDS (MAISON DE LA SIMULATION)

Équipement / Equipment

Small equipment (workstation for the post-doc,…)	7000 Euros
Storage for large simulation data	20000 Euros
Total	**27 KEuros**

Personnel / Staff

Permanents Staff			**406 KEuros**
Researchers/ingeneers	51 months	6966 Euros/month	355 KEuros
Non-permanent Staff without ANR financing			
Research engineer	12 months	4257 Euros/month	51 KEuros
Non-permanent Staff with ANR financing			**166 KEuros**
Post-Doc	36 months	4500 Euros/month	162 KEuros

Master student training period	4 months	1000€/month	4 k€

Post-Doc :
Title : Development of 3D visualization tools for Tokamak plasmas
Topics: Scientific visualization
Team-host : Maison de la Simulation
Program for 18 months:
This Post-Doc is devoted to the development of a visualization tool dedicated to Tokamak plasmas. He will work with the visualization team at the Maison de la Simulation and in the rich scientific environment of the Digiscope Equipex project.

Post-Doc :
Title : Development of 3D-cuvilinear finite element formulation for Tokamak geometry and application to pellet injection.
Topics: Applied Mathematics, scientific &parallel computing, Plasma modeling.
Team-host : Maison de la simulation.
Program for 18 months:
This Post-Doc is devoted to the development of a 3D-cuvilinear finite element for MHD models. The formulation will be based on Bezier patches in the poloidal plan and B-splines in the toroidal direction. This well need an efficient reformulations of graphs, matrix, communications structures, … This new JOREK version will be compare to the actual formulations using Fourier decomposition in the toroidal direction. Target application is the dynamic of pellet injection and consequences on ELM's instabilities.

… Missions / Travel

Travels in France (collaboration, conferences)	6000 Euros
International conferences (2 during the project)	4000 Euros
Total	**10 KEuros**

7. ANNEXES

7.1. REFERENCES

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[VTK] The Visualization Toolkit. http://www.vtk.org/
[Xu 2010] Xu et al Phys Rev Letters 2010

7.2. CV, RESUME

Boniface Nkonga

Situation professionnelle : Professeur
Laboratoire de Mathématiques, JAD, Université de Nice (UNS) et UMR du CNRS 6621.
Parc Valrose, 06108 Nice, France
Membre du projet PUMAS commun UNS-INRIA
Tel: 00 33 4 92 07 64 83 *fax*: 00 33 *e-mail*: nkonga@unice.fr

Cursus et carrière :
1993 Thèse de doctorat en Mathématiques appliquées (Nice-Sophia Antipolis)

1993 Ingénieur expert à l'Inria Sophia-Antipolis
1995 Maître de conférences à l'université Bordeaux 1, HDR en 2001.
2008 Professeur à l'université de Nice Sophia-Antipolis

Thématique de recherche

Twophase flow and multifluid modeling, Low Mach number flows, Parallel computing and Large scale CFD applications, numérical modelling, Lagrangian hydrodynamic, Laser-plasma interaction, Plasma modeling, Granular flow.

Activités de responsabilités

Responsable scientifique LRC CEA/Bordeaux 1 de 2007 à 2008, Responsable de la cellule informatique de l'IMB 2003-2006, Chargé de mission valorisation à l'IMB 2006-2008, actuellement responsable permanent du projet Pumas (Inria Sophia Antipolis).

Publications significatives

Relaxation method for low Mach number compressible multiphase flow, ***B. Braconnier and B. Nkonga*** *Journal of Computational Physics, 228(16):5722-5739, 2009.*

Multi-scale Godunov-type method for cell-centered discrete Lagrangian hydrodynamics. ***P.-H. Maire and B. Nkonga,*** *Journal of Computational Physics, 228(3):799-821, 2009*

Dry granular flows with erosion/deposition process.. ***C-Y. Kuo, B. Nkonga, M. Ricchiuto, Y.-C. Tai and B. Braconnier.****, ESAIM: Proc 28:135-149 , 2009*

Multifluid numerical approximations based on a multipressure formulation. **C. Berthon and B. Nkonga,** *Computers&Fluids 6(2):467-479, 2007.*

Marina Becoulet -52ans,

Situation professionnelle : Ingénieur chercheur, IRFM, CEA Cadarache, St-Paul-lez-Durance, 13108, France ; e-mail marina.becoulet@cea.fr

Cursus et carrière :

1981 : Diplômée de l'Université d'Etat de Moscou, faculté de la physique, département de la physique des plasmas.
1985 : Doctorat de Physique et de Mathématiques, Institut de Mathématiques Appliquées de l'Académie des Sciences de Russie à Moscou.
1983-1991 : Ingenieur chercheur, Institut Keldysh de Mathématiques Appliquées, Académie des Sciences de Russie, Moscou
1991-1992 : Collaborateur temporaire étranger, JET, Joint European Torus, Abingdon, Oxfordshire, Angleterre
1993-1993 : Collaborateur temporaire étranger, DRFC, CEA, Cadarache
1994-1994 : enseignant Association de Promotion du Centre International des Langues
1998- présent : Ingénieur chercheur (E5), SIPP/ IRFM, CEA
2001-2002 : secondment JET, Joint European Torus, Abingdon, Oxfordshire, Angleterre
2009 : Habilitation à Diriger des Recherches, Université Aix-Marseille I

Thématique de recherche :

Physique des plasmas. Théorie et modélisation. Modélisation de la propagation-absorption des ondes dans les plasmas de fusion, de la physique et du transport des

particules dans des gaines HF, du transport de la chaleur dans la zone ergodique, de la physique non- linéaire des Egde Localized Modes (ELM) et leurs contrôles par les champs ergodiques.

Activités de responsabilités

Membre d'ITPA (G Piédestal) , TG-MHD (ELMs) d'EFDA.

Encadrement au CEA/IRFM/SIPP 1 thésard (E. Nardon en 2004-2007), 2 stagiaires en 2003 et 2004. 3 thésards à l'Institut Keldysh de Mathématiques Appliquées (Académie des Sciences de Russie, Moscou)

Publications significatives (H=21)

"Physics of Penetration of Resonant Magnetic Perturbations Used for Type I Edge Localized Modes Suppression in Tokamaks." **Becoulet M** , Huysmans G. et al Nucl. Fusion, 49 (2009) *085011*

'Numerical study of the resonant magnetic perturbations for Type I edge localized modes control in ITER' **Becoulet M**, Nardon E, Huysmaws G, et al. Nucl. Fusion, 48 (2008).

Edge localized modes control by stochastic magnetic fields, **M. Becoulet ,** G. Huysmans , P. Thomas , P. Ghendrih , E. Nardon , A. Grosman , X. Garbet , W. Zwingman , R. Moyer T. Evans , M. Schaffer and A. Leonard, Nucl. Fusion 45 (2005)1284

Edge localized modes control: experiment and theory (review paper) .
Journal of Nuclear Materials, Vol 337-339(2005)p 677-683

M. Becoulet, G. Huysmans, P. Thomas, E. Joffrin, F. Rimini, P. Monier-Garbet, A. Grosman, P. Ghendrih, V. Parail, P. Lomas *et al.*

Edge Localised Modes physics and operational aspects in tokamaks (review paper).
M Becoulet et al Plasma Physics and Controlled Fusion, 45(2003), issue 12.1, A93-A113.

Virginie Grandgirard – 37 ans

Email : virginie.grandgirard@cea.fr

Formation

Doctorat en Mathématiques et Applications, université de Besançon (1999).
DEA Mathématiques et Applications, université de Besançon (1996).
DESS Calcul Scientifique et Statistique, université de Besançon (1996).

Activité professionnelle

Ingénieur-Chercheur CEA depuis (juillet 2001)
mars 2000 - juin 2001 : Post-doctorat (Ecole Polytechnique Fédérale de Lausanne)
novembre 1999 - février 2000 : Post-doctorat (LPIIM, université Aix-Marseille II)
octobre 1996 – octobre 1999 : Thèse (DRFC CEA Cadarache)

Encadrement

Encadrement de 8 stages DESS/DEA : 1998 (4 mois + 5 mois) ; 1999 (7 mois) ; 2002 (7 mois + 3 mois), 2003 (3 mois), 2006 (5 mois), 2009 (5 mois).
Encadrement de 2 post-doctorants : 2007-2008 + 2009-2010
Encadrement d'une thèse : 2009-2012

Publications

[1] Global full-f gyrokinetic simulations of plasma turbulence, V. Grandgirard, Y. Sarazin, P. Angelino, A. Bottino, N. Crouseilles, G. Darmet, G. Dif-Pradalier, X. Garbet, Ph. Ghendrih, S. Jolliet, G. Latu, E. Sonnendrücker, L. Villard, *Plasma Phys. Control. Fusion, vol 49, B173-B182 (2007).*
[2] A drift-kinetic Semi-Lagrangian 4D code for ion turbulence simulation, V. Grandgirard, M. Brunetti, P. Bertrand, N. Besse, X. Garbet, Ph. Ghendrih, G. Manfredi, Y. Sarazin, O. Sauter, E. Sonnendrücker, J. Vaclavick, L. Villard, *Journal of Computational Physics, Volume 217, Issue 2 , Pages 395-423 (2006).*
[3] Computing an ITG turbulence with a full-f Semi-Lagrangian code, V. Grandgirard, Y. Sarazin, X. Garbet, G. Dif-Pradalier, Ph. Ghendrih, N. Crouseilles, G. Latu, E. Sonnendrücker, N. Besse, P. Bertrand,*Commun. Nonlinear Science Num. Simul. doi:10.1016/j.cnsns.2007.05.016 (2007).*
[4] Gysela, a full-f global gyrokinetic Semi-Lagrangian code for ITG turbulence simulations, V. Grandgirard, Y. Sarazin, X. Garbet, G. Dif-Pradalier, Ph. Ghendrih, N. Crouseilles, G. Latu, E. Sonnendrücker, N. Besse, P. Bertrand, *Proceedings of Theory of Fusion Plasmas, Varenna (2006).*
[5] Une méthode de sur- et sous-solutions appliquée à la localisation de solutions d'équilibre axisymétrique du plasma dans un tokamak, V. Grandgirard, J.C. Miellou, *C. R. Acad. Sci. Paris, t. 330, Série I, p.153-156 (2000).*

Nombre de publications
Dans les revues internationales à comité de lecture : 3 en premier auteur + 18 en tant que co-auteur
Dans les actes de congrès à comité de lecture : 2 en premier auteur + 10 en tant que co-auteur

Guillaume Latu- 34 ans

Ingénieur chercheur, IRFM, CEA Cadarache, St-Paul-lez-Durance, 13108, France ; e-mail guillaum.latu@cea.fr

Cursus
Doctorat en Informatique, Université de Bordeaux 1 – projet ScAlApplix
(INRIA) au LaBRI. Algorithmique parallèle et calcul haute performance dédiés à la simulation d'un système hôte-parasite 12/2002 DEA d'Informatique, LaBRI, Université de Bordeaux 1.
Ecole d'ingénieur en Informatique (ENSEIRB).
Expériences professionnelles :
Depuis 2010 , Ingénieur chercheur, IRFM, CEA
2003-2010 : Maître de Conférences - Université Strasbourg 1.
09/2002 – 08/2003 : demi-ATER à l'ENSEIRB, Ecole d'ingénieur en Informatique.
Liste des cinq publications les plus significatives dans les cinq dernières années :

- G. Latu, N. Crouseilles, V. Grandgirard, E. Sonnendrücker. Gyrokinetic Semi-Lagrangian Parallel Simulation using a Hybrid OpenMP/MPI Programming, Recent Advances in PVM and MPI, LNCS 4757, 356-364 (2007).

- N. Crouseilles, G. Latu, E. Sonnendrücker. Hermite spline interpolation on patches for the parallel solving of the Vlasov-Poisson equation, Int. J. Appl. Math. Comput. Sci., 17, 335-349 (2007).
- N. Besse, G. Latu, A. Ghizzo, E. Sonnendrucker, P. Bertrand, Wavelet-MRA-based adaptive semi-Lagrangian method for the relativistic Vlasov-Maxwell system, J. Comput. Phys., 227, 7889-7916 (2008).
- S. Genaud, P. Gancarski, G. Latu, A. Blansché, C. Rattanapoka, D.Vouriot, Exploitation of a parallel clustering algorithm on commodity hardware with P2P-MPI, J. Supercomputing, 43, 21-41 (2008).
- N. Crouseilles, G. Latu, E. Sonnendrücker. A parallel Vlasov solver based on local cubic spline interpolation on patches. J. Comput. Phys. Vol. 228, Num. 5, 1429-1446 (2009).

Nombre de publications
Dans les revues internationales à comité de lecture : 8
Dans les actes de congrès à comité de lecture : 17

Chantal Passeron - 50 ans

Email : chantal.passeron@cea.fr

Formation

Diplôme Universitaire de Technologie en Informatique (1981)

Activité professionnelle

Technicienne en informatique scientifique.
Développement, maintenance et portage de codes, post-traitement graphique et visualisation, service aux utilisateurs dans le domaine du calcul scientifique.
CEA (Département de Recherche sur la Fusion Contrôlée) depuis juillet 1997.
CISI (Compagnie Internationale de Service en Informatique) au CEA/Cadarache de juillet 1982 à juillet 1987.
SIMINEX (Systèmes d Exploration Minérale) à Marseille de décembre 1981 à juin 1982.

André Galligo (ne le 4/6/1946)

Situation professionnelle : Professeur, classe exceptionnelle, de Mathématiques.
Laboratoire de Mathématiques, JAD, Université de Nice (UNS) et UMR du CNRS 6621.
Membre du projet Galaad commun UNS-INRIA.
Tel: 00 33 4 92 07 64 83 *fax*: 00 33 *e-mail*: nkonga@unice.fr

Thèmes de recherche

Géométrie et Calcul formel, Différentiation automatique de programmes, Résolution approchée de systèmes d'équations polynomiales et applications a la C.A.O. (Conception Assistée par Ordinateur),
Analyse isogéometrique de la résolution d'EDP.

Activités de responsabilités

Chairman du Steering committitur de la série de conférences ISSAC.

Partenaire de l'ANR Gecko, Approche géométrique de la complexité et application,(2005-08), du contrat Européen Exciting, EXaCt geometry sImulaTIoN for optimized desiGn of vehicles and vessels, (en cours).
Liste de publications sur MathSciNet, Encadrement de 25 thèses.

Hervé Guillard

Situation professionnelle : Directeur de Recherche
Etablissement : Inria Centre de Sophia-Antipolis-Mediterranée
2004 routes des lucioles,BP 93 - 06902 Sophia Antipolis, France
Tel: 00 33 4 9238 7796 *fax*: 00 33 *e-mail*: herve.guillard@inria.fr
Cursus et carrière :
1984 Thèse de doctorat en Aérodynamique de l'Ecole des Mines de Paris
1984 Chargé de recherche à l'INRIA Sophia Antipolis
1996 HDR en Mathématiques Appliquées à l'Université de Provence
1998 Directeur de recherche à l'INRIA Sophia Antipolis
Thématique de recherche
Twophase flow and multifluid modeling, Low Mach number flows, Astrophysical flows Multigrid algorithms: Geometrical MG, Algebraic MG, Parallel and Grid computing and Large scale CFD applications, Plasma modeling
Activités de responsabilités
Responsable scientifique du projet Smash de l'Inria Sophia-Antipolis de sa création en 2000 jusqu'en 2007, actuellement responsable permanent du projet Pumas.
Publications significatives
On the behavior of upwind schemes in the low Mach number limit. IV: P0 approximation on triangular and tetrahedral cells. ***H. Guillard***, *Computers & Fluids, Volume 38, Issue 10, December 2009, Pages 1969-1972, ISSN 0045-7930, DOI: 10.1016/j.compfluid.2009.06.003.*
Analysis of an Algebraic Petrov-Galerkin Smoothed Aggregation Multigrid Method. ***H.Guillard, A.Janka and P.Vanek,*** *Applied Numerical Mathematics 58 (2008), pp. 1861-1874*
Behavior of upwind scheme in the low Mach number limit: III. Preconditioned dissipation for a five equation two phase model. **A. Murrone and H.Guillard**, Computers&Fluids 37 (2008), pp. 1209-1224.
A Darcy law for the drift velocity in a two-phase model. ***H. Guillard and F. Duval***, *J. Comput. Phys., 224, pp 288--313, 2007.*
Recent developments in the computation of compressible low Mach number flows. **H. Guillard**, Flow, Turbulence and Combustion, 76, pp 363--369, 2006
Distinctions *:* First prize of the 1991 Seymour Cray (with the Sinus team)

Alain Dervieux

Situation professionnelle : Directeur de Recherche
Etablissement : Inria Centre de Sophia-Antipolis-Mediterranée
2004 routes des lucioles,BP 93 - 06902 Sophia Antipolis, France

Tel: 00 33 4 9238 7796 *fax*: 00 33 *e-mail*: alain.dervieux@inria.fr

Thématique de recherche

His main involvements in CFD concerns are

(1) the development of numerical methods: Mixed-Element-Volume approximations for compressible flows, Agglomeration Multigrid and multilevel, optimal design by adjoint methods, continuous-metric mesh adaptation models, hybrid-VMS turbulence models

(2) the participation to industrial software development (NATUR, N3S, THESEE, ANANAS, all these codes are running dayly).

At the instant, he is responsible of workpackages in European projects HISAC and NODESIM. He has been coordinator of project ETMA on Turbulence models (19 partners), and of a French COST program on Supersonic aircrafts, he was for four years president du comite des projets au centre INRIA de Sophia-Antipolis.

Afeintou Sangam,

Situation professionnelle : Maître de conférences

Laboratoire de Mathématiques, JAD, Université de Nice (UNS) et UMR du CNRS 6621.
Parc Valrose, 06108 Nice, France
Membre du projet PUMAS commun UNS-INRIA
Tel: 00 33 4 92 07 60 22 *fax*: 00 33 *e-mail*: sangam@unice.fr

Cursus et carrière :

2004 Ingénieur MATMECA (Bordeaux 1).
2007 Thèse de doctorat en Mathématiques appliquées et calcul scientifique (Bordeaux 1)
2007 Post. Doc. CNRS à l'Institut de Mathématiques de Toulouse
2008 Maître de conférence à l'université de Nice Sophia Antipolis.

Thématique de recherche

Modélisation numérique, interaction Laser-plasma, Transport de Particules Chargées, Equations Cinétiques, Magneto-HydroDynamique, Mécanique des Fluides à l'équilibre thermodynamique et hors équilibre thermodynamique.

Activités de responsabilités

Publications significatives

Anisotropic instability in a laser heated plasma, **A. Sangam, J.-P. Morreeuw, V.T. Tikhonchuk** , *Physics of Plasmas, Volume 14, 053111 (2007), Journal Virtual Journal of Ultrafast Science(2007*).

An HLLC Scheme for Ten-Moments coupled to Magnetic Field, **A. Sangam**, *International Journal of Computing Sciences and Mathematics, Volume 2, 73 (2008).*

An Asymptotic Preserving Scheme for the Euler equations in a strong magnetic Field, **P. Degond, F. Deluzet, A. Sangam, M.-H. Vignal,** *Journal of Computational Physics Volume 228, 3540 (2009).*

Edouard Audit

Situation professionnelle : Ingénieur de Recherche CEA.
SACLAY
Tel: 00 0169084235 *fax*: 00 33 *e-mail*: edouard.audit@cea.fr
Cursus et carrière :
1997-1998 : Post-doctoral position at DAEC, Observatoire de Meudon
1999-2001 : Post-doctoral position at Service d'Astrophysique
2001- : Permanent position at Service d'Astrophysique
Thémes de recherche
Experience of numerical modelling in the fields of radiative transfer, star formation, interstellar medium and cosmology
Activités de responsabilités
2008 - : Professor at CEA/INSTN
2007 - : Co-organizer of the Astronum conference series who gather every year around 100 scientists specialist of the numerical modelling of astrophysical fluid flows.
2006 - : Member of the scientific board of the "Programme National de Physique Stellaire" (funding organisation for stellar physics)
2005 - : Head of the French national computing time allocation comity for astro- and geophysics.
Supervision of several doctoral (3) and post-doctoral (4) students.
Leader of the ANR project SiNERGHy (2006-2010) which gather several labs on the topics of parallel computing for astrophysical and laser created plasmas.
CEA leader for the ANR project MAGNET on the modelling of astrophysical MHD flows
Publications significatives
Audit & Hennebelle, A&A, 2005, 433, 1Thermal condensation in a turbulent atomic hydrogen flow
Audit & Hennebelle, A&A, 2009, in press,, On the Structure of the Turbulent Interstellar Clouds III
Gonzalez, M., **Audit**, E., Huynh, P., A&A, 2007, 464, 429, HERACLES: a three-dimensional radiation hydrodynamics code
Hennebelle P., **Audit**, E., A&A, 2007, 465, 431, On the structure of the turbulent interstellar atomic hydrogen. I. Physical characteristics. Influence and nature of turbulence in a thermally bistable flow
Hennebelle P., **Audit**, E. & Mivilles-Deschênes M.-A., A&A, 2007, 465, 445, On the structure of the turbulent interstellar atomic hydrogen. II. First comparison between observation and theory.

B. Thooris

Situation professionnelle : Ingénieur-chercheur au laboratoire SEDI/LILAS de l'IRFU.
Activités de responsabilités
Project Manager du projet COAST (COmputational ASTrophysics) à l'IRFU (depuis 2005) comprenant des astrophysiciens du SAp et des ingénieurs du SEDI/LILAS
Responsable du groupe Software de la collaboration internationale MPPC et développement

d'une partie du software de la machine massivement parallèle ASTRA.(1990-1994)
Développement de codes pour la résolution de problèmes liés à la physique des plasmas dans les tokamaks TORE-SUPRA,JET et NET/ITER (1979-1888)
- code d'électromagnétisme en éléments finis 2D.(code MAGNETIX).
- code d'éléments finis 2D à frontière libre Self-Consistant d'Equilibre et de Diffusion du plasma dans un tokamak (code SCED)
- code d'éléments finis de calcul des Courants de Foucault dans des coques minces, (code CORFOU)

Publications significatives

- B.Thooris,E.Audit, A.S.Brun, Y.Fidaali, F. Masset, D.Pomarède, R.Teyssier, "The COAST Project: a Program of Massively Parallel Numerical Astrophysics Simulations", Proceedings of the HPC-Asia 2009 conference (march 2-5, Kaohsiung, Taiwan)
- B. Thooris, E. Audit, A. S. Brun, Y. Fidaali, F. Masset, D. Pomarède, R. Teyssier, " Massively Parallel Simulations of Astrophysical Plasmas: Status and Perspectives of the COAST Project", Proceedings of HPCS 2008 'The 2008 High Performance Computing & Simulation Conference' (june 3-6, University of Cyprus, Nicosia, Cyprus)
- Thooris, B., Orsini, L., Vesztergombi, G., [et al.] "ASTRA-2 Tutorial (A 4096 processors SIMD machine for real time algorithms) ", *The 1994 CERN School of Computing* Sopron (Hongrie) Aout-Septembre 1994
- Blum, J., LeFoll, J., Thooris, B. "The Self Consistent Equilibrium and Diffusion Code SCED", *Computer Physics Communications*, vol. 24,, pp. 235

Pierre Ramet

Situation professionnelle :Maître de conférences à l'université Bordeaux 1
Recherches : LaBRI (UMR 5800), projet Bacchus (INRIA Bordeaux Sud-Ouest)
Enseignements : Département Informatique de l'IUT
Université Bordeaux 1, 351 cours de la libération, 33405 Talence Cedex
Tél. : 05 24 57 40 39 Email : ramet@labri.fr

Diplômes académiques

Thèse de doctorat de l'Université Bordeaux I soutenue en janvier 2000
Titre : *Optimisation de la Communication et de la Distribution des Données pour des Solveurs Parallèles Directs en Algèbre Linéaire Dense et Creuse*

Thématique de recherche

Ma problématique de recherche concerne l'algorithmique parallèle hautes performances. Le thème général de mes travaux concerne le calcul parallèle scientifique pour les problèmes réguliers et irréguliers. Je m'intéresse principalement aux problèmes posés par la distribution et l'ordonnancement des calculs conduisant à la réalisation d'un solveur parallèle performant

pour la résolution de très grands systèmes linéaires creux. Ces techniques sont des briques de base algorithmique fondamentale pour les applications scientifiques de calcul intensif.

Principales publications depuis 2005

R. Abgrall, R. Huart, and P. Ramet. **Numerical simulation of unsteady MHD flows and applications**. *MagnetoHydroDynamics Journal*, 2009, to appear.

P. Hénon, P. Ramet, and J. Roman. **On finding approximate supernodes for an efficient ILU(k) factorization**. *Parallel Computing*, 34:345-362, 2008.

M. Barrault, B. Lathuilière, P. Ramet, and J. Roman. **A domain decomposition method applied to the simplified transport equations**. In *IEEE 11th International Conference on Computational Science and Engineering*, Sao Paulo, Brazil, pages 91-97, July 2008.

Y. Caniou, J.-S. Gay, and P. Ramet. **Tunable parallel experiments in a GridRPC framework: application to linear solvers**. In *VECPAR'08, 8th International Meeting High Performance Computing for Computational Science*, volume 5336 of *LNCS*, Toulouse, France, pages 430-436, June 2008.

M. Faverge and P. Ramet. **Dynamic Scheduling for sparse direct Solver on NUMA architectures**. In *Proceedings of PARA'2008*, Trondheim, Norway, May 2008.

P. Hénon, P. Ramet, and J. Roman. **Partitioning and Blocking Issues for a Parallel Incomplete Factorization**. In *Proceedings of PARA'2006, Umea, Sweden, volume 4699 of LNCS*, pages 929-937, June 2006.

P. Hénon, P. Ramet, and J. Roman. **On using an hybrid MPI-Thread programming for the implementation of a parallel sparse direct solver on a network of SMP nodes**. In *Proceedings of Sixth International Conference on Parallel Processing and Applied Mathematics, Workshop HPC Linear Algebra, Poznan, Pologne, LNCS 3911*, pages 1050-1057, September 2005.

Réalisations logicielles

PaStiX : (Parallel Sparse matriX package) est une bibliothèque scientifique qui implémente un solveur directe pour la résolution en parallèle de grands systèmes linéaires creux. Elle implémente aussi une méthode itérative parallèle pré-conditionnée par une factorisation incomplète ILU(k) par bloc. La bibliothèque PaStiX est disponible sous licence CeCILL. Site web : http://pastix.gforge.inria.fr

Numéro de dépôt APP : IDDN.FR.001.230016.000.S.C.2008.000.31235

Co-auteurs : Mathieu Faverge, Pascal Hénon, Xavier Lacoste.

Bernard Mourrain

Situation professionnelle : Directeur de recherche

Établissement : Inria Centre de Sophia-Antipolis-Mediterranée

2004 routes des lucioles, BP 93 - 06902 Sophia Antipolis, France

Tel: 00 33 4 9238 7828 *fax*: 00 33 92 38 79 78 *e-mail*: mourrain@sophia.inria.fr

Cursus et carrière :

1991 Thèse de doctorat, Centre de mathématique de l''Ecole Polytechnique

1991 Chargé de Recherche à l'INRIA Centre de Sophia-Antipolis-Mediterranée

1997 HDR de l'université de Nice Sophia Antipolis

2005 Directeur de recerche à l'INRIA Centre de Sophia-Antipolis-Mediterranée
Thématique de recherche
Calcul algébrique et géométrique, modélisation géométrique,
Activites de responsabilités
Responsable scientifique de l'EPI GALAAD de l'Inria, Editeur associé à J. of Symbolic Computation, Editeur invité de Theoretical Computer Science. Membre de l'advisory board de la conférence MEGA (Effective methods in Algebraic Geometry), Président de programme pour la conférence ISSAC 2007,
Coprésident de programme de la conférence Geometric Modeling and Processing 2010.
Implication dans les projets européens : PoSSo, Frisco, ECG, GAIA, AIM@SHAPE and ACS (Algorithms for Complex Shapes), the reseau Matrie-Curie ITN SAGA (ShApe, Geometry and Algebra), Exciting (Isogeoometrie 2008-2011).
Publications significatives
Topology and arrangement computation of semi-algebraic planar curves, ***Alberti L., Mourrain B. and Wintz J.*** *Comp. Aided Geometric Design, 25(25): 631-651, 2008.*
Stable normal forms for polynomial system solving. ***Mourrain B. and Trébuchet P,*** Theoretical Computer Science, *409: 229-240, 2008*
Introduction à la résolution des systèes d'équations algébriques. **Elkadi M. and *Mourrain B.,*** *Mathématiques&Applications 59:310, 2007.*
Resultant over the residual of a complete intersection. **Busé L., Elkadi M. and *Mourrain B.,*** *J. of Pure and Applied Algebra 164:33-57, 2001*
Multivariate Polynomials, Duality and Structured Matrices. ***Mourrain B. and Pan V. Y.,*** J. of Complexity, *16: 110-180, 2000*
Distinctions
"Multivariate Polynomials, Duality and Structured Matrices",
B. Mourrain and V.Y. Pan, best paper award 2000, J. of Complexity.
"Generalized normal forms and polynomial system solving"
B. Mourrain and Ph. Trebuchet, ISSAC'05 Distinguished Paper Award.

Kestener Pierre

Research engineer, CEA, Maison de la Simulation, Saclay, France
Education

- 2003: PhD in Physics and Signal/Image Processing, University of Bordeaux I
- 1998: Certification to teach Physics & Electrical Engineering to undergraduates (Agrégation de Physique Appliquée)
- 1995-1999: Undergraduate Fellow, École Normale Supérieur de Cachan, Applied Physics Departement, Cachan, France

EMPLOYMENTS

- since Feb. 2011 : research engineer at CEA, Maison de la Simulation, Saclay, France
- Nov. 2003 – Feb. 2011: research engineer at CEA, DSM, IRFU, Sedi, Saclay, France
- Sep. 2000 – Nov. 2003 :Predoctoral Fellow, CRPP, Pessac, France and Teaching Assistant, Université Bordeaux I, France

Career and responsabilities:

- Past activities : development of data acquisition system and digital signal processing for high-energy physics and astrophysics experiments. I did embedded software development in C++ for the test-bench of the ANTARES DAQ board, as well as for the UTS sub-system of the Eclairs gamma ray burst on-board telescope. I also did some firmware development (FFT core in VHDL) for a prototype BAO (Baryonic Acoustic Oscillations) correlator. I also developed some wavelet-based image processing tools (legacy of my PhD thesis) to study multifractal properties of active regions in solar magnetograms.
- Current activities (since 2010): Software development and GPU parallel programing for astrophysics simulations codes (Finite Volume Methods for Hydrodynamics, MHD, …).
- Since January 2010, teaching GPU parallel programming at ENSTA (French Engineering Institute), Paris, France.

5 REFEREED PUBLICATIONS:

- **Pierre Kestener**, Frédéric Château, and Romain Teyssier. Accelerating Euler equations numerical solver on graphics processing units. In Ching-Hsien Hsu, Laurence Yang, Jong Park, and Sang-Soo Yeo editors, *Algorithms and Architectures for Parallel Processing*, volume 6082 of *Lecture Notes in Computer Science*, pages 281--288. Springer Berlin / Heidelberg, 2010.
- **P. Kestener** et al, Characterizing Complexity in Solar Magnetogram Data Using a Wavelet-based Segmentation Method. *The Astrophysical Journal*, Volume 717, Issue 2, pp. 995-1005 (2010)
- R.T.J. McAteer, **P. Kestener**, A. Arneodo, and A. Khalil. Automated Detection of Coronal Loops Using a Wavelet Transform Modulus Maxima Method. *Solar Physics*, vol 262, issue 2, p 387-397, 2010.
- P.A. Conlon et al, Multifractal properties of evolving active regions. *Solar Physics*, vol 248(2):297--309, 2008.
- A. Khalil et al, Morphological analysis of hi features. ii. wavelet-based multifractal formalism. *The Astrophysical Journal Supplement Series*, Volume 165, number 2, pages 512

Daniel Pomarède

Research Engineer at CEA/Saclay

Career and responsabilities:

- 1999-2003 physicist in charge of the ATLAS Muon Spectrometer Detector Description Database and its impact on the performances of the experiment
- 2003-2005 coordinator of the ATLAS Muon Spectrometer Detector Description Group at the CERN/LHC
- 2005-2011 designer/programmer of the SDvision visualization software

Scientific experience:

- 1994-1996 : MSc Thesis in photonuclear physics at Brookhaven National Lab.
- 1996-1999 : PhD Thesis in cosmology at PNHE/Ecole Polytechnique
- 1999-2000 : Postdoc in particle physics at CEA/Saclay
- 2000-2002 : Postdoc in particle physics at INFN/Rome La Sapienza

5 REFEREED PUBLICATIONS:

1) D. Pomarède & A.S. Brun, "*Visualization of ASH Simulations of Stellar MHD with SDvision*", Proceedings of the Conference on Astronomical Data Analysis Software and Systems XIX, ADASS2009, Sapporo, Japan, October 4-8, 2009, Ed. Y. Mizumoto, K.-I. Morita, M. Ohishi, Astronomical Society of the Pacific Conference Series, 434 (2010) 378.
2) D. Pomarède, Y. Fidaali, R. Teyssier, "*A Visual Insight into the Horizon Simulation at MareNostrum*", Proceedings of the IGPP/DAPNIA International Conference on Numerical Modeling of Space Plasma Flows, ASTRONUM2008, Saint John, US Virgin Islands, June 8-13, 2008, Ed. N.V. Pogorelov, E. Audit, G.P. Zank, Astronomical Society of the Pacific Conference Series, 406 (2009) 317.
3) D. Pomarède, Y. Fidaali, R. Teyssier, "*Visualization of Hybrid, N-body and Octree-based Adaptive Mesh Resolution Parallelized Simulations*", Proceedings of the 5th IEEE Conference on Computer Graphics, Imaging and Visualization, CGIV08, Penang, Malaysia, August 25-28, 2008, IEEE Computer Society, Ed. M. Sarfraz, E. Banissi, and W. Chow Jeng, ISBN:978-0-7695-3359-9, p. 295.
4) D. Pomarède, Y. Fidaali, E. Audit, A.S. Brun, F. Masset, R. Teyssier, "*Interactive visualization of astrophysical plasma simulations with SDvision*", Proceedings of the IGPP/DAPNIA International Conference on Numerical Modeling of Space Plasma Flows, ASTRONUM2007, Paris, France, June 11-15, 2007, Ed. N.V. Pogorelov, E. Audit, G.P. Zank, Astronomical Society of the Pacific Conference Series, 385 (2008) 327.
5) D. Pomarède, E. Audit, A.S. Brun, V. Gautard, F. Masset, R. Teyssier, B. Thooris, "*Visualization of astrophysical simulations using IDL Object Graphics*", Proceedings of the 4th IEEE Conference on Computer Graphics, Imaging and Visualization, CGIV07, Bangkok, Thailand, August 13-16, 2007, IEEE Computer Society, ed. E. Banissi, M. Sarfraz, and N. Dejdumrong, ISBN:0-7695-2928-3, p. 471.

7.3. STAFF INVOLVEMENT IN OTHER CONTRACTS

Part.	Nom de la personne participant au projet / name	Personne . Mois / PM	Intitulé de l'appel à projets, source de financement, montant attribué / Project name, financing institution, grant allocated	Titre du projet : Project title	Nom du coordinateur / coordinator name	Date début & Date fin / Start and end dates
N°1	B. Nkonga	8	ANR /SPI. : 520KE	ESPOIR	Eric Serre	09-12
N°1	H. Guillard	20	ANR /SPI. : 520KE	ESPOIR	Eric Serre	09-12
N°1	A. Sangam	8	ANR /SPI. : 520KE	ESPOIR	Eric Serre	09-12
N°1	A. Dervieux	12	ANR /Cosinus 533KE	ECINADS	A. Dervieux	09-13
N°1	A. Galligo	5	ERC	Exciting	T. Dokken	08-12
N°1	B. Mourrain	5 5	ITN Marie Curie ERC	SAGA Exciting	T. Dokken T. Dokken	08-12 08-12

Part.	Nom de la personne participant au projet / name	Personne . Mois / PM	Intitulé de l'appel à projets, source de financement, montant attribué / Project name, financing institution, grant allocated	Titre du projet : Project title	Nom du coordinateur / coordinator name	Date début & Date fin / Start and end dates
N°						
2(CEA/IRFM)	Becoulet M.	4ppm	1)F4E-GRT-055 (PMS-PE). Fusion for Energy, Barcelona.	"Study of power and particle fluxes to plasma-facing components during ELM control by IVC in ITER and	Oliver Schmitz (Forschungszentrum Juelich Germany)	04/07/2010 - 31/12/2011

				evaluation of plasma response effects"		
		4ppm	2)ANR blanc-E2T2	"Electromagnetic effects in hot plasmas"	Peter Beyer (Univ. of Marseille)	2010-2014
2(CEA/IRFM)	Latu G.	4ppm	1)ANR blanc-E2T2	"Electromagnetic effects in hot plasmas"	Peter Beyer (Univ. of Marseille)	2010-2014
		19.2ppm	2)ANR blanc-GYPSI	GYrokinetic high Performance Simulations for ITER	Philippe Ghendrih (IRFM)	01/2011-12/2014
		4.8ppm	3) ADT Inria : SELALIB	Développement d'une bibliothèque modulaire pour la simulation du modèle gyrocinétique par une méthode semi-Lagrangienne.	Eric Sonnendrücker	2010-2014
2(CEA/IRFM)	Grandgirard V.	19.2mpp	1)ANR blanc-GYPSI	GYrokinetic high Performance Simulations for ITER	Philippe Ghendrih (IRFM)	01/2011-12/2014
		4.8ppm	2) ADT Inria : SELALIB	Développement d'une bibliothèque modulaire pour la simulation du modèle gyrocinétique par une méthode semi-Lagrangienne	Eric Sonnendrücker	2010-2014

2(CEA/IRFM)	Passeron C.	19.2ppm	1)ANR blanc-GYPSI	GYrokinetic high Performance Simulations for ITER	Philippe Ghendrih (IRFM)	01/2011-12/2014
		4.8ppm	2) ADT Inria : SELALIB	Développement d'une bibliothèque modulaire pour la simulation du modèle gyrocinétique par une méthode semi-Lagrangienne	Eric Sonnendrücker	12/2010 12/2014

Part.	Nom de la personne participant au projet / name	Personne . Mois / PM	Intitulé de l'appel à projets, source de financement, montant attribué / Project name, financing institution, grant allocated	Titre du projet : Project title	Nom du coordinateur / coordinator name	Date début & Date fin / Start and end dates
N°3	E. Audit	24	ANR /Blanc. : KE	COSMIS	P. Hennebelle	11-14