Ministero dell'Istruzione, dell'Università e della Ricerca

DAAD Deutscher Akademischer Austauschdienst
German Academic Exchange Service

Istituto Italiano di studi germanici

MIUR-DAAD Joint Mobility Program (PPP Italien)

Form sheet „Details of the project“ for a monolingual application (in English)

Instructions to complete the form sheet:
If you want to submit a bilingual application, please use the form sheet in German and Italian!

Host country of the German group	Name of principal investigator (PI) in Germany	Institution in Germany
Italy	Ahmed Ratnani	Max-Planck-Institut für Physik
Host country of the Italian group	**Name of principal investigator (PI) in Italy**	**Institution in Italy**
Germany	Hendrik Speleers	Università degli Studi di Roma “Tor Vergata”

1) Complete title of the project	Advanced Spline Technologies for simUlation of magneTizEd plasmas (ASTUTE)

2)Scientific goals

The project aims to develop fast and accurate numerical discretization techniques for the magneto-hydrodynamic (MHD) equations appearing in the simulation of magnetized plasmas, in particular, for the plasma confined in the core of the tokamak. The latter is a toroidal device considered the best performance for plasma confinement, see the ITER project [10].

Solving the MHD equations in tokamak geometry requires fast numerical methodologies that are flexible with respect to geometry and that can provide high order accuracy. They should also be incorporated in existing large numerical codes like the European non-linear MHD code JOREK [7,9]. More precisely, the requirements are:

- the use of compatible discretizations, i.e., discrete spaces where it is possible to completely mimic the structure and the properties of the continuous problem;
- an exact/accurate description of the involved (toroidal/helical) geometry;
- the treatment of strong temporal and spatial multi-scale nature of the problem;
- the capability to address anisotropies up to ten orders of magnitude which are introduced by the magnetic field;
- no restriction to quadrangular meshes;
- the use of at least C^1 regular elements.

Isogeometric Analysis (IgA) is a recent but well established technology for numerical simulation unifying Computer Aided Design (CAD) and Finite Element Analysis (FEA), see [6,8]. It has the great potential of providing a true design-through-analysis connection by exploiting a common representation model. B-splines and their rational version NURBS are the classical discretization spaces used in IgA. Besides these splines, we also want to explore the potential of more advanced spline technologies:

	• Generalized B-splines (GB-splines) are smooth piecewise functions with sections in more general spaces than polynomials (like B-splines). • Powell-Sabin splines (PS-splines) are smooth splines defined on arbitrary triangulations. • Box-splines are splines on regular triangulations. We intend to exploit the adaptivity of PS-splines, the "directional properties" of Box-splines, and the flexibility of GB-splines to achieve a significant gain in addressing some of the above mentioned requirements. More precisely, this project has two main short-term goals: 1. Enrich the European non-linear MHD code JOREK [7,9], by extending the actual geometry and basis to the Powell-Sabin elements in order to overcome the drawback of using quadrangular meshes. In this context, the C^1 regularity of (quadratic) PS-splines is crucial. The coupling of quadrangular and triangular elements will also be addressed. 2. Investigate the use of GB-splines and Box-splines to develop new and innovative numerical methods for different and separate problems, mainly focusing on: Compatible discretizations, Boundary layers, Anisotropic Diffusion, Particle transport and geometry singularities.
3) (Current) relevance and degree of innovation of the project	Magnetic confinement fusion aims to harvest energy from the fusion of small atomic nuclei, typically Deuterium and Tritium, which are heated to the plasma state and confined by a toroidal magnetic field configuration. The tokamak concept is at present the best developed magnetic confinement device, in which the confining magnetic field is produced by external magnetic field coils and a toroidal plasma current. The ITER tokamak, currently under construction in the South of France, aims to demonstrate 500 MW of power from the fusion processes. A successful ITER operation requires robust mitigation or suppression techniques for large-scale plasma instabilities like disruptions and edge localized modes (ELMs) which are, for instance, driven by the large pressure gradients and large plasma current densities required. Many aspects of these large-scale instabilities can well be described in the magneto-hydrodynamic (MHD) framework (with additional physics extensions). Solving these equations globally in the complicated geometry of a divertor tokamak is a highly demanding task due to the strong temporal and spatial multi-scale nature of the problem and the anisotropies reaching up to ten orders of magnitude which are introduced by the magnetic field. Therefore, solving the MHD equations in tokamak geometry requires fast numerical methodologies that are flexible with respect to geometry and that can provide high order accuracy, and large numerical codes. The IgA approach has been proved to be superior with respect to classical FEA in various engineering application areas, including structural mechanics and electromagnetics. The keystones of this success are the outstanding properties of the considered discretization (spline) spaces and the associated B-spline bases. The use of the IgA methodology combined with the potential of advanced spline technologies for solving (MHD) equations in the tokamak geometry assign a high degree of innovation to the project.

4) Status of relevant preparatory work	IgA is a technology created ten years ago that combines and extends FEA with CAD methods. The key concept in IgA is the development of a new paradigm for FEA, based on rich geometric descriptions originating in CAD, namely B-splines and their rational version NURBS [6,8]. The isogeometric frameworks based on B-splines/NURBS result in some important advantages w.r.t. classical FEA. In particular, they: • give more flexibility to generate and refine the computational mesh; • provide a more accurate description of the geometry; • allow for an easy treatment and refinement of spaces with high approximation order and an inherent higher smoothness, leading to a higher accuracy per degree-of-freedom. The above main advantages are not a distinguishing property of B-splines or NURBS, and they are not a requisite ingredient in IgA. In particular, GB-splines and PS-splines have proven to be interesting alternatives to B-splines/NURBS, see [2,5,11,12] and [1,20-22] respectively. In the ten years since its inception, IgA has been successfully applied in various areas, including structural mechanics and electromagnetics [3,4,6,8,13-18], and it is rapidly becoming a mainstream analysis methodology and a new paradigm for geometric design [19]. JOREK [7,9] is a large European code for solving the MHD equations in tokamak geometry. It solves the equations fully implicitly with a poloidal 2D quadrangular cubic Bézier-Hermite discretization, a toroidal Fourier representation allowing a C^1 regularity, and uses a direct linear solver for the preconditioner. A new version (JOREK-DJANGO) is currently under development, in collaboration with INRIA Nancy Grand-Est and Sophia-Antipolis. This new version is based on Bézier extractions for both triangular and quadrangular meshes. The toroidal direction uses either Fourier, Hermite-Bézier or B-splines. The innovative IgA tools can also be exploited to construct a new class of physics-based preconditioners, needed to reduce the memory consumption.
5) Complementarity of the partner's contributions to the project	Both partners will work towards the overall objectives of the project but each of them has a specific role. The partner's contributions will be fully complementary, mainly thanks to their different backgrounds and expertises: The German partner will contribute to the project by providing the proper mathematical formulation of the physical models, by coding the proposed schemes, and by testing the resulting software. The Italian partner will select the most appropriate spline technologies and will design the numerical schemes tailored for the proposed physical models.

6) Integration of young scientists (master students, doctoral students and young postdocs)	Besides the fact that the German and Italian project leaders are both young researchers (the former got his PhD in 2011 and the latter in 2008), the project aims to reach a significant integration of young scientists at different levels. MASTER STUDENTS We plan to involve master students which could write their master thesis in the frame of this collaboration. In this perspective, the students are assumed to have an extended visit at the other institution during their thesis period, in order to complement their knowledge and to experience a first integration in an international team. PHD STUDENTS For PhD students related to one institution, we promote an extended visit to the other institution in order to complement their knowledge.
7) Selection criteria for project participants as well as – if necessary - a description of the selection process of project participants	Experienced participants are selected according to international criteria commonly used for research evaluation (like CV, quantity and quality of the publications relevant for the project, etc.). Master and PhD students are selected according to their potential for excellent research, and their thesis topic has to fit within the frame of this joint research cooperation between between Università degli Studi di Roma “Tor Vergata” and Max-Planck-Institut für Physik.
8) Expectations of industrial or otherwise practical applicability of the research results	Fusion, the nuclear reaction that powers the Sun and the stars, is a potential source of safe, non-carbon emitting and virtually limitless energy. Harnessing fusion's power is the goal of ITER (“The Way” in Latin), which has been designed as the key experimental step between today's fusion research machines and tomorrow’s fusion power plants. ITER is based on the tokamak which is at present the best developed magnetic confinement device. The ITER tokamak, currently under construction in the South of France by a large international collaboration, aims to demonstrate 500 MW of power from the fusion processes. It will be the world’s largest tokamak, with a plasma radius of 6.2 m and a plasma volume of 840 m^3. With ten times the plasma volume of the largest machine operating today, the ITER tokamak will be a unique experimental tool, capable of longer plasmas and better confinement. The modeling and simulation of magnetized plasmas, in particular, the development of fast numerical methodologies for solving the MHD equations in tokamak geometry, is a key issue for controlled thermonuclear fusion, which offers the tantalizing possibility of clean, sustainable and almost limitless energy.

9) Added value of the co-operation with the foreign partner	The German and Italian partners in this project have completely complementary backgrounds, expertises, and scientific networks. This cooperation will enable a constructive interaction between the two complementary partners, and will result in a mutual cross-fertilization generating a virtuous and fruitful feedback process. This is a necessary ingredient for a successful treatment of the challenging scientific goals of the project. We also refer to Section 5 for more details on the complementarity of the partner's contributions. The mutual cross-fertilization between the two complementary expertises and the connection of the different scientific networks are the main added values of this cooperation, and their importance definitely goes beyond the scientific goals of the project.

10) Goals beyond purely scientific purposes (e.g. intensifying exchange, EU-funding etc)	Besides the purely scientific purposes, the project aims to intensify the exchange and the collaboration between the German and Italian academic/research systems, mainly through the promotion and specialization of young researchers. The project is intended as the first step in a long-term cooperation that may create the foundations for a wide range of other research projects: • The established contact and collaboration can be an optimal starting point for the PhD students involved in the project to apply, subsequently, for prestigious post-doc programs funded at European level, such as the Marie Skłodowska-Curie actions. • The expected scientific results and the created collaboration are intended to pave the path for a possible application to forthcoming ERC calls by experienced researchers.

11) Form of co-operaton	☒ Setup of a co-operation ☐ Expansion of a co-operation Name, type (e.g. Erasmus) and year of existing cooperation Texteingabe optional (maximal 200 Zeichen)

12) Prior funding in the same PPP and with the same partner?	☒ no ☐ yes, in year:

Instructions to complete table 13):
If you still don't know the name of the project participant, please write only NN

13) Research stay of the German researchers				
Date of stay (month/year)	Name project participant	*Position	* Purpose of stay	Duration in days
09/2016	Ratnani	Postdoc	Working on PS-splines	14
05/2017	Ratnani	Postdoc	Working on GB-splines	7
12/2017	Ratnani	Postdoc	Working on Box-splines	7
10/2016	Gaja	Phd Student	Working on DeRham sequences	14
10/2017	Gaja	Phd Student	Working on DeRham sequences	14
06/2016	NN	Phd Student	Working on Integration rules	14
06/2017	NN	Postdoc	Working on MultiGrids for PS-Splines	14

Instructions to complete table 14):
If you still don't know the name of the project participant, please write only NN

14) Research stay of the Italian researchers				
Date of stay (month/year)	Name project participant	* Position	* Purpose of stay	Duration in days
07/2016	Speleers	Professor	Setup of workplan	7
11/2016	Speleers	Professor	Working on PS-splines	7
02/2017	Speleers	Professor	Working on GB-splines	7
07/2016	Manni	Professor	Setup of workplan	7
11/2016	Manni	Professor	Working on GB-splines	7
02/2017	Manni	Professor	Working on PS-splines	7
10/2016	NN	master or PhD student	Working on thesis	21
04/2017	NN	master or PhD student	Working on thesis	21
10/2017	NN	master or PhD student	Working on thesis	21

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Declaration:	*Declaration:*
This is to certify that if necessary, the implementation of the project will be guaranteed by the German section.	*This is to certify that if necessary, the implementation of the project will be guaranteed by the Italian section.*
Date and Place:	*Date and Place:* Rome, 25/11/2015
Signature of the supervisor in Germany:	*Signature of the supervisor in Italy:*