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PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

# PRACE Digest 2015

## Celebrating the scientific achievements of women in HPC

WHPC

WOMEN IN HIGH PERFORMANCE COMPUTING

## PRACE Digest 2015 – Celebrating the scientific achievements of women in HPC

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# PRACE Digest 2015

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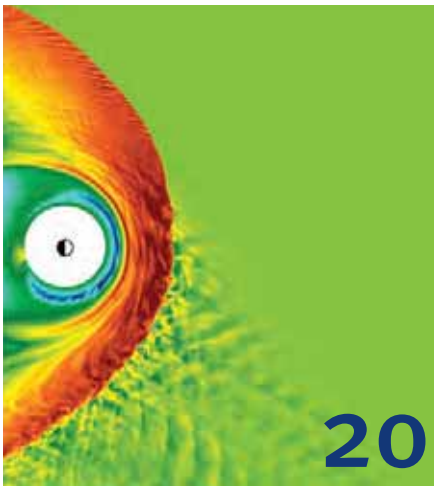





# Editorial

## PRACE Digest

I am pleased and honoured to present this edition of the PRACE Digest dedicated in its entirety to Women in HPC. This special edition represents the culmination of the "PRACE Year of Women in HPC" – a year celebrating the contribution of women to the world of HPC and computational science in collaboration with the "Women in HPC" network.

Over the past year, the productive and ground-breaking partnership between PRACE and the "Women in HPC" network has resulted in a series of important events and publications. These include well-attended training workshops and BoF sessions at ISC '15 in Frankfurt and the publication of the PRACE Women in HPC Magazine in June 2015. The Women in HPC magazine briefly showcased some of the projects included in this Digest and focused on the contribution of women towards strengthening PRACE as a world-leading force in HPC-enabled research and the transition towards exa-scale computing.

The "Women in HPC" network addresses gender imbalance issues in HPC through support, research and initiatives to raise the professional profiles of women in HPC, increase participation of women through outreach activities and assess the influence of equality initiatives on the HPC community.

I am proud that PRACE has taken an active role in promoting and collaborating with this initiative. Part of PRACE's mission is to improve European competitiveness by promoting HPC, a key economic driver. PRACE recognizes that enabling equal opportunity and participation is also vital to enhance competitiveness. By publishing the first magazine and scientific Digest of this kind in the field of HPC, PRACE demonstrates Europe's leadership in this increasingly important field.

We are confident that showcasing the talents of these extraordinary women will inspire the next generation of researchers – both male and female. These publications and events are evidence that HPC has a steadily growing proportion of female experts and users. At international events the "Women in HPC" programmes and presentations draw a great deal of interest. As the number of women working in HPC continues to grow, it is our hope that through the publications and projects of the "PRACE Year of Women in HPC" and the "Women in HPC" network initiative, very soon women in HPC will no longer feel that they are the exception but rather the norm.

We invite you to join us in challenging stereotypes and help realise a vision of diversity and equal opportunity. We hope you enjoy reading about excellent scientific research which just happens to be undertaken by women who are already in the forefront of HPC today – and who can inspire the HPC researchers of tomorrow.

**Alison Kennedy**
**Executive Director EPCC, University of Edinburgh and Member of the PRACE Board of Directors**


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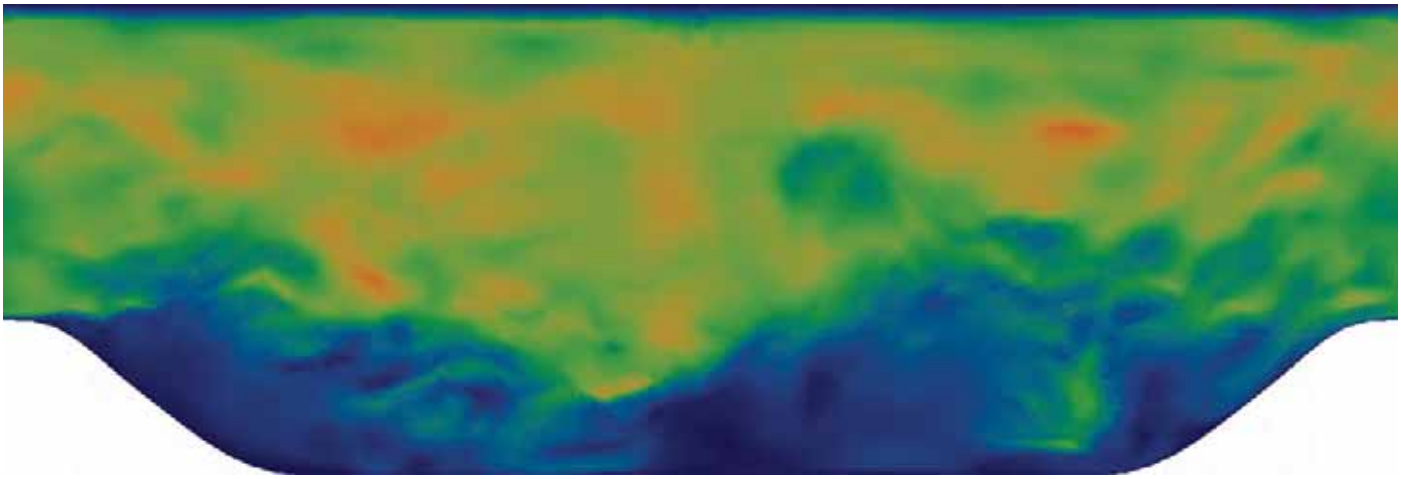
# A hybrid approach to understanding turbulent flows

**Professor Antonella Abbà** of Politecnico di Milano has developed a hybrid RANS-LES approach to understanding turbulent flows using PRACE computing power. Not only will this provide high levels of accuracy and reliability in its results but will help save both computational time and money



Velocity field in the turbulent periodic hill flow

The comprehension of turbulent flows over objects is an extremely important part of design, engineering and construction. Turbulence can produce noise, weakens structures and impacts performance. Cars, buildings and aircraft are just some of the everyday objects that benefit from highly accurate simulation of flows and turbulence, with resulting improvements in noise reduction, energy efficiency, overall performance and safety just some of the benefits.

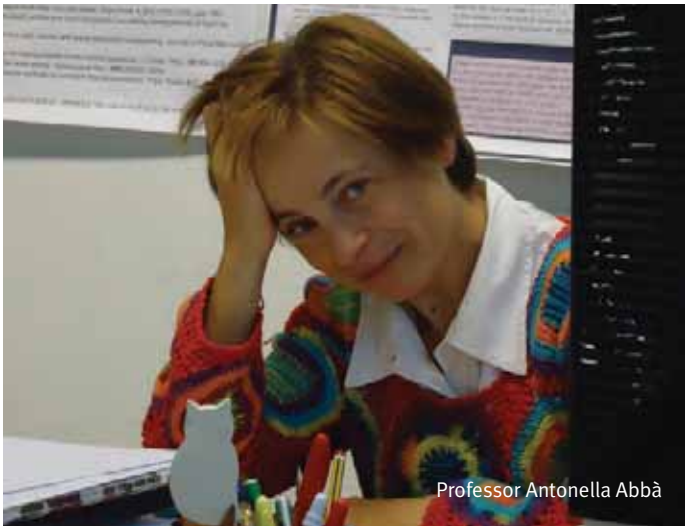
In a turbulent flow, vortices of different sizes are present. The Direct Numerical Simulation (DNS) is an approach to solve the Navier-Stokes (NS) equation, which describes a flow at the smallest turbulent structure size. This technique is very expensive and cannot be applied to very complex turbulent flows to be of any practical interest. The solution of the Reynolds Averaged Navier-Stokes equations (RANS) is another method suitable for the simulation of turbulent flows and also used for industrial applications, but it resolves only the mean flow and not all the detail of the turbulence. The Large Eddy Simulation (LES) is a good compromise between these two methods. In the LES, a space filter $F(\Delta)$ is applied to the NS equations and the eddies larger than the filter size $\Delta$ are simulated while the smaller ones are modelled. In this way a so-called subgrid-scale stress tensor $\tau SGS$, to model the small eddies in function of the resolved field, is added to the equations.

A good way to imagine this method is to consider simulating the flows around a building. The large vortices, of similar size to that of the building, are simulated while a model is used for the smaller vortices, the expression of which represents the behaviour of the small vortices in the equation.

There are many applications for which the grid resolution required by a LES is still very expensive to achieve, especially in the wall-bounded flows where the size of turbulent structures requires a very high resolution, similar to the ones required by Direct Numerical Simulation (DNS). On the other hand, the cheaper RANS methods do not provide the amount of information required in many simulations as they do not deliver the same detail.

*"We have been working to provide reliable high-performance computational models that are both time and cost effective"*

Therefore, combining the LES approach with RANS models is often used as a sensible way to achieve an appropriate description of turbulent flows at a reasonable cost. As a consequence, since 1997, when Professor P.R. Spalart proposed the Detached Eddy Simulation when considering LES for wings, hybrid RANS/LES methods have received great interest in computational fluid dynamics research.


Professor Antonella Abbà

A particular hybrid RANS-LES approach is something Professor Antonella Abbà of Politecnico di Milano is working on using PRACE's high-performance computing resources in the HyDIG project. The project was awarded 2 million core hours on NIIF at Dip. di Scienze e Tecnologie Aerospaziali, Politecnico di Milano. "We have been working on a hybrid RANS-LES approach, proposed by Professor M. Germano" she explains. "We are testing this hybrid approach using advanced LES models for the simulation of compressible turbulent flows in complex geometries. In this prospect, the aim of present work is to improve and to optimize the numerical code." With this method a hybrid filter H is defined as:

$$H = k F + (1 - k)E$$

This is applied to the NS equations, where F is the space LES filter, E is an ensemble RANS operator and k is a blending factor: k=1 corresponds to pure LES, while k=0 to RANS. The additional modelling term in the equations results as

$$\tau H = k \tau SGS + (1 - k) \tau E + G$$

where τE is the Reynolds turbulent stress tensor, introduced in the classical RANS approach, and

$$Gij = k(1-k)(uFi - uEi)(uFj - uEj)$$

is an additional stress, peculiar of the hybrid filter approach, function of the LES field uF and of the RANS field uE.

Essentially, this hybrid method enables LES simulation where needed while at the same time providing RANS results, thus saving computational time and cost. This is one of the principle objectives of Professor Abbà's work. "We have been working to provide reliable high-performance computational models that are both time and cost effective," she explains. "If you can merge the two models you can obtain detailed information where you need it, while at the same saving computational time and resources," she explains.

At the early stages of the work, this resource was still performed at the academic level, with the aim of enabling a better understanding of the model's behaviour. As the project progressed, however, Professor Abbà and her team have been able to apply the hybrid model to more complex geometry and more complex configurations.

"The numerical code we developed in Milan is very interesting because we have integrated more sophisticated models," she explains. "But the numerical method itself is very interesting because it is uses a Discontinuous Galerkin method which is very useful because it shows good scalability on HPC and very high accuracy.

"This numerical code, based on a Local Discontinuous Galerkin (LDG) method, solves the Navier-Stokes equations for compressible fluids," continues Professor Abbà. "In the code, together with the hybrid RANS-LES model, several subgrid-scale models for Large Eddy Simulation are also implemented.

"Using this numerical approach, the equations are solved independently inside each element of the computational grid, and fluxes are exchanged at the interface between elements. Each element can be independent of each other, something that is not possible with other classical approaches because where in all the elements you have to use the same method of discretization.

"So in the Discontinuous Galerkin method, the equations are discretized in an independent way inside each element, using many different orders of polynomial and different accuracy degree. For example, instead of increasing the grid resolution, you can refine the order of the polynomial of each element."

Professor Abbà's approach has an extremely high level of reliability, while also providing a high level of accuracy at the same time. Both these qualities are needed to measure complex flows and it is something she is now applying to simulate airflow around aircraft wings to study turbulence and reduce noise levels.

"The partnership with PRACE has been central to being able to apply this hybrid approach and we are now hoping to work on the Tier-0 platform with the organisation," concludes Professor Abbà.

## For more information

www.polimi.it

## Core hours

This project was awarded 2 million core hours on NIIFI SC at the NIIF Institute, Hungary

## Publications

1. M. Nini, A. Abbà, M. Germano, and M. Restelli. Analysis of a Hybrid RANS/LES Model using RANS Reconstruction. Proceedings of the ITI2014 Conference on Turbulence, Bertinoro, Italy, September 21-24, 2014.
2. A. Abbà, M. Germano, M. Nini and M. Restelli. Analysis of a novel Hybrid RANS/LES Technique based on Reynolds stress tensor reconstruction. Submitted for publication.

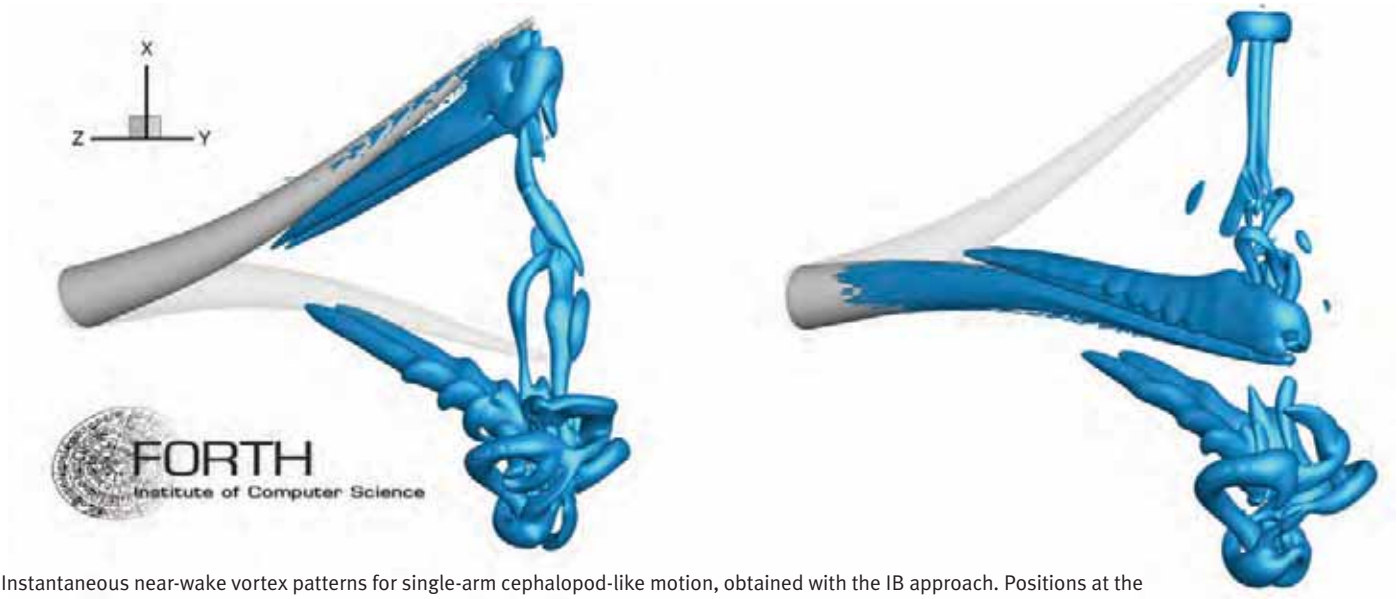
# Hydrodynamics of cephalopod movement for bio-inspired marine soft-robotics

Major challenges surround the modelling and simulation of cephalopod motions but with **Dr Asimina Kazakidi's** efforts to unravel the complex hydrodynamics of cephalopod swimming, a deeper insight has been achieved towards the development of revolutionary bio-inspired robotic swimmers for marine monitoring and surveillance

A research fellow with the Greek Foundation for Research and Technology - Hellas (FORTH), Dr Asimina Kazakidi's latest European Social Fund-General Secretarial of Research & Technology-funded project (HYDRO-ROB) is an evolution from her previous explorations into the ways in which hydrodynamic effects influence the locomotion of aquatic robots. The project was awarded to her through a competitive research call with the support of her research supervisors, Dr Dimitris P. Tsakiris and Prof John A. Ekaterinaris, also of FORTH. In the Computational Vision and Robotics Laboratory at FORTH's Institute of Computer Science, Kazakidi is now focusing on the role of cephalopod arms in aquatic motion, a vital piece of the puzzle that will help FORTH and Tsakiris' team in their aim to develop novel octopus-inspired robots. With the potential capabilities for both manipulation and propulsion, such a robotic device could prove to be of major interest in underwater applications.

Benthic and deep-water octopuses use several swimming modes to propel themselves above the seabed. Although the predominant mode appears to be jet swimming—which involves usage of their siphon with the arms trailing tightly behind the head and the mantle—arm swimming is the only mode in which the octopus actively employs all eight arms in a synchronized and coordinated manner. Pertaining to all other swimming modes, there is not much known about the part that cephalopod appendages play in aquatic locomotion due to the complexity of their structure and movement. Attempts to accurately model and simulate intense deformations are more than a little tricky and even the most advanced numerical techniques have trouble with them. "The difficulty in my case was how to achieve high accuracy in the simulation of the hydrodynamics around cephalopod-like appendages undergoing intense movements," explains Kazakidi. "These movements were based on 3D reconstructions from video acquisitions on adult octopuses."

Choosing the right methodology for the simulations boils down to how you define the geometry. Body-conforming methodologies use the geometry that is included in the background environment, while the immersed boundary (IB) approach separates the body from the background geometry. With body-conforming approaches it is possible to achieve a highly detailed boundary layer around the body, but because the mesh must conform to the body at all times, they are not so good at tackling the large deformations that characterise cephalopod-like movements. Furthermore, the computational demands of this finite volume approach are simply too high. The IB approach, which is a fixed-grid method, is far more appropriate




Instantaneous near-wake vortex patterns for single-arm cephalopod-like motion, obtained with the IB approach. Positions at the opposite maximum amplitude are also depicted with light colour, to indicate the direction of movement and the angular span. (Kazakidi et al., Computers & Fluids Computers & Fluids 2015, vol. 115, pp. 54-65.)

for dealing with problems of complex fluid-structure interaction and prescribed body motion.

Both methods have their upsides and downsides, but Kazakidi is currently working within the framework of the IB approach, first introduced by Peskin in the 70s. Developed in 2005 by the group of Professor Fotis Sotiropoulos of St. Anthony Falls Laboratory, the University of Minnesota, to simulate internal flows containing complex moving immersed boundaries, the IB code employed is essential for sufficiently capturing the boundary layers in extreme forced motions. "The code has been applied to smaller motions, but it introduces challenges for large, deformable geometries," states Kazakidi.


Dr Asimina Kazakidi

*"PARADOX is an excellent machine, very efficient for the code we are running"*

The project was awarded 1.2 million core hours on the Tier-1 PARADOX High Performance Computing (HPC) cluster in Serbia, at the Scientific Computing Laboratory of the Institute of Physics in Belgrade. Thankfully, it was up to the challenge. "PARADOX is an excellent machine, very efficient for the code we are running," states Kazakidi. "Our computer simulations involve geometries that are quite large and computationally demanding, but PARADOX has given us a lot of flexibility in carrying out production runs."

"The idea here is to examine different aspects of the motions that could be applied in the robot," explains Kazakidi, "For example, the hydrodynamic forces that I calculate are used in models of the robot and compared with force measurements in the robot itself, allowing us to build a prediction tool for robotic motion design." The main concern for Kazakidi is the methodological aspect; how the IB code can be extended to accurately capture the propulsive hydrodynamic forces produced by the rapidly moving cephalopod-like model.

In this project the IB solution has been computed using the CURVIB approach, a curvilinear IB method that has previously been applied to a wide range of scenarios including vortex-induced vibrations, flows in mechanical heart valves and turbulent flows in rivers with hydraulic structures. Rather than having to use a restrictive body-conforming mesh, the immersed body—or cephalopod arms—is discretised with an unstructured mesh while the fluid domain is discretised with a background curvilinear fixed-grid. The position of the immersed body is tracked and its motion is accounted for by reconstructing the solution in the immediate vicinity of the fluid/solid interface. "In this case we have a more direct implementation of the motion in a fixed computational domain," explains Kazakidi. In order to do that the motion is added as external forces in the governing equations of the fluid in motion.

While it is less restrictive and lower in computational cost, the disadvantage of the IB approach is that one needs to take extra care in capturing the boundary layer effects on the deformable geometry. It is a more complex job to carry out than it is in the body-conforming approach and errors can have a serious impact on the accuracy of the numerical schemes. "Although we have to be very careful on the boundary layer results, we can do any large deformations we want," says Kazakidi, "so there is a trade off in using these approaches." Force measurements acquired experimentally on custom-made robotic prototypes are in good agreement with the numerical simulation results and validate the numerical approach.

Much has already been discovered about the key principles of manipulation and locomotion in cephalopods. Kazakidi's studies have managed to increase the output thrust of a single-arm system by incorporating arm deformation and have discovered that a combination of sculling motion and arm undulations is conducive to an effective propulsive scheme. Beyond the one-armed system they have also been looking at how different patterns of arm coordination affect the generation of backward and forward propulsion and turning. "We are also investigating the interaction between different arms and the effects of various arm morphologies, while the next step will be to examine interactions between different robots," states Kazakidi.

All of this inches the project closer to its goal: to produce a computational tool that can model the intense motions of cephalopod manipulation and locomotion. The fluid, dextrous movements of cephalopods may stand in stark contrast to robots of popular imagination but as Kazakidi's work progresses together with efforts of Tsakiris, Ekaterinaris, Sfakiotakis, Zabulis, Chatzidaki and Evdaimon and the FORTH group, imitation gets closer and closer to reality.

### For more information

www.ics.forth.gr/~kazakidi/
www.ics.forth.gr/cvrl/octopus/

### Core hours

This project was awarded 1.2 million core hours on the PARADOX High Performance Computing (HPC) cluster in Serbia, at the Scientific Computing Laboratory of the Institute of Physics in Belgrade.

### Publications

A. Kazakidi, D.P. Tsakiris, J.A. Ekateriaris 2016. Arm morphology and hydrodynamic behavior of a two-arm robotic swimmer. Robotics & Automation Letters, *under review*

# Scaling strategy in solid rocket motor research using Large Eddy Simulation

Research on the instabilities of solid rocket motors (SRMs) notably relies on scaled-down simulations and only partial representations of the whole geometry. Together with **Safran Herakles**, **Dr Eleonore Riber** and researchers at CERFACS are attempting for the first time to determine the impacts of these modelling assumptions on SRM design

The solid rocket motor (SRM) concept is found in a variety of applications, providing extra thrust for rockets but most notably in launching spacecraft with substantial payloads. Unlike rockets that use liquid propellants, SRMs employ a solid mixture of fuel and oxidiser which is ignited inside a combustion chamber to produce high levels of exhaust gas pressure. Passing through a nozzle inside the motor, gas flow accelerates and thrust is generated.

However, the formation of unwanted vibrations is impacting the load carrying capabilities of SRMs. Originating with the existence of small pressure oscillations, these in turn lead to strong thrust oscillations detrimental to carrying load. Over the last several decades, research about these small pressure oscillations have resulted in design innovations that mitigate or completely eradicate some of the mechanisms leading to such instabilities, but some still remain an open challenge in SRM design.

*"We do not really know if using the same particle characteristics for the dispersed phase will give us a real answer"*

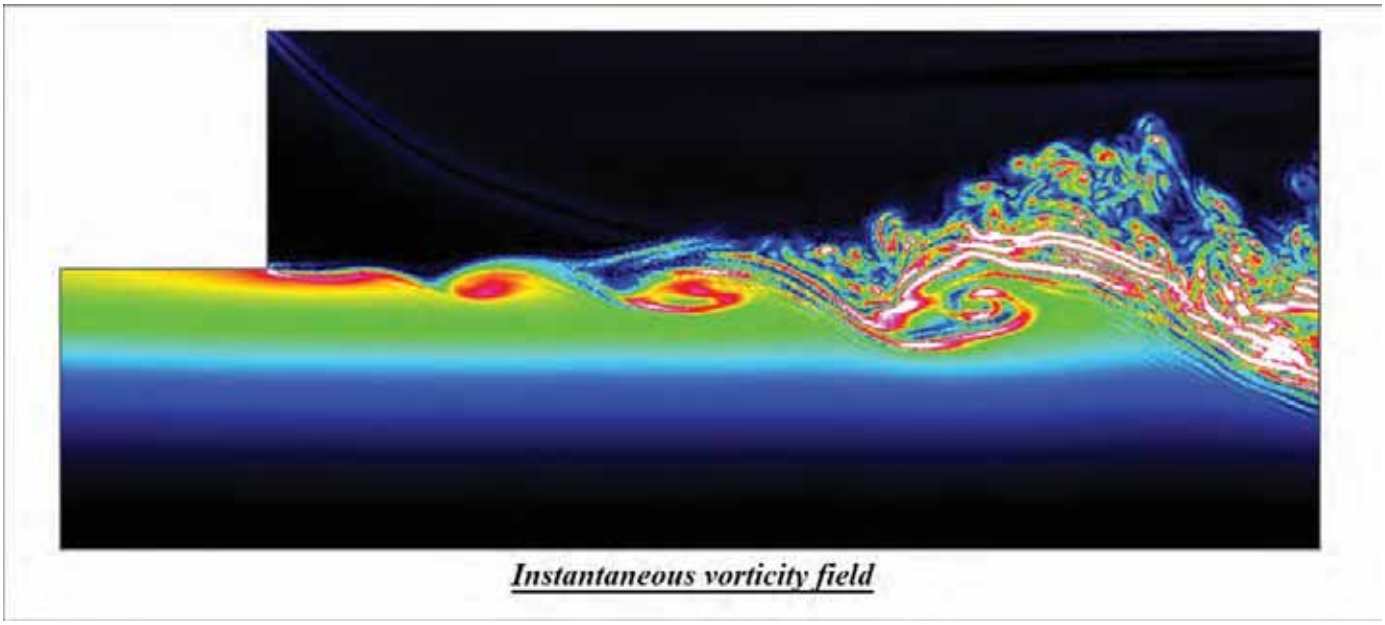
In order to produce the smallest pressure oscillations possible, industrial rocket manufacturers like Safran Herakles, a subsidiary within the Safran Group's aerospace propulsion branch, are using high-fidelity Large Eddy Simulations (LES) to help understand where these instabilities come from and how they can be controlled. Dr Eleonore Riber, a senior researcher at the European Centre for Research and Advanced Training in Scientific Computing (CERFACS), is teaming up with engineers at Herakles. Dr Riber is an expert in modelling and simulating turbulent reacting flows, and collaborates with PhD student Laura Lacassagne, Dr Franck Nicoud, Dr Bénédicte Cuenot and Dr Olivier Vermorel, who bring their own expertise in computational fluid dynamics (CFD) to the venture.

Through PRACE, Dr Riber was awarded 23.5 million core hours on the CURIE supercomputer at GENCI in France to carry out investigations of SRM instabilities with LES, an important CFD tool for tackling problems associated with turbulent flows. Project objectives are twofold: first, predict the overall stability of an SRM engine by studying a reduced scale motor and second, assess whether these methods actually tell the whole story of what is going on inside the SRM.


Dr Eleonore Riber

It is known today that SRM pressure oscillations arise from two areas: combustion instabilities and hydrodynamic instabilities. The latter are caused by vortex shedding phenomena, the most common of which used to be obstacle vortex shedding (VSO) and parietal vortex shedding (VSP) (Lupoglazoff et al. 2002). New generations of engines can now avoid vortex shedding phenomena altogether or at least significantly limit their occurrence. Corner vortex shedding (VSA), on the other hand, remains an under studied phenomenon. "We really do not know how VSA occurs," states Dr Riber. "We know it occurs at the corner, but we do not know the conditions in which it can occur and how it can damage the SRM afterwards."

Often 10 metres in length, the size of SRM engines and the complexity of the flow make experiments and numerical simulations unfeasibly expensive and computationally challenging at real scales. The solution is to run simulations at reduced scaled geometries so that the behaviour of the real engines can be estimated. This approach allows Dr Riber to first model the small turbulence scales and then resolve the large scales on the simulation mesh. The challenge is to work out how to correctly encode things in the reduced scale geometry.




Numerical simulations of the unsteady flow inside segmented solid-propellant motors with burning aluminum particles. N. Lupoglazoff, F. Vuillot, J. Dupays, Y. Fabignon. Reston, Virigina: American Institute of Aeronautics and Astronautics, 2002.

The idea is to determine whether the parameters used for reduced scale simulations actually allow the results to be correctly transposed to full-scale geometries. In the SRM engine, the combustion of aluminised propellants results in a dispersed reactive phase that strongly affects the stability of VSA, making a reliable scaling-up strategy essential. At the real scale, characteristics like the diameter and mass flow of the aluminium particles are known but these same characteristics are also used in the reduced scale simulations. "We do not really know if using the same particle characteristics for the dispersed phase will give us a real answer," says Dr Riber.

In order to define the dispersed-phase parameters of reduced scale simulations, Dr Riber aims to carry out LES at both the reduced scale and the full scale. However, the challenges associated with full-scale simulations mean that a single sector is studied instead of the full annular geometry of the SRM combustion chamber. First up is the simulation of the reduced scale geometry. Having carried out modifications to enhance VSA phenomena, the project is now at a stage where aluminium particles are being introduced in order to see what effects they have on VSA. The next goal is to simulate the real geometry to identify and analyse the different scaling effects. Once complete, these will be used to improve the interpretation of results from reduced scale experiments.

However, a reliable scaling-up strategy is not the project's only concern, as Dr Riber explains. "The second question is: what do we miss when we only concentrate on one sector of the geometry?" Although normal practice, it is possible that by neglecting the full geometry, potential 3D effects may be unaccounted for, particularly as single sector computations could have a large impact on the stability of the flow. While resource constraints make it a challenge to consider the full geometry at real scales, access to CURIE gives Dr Riber the unique opportunity to perform the first ever LES in the full annular geometry of an SRM engine at a reduced scale. Although still a considerable demand on computational resources, Dr Riber will be able to take the results from the reduced full geometry and compare them with those produced by simulations of a single sector at the same scale.

*"The second question is: what do we miss when we only concentrate on one sector of the geometry?"*

This is new territory for both LES and SRM design. As yet, it is not known what new information may crop up regarding 3D turbulent mechanisms but it will be the first of its kind, presenting a novel opportunity for the engineers at Safran Herakles to move forward in proposing new geometries and concepts. Together with a reliable scaling-up strategy, a clearer picture of the instabilities in SRM engines will give rocket manufacturers the best chance yet to address the problems presented by VSA phenomena.

**For more information**
www.cerfacs.fr

**Core hours**
This project was awarded 23.5 million core hours on CURIE TN @ GENCI@CEA, France

# Advances in aeroacoustic simulation


Through optimisation of the wave expansion method (WEM), a team from the Royal Institute of Technology (KTH) in Sweden is aiming to exploit the potential of increasingly powerful HPC resources to tackle problems in highly complex acoustic wave propagation

The impact of noise pollution is easy to underestimate but its effect on human health means that it is perceived as a major environmental concern. Persistent noise irritation has been shown to cause disturbances in sleep, elevated blood pressure, hearing impairments and even the development of ischaemic heart disease. One of the biggest contributors to such environmental noise is the increase in air traffic, a fact that has led organisations like the Advisory Council for Aeronautics Research in Europe (ACARE) to put in place provisions for a dramatic reduction in perceived aircraft noise levels by 2020 (with a 10 dB reduction requested).

Of course, innovations in aircraft engine design have been reducing noise levels for some time, but the engine is only half the story. Aeroplanes are at their most audible when they are coming into land because of the drag they intentionally create to slow their approach. A major cause of their distinctive roar are the turbulent flows that pass around the landing gear's complex structure.


Professor Gunilla Efraimsson

*"The results achieved so far are a product of the working relationship between KTH and PRACE"*

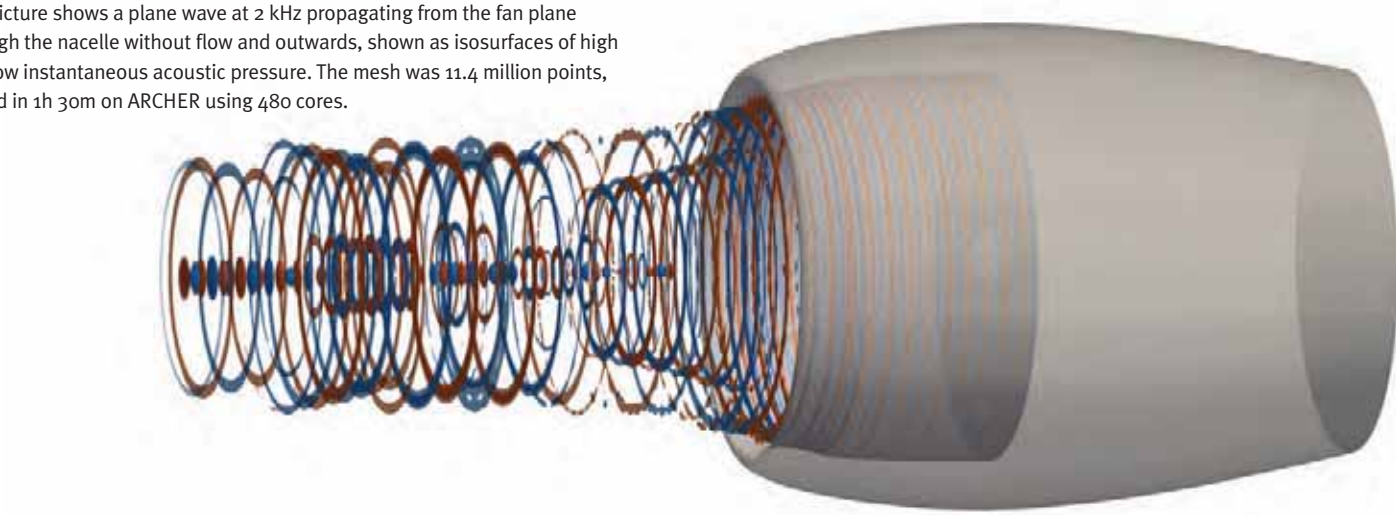
Efforts toward noise reduction in aeroplane landing gear are underscored by research in the field of aeroacoustics where accurate modelling and the simulation of aerodynamically generated sound waves are essential for guiding future designs. At Sweden's Royal Institute of Technology (KTH), a small group of aerodynamics researchers from the Aeronautical and Vehicle Engineering Department have embarked on ParaWEM, a project that aims to assess the wave expansion method (WEM) for acoustics in engineering problems.

Led by Professor Gunilla Efraimsson, the project uses high performance computing to optimise WEM for a higher order of acoustic wave propagation. It is not just for handling the complex geometry involved in aeroplane landing gear, though. Through better optimisation of WEM, a better understanding of the field will help noise reduction efforts across a wide range of domains.

The inspiration for the project first came about when students in the Aerodynamics Group noticed the potential for upward scalability in WEM. Through PRACE, Efraimsson has taken the project to the UK to and was awarded 5 million core hours to test the code on ARCHER, the recently installed Cray XC30 system at the University of Edinburgh. "We started there to propagate it further and develop it on really large scale computers to bring the methodology to a higher level," Efraimsson recounts.

First described in 1996, WEM is a highly efficient computational method for analysing complex flows that has distinct advantages

The picture shows a plane wave at 2 kHz propagating from the fan plane through the nacelle without flow and outwards, shown as isosurfaces of high and low instantaneous acoustic pressure. The mesh was 11.4 million points, solved in 1h 30m on ARCHER using 480 cores.



over several other methods. A good way to picture the pros and cons of different methods is to think of a diver's flipper moving up and down in the water. This motion creates a wave that can be described numerically on a grid. Using a more traditional approach, like the finite-element method (FEM) or finite-difference methods (FDMs), depending on the efficiency of the scheme you might need as many as eight or even twenty grid points for each wave length, creating a fine mesh. The advantage of WEM is that it requires just two points per wavelength to achieve the same accuracy with a coarse mesh as the traditional methods do with a fine mesh. Such low dispersion with minimal points per wave is hugely beneficial given the complexity of the geometry and the 3D space they need to account for. Furthermore, computational time is dramatically reduced as well.

*"Developing the code on a large scale computer such as ARCHER has helped to bring the methodology to a higher level"*

While other methods have their own advantages, WEM enables studies in domains at far larger sizes than classical approaches allow, making it a good tool to approach aeroacoustic problems in landing gear. "We anticipate that this may enable us to propagate acoustic waves further than other methods can," explains Efraimsson. "We need to see whether it works well on larger, more realistic simulations and whether it scales in the way we hope it will."

Prior test cases on much smaller scales were only able to handle relatively simple geometries. Efraimsson's work on the WEM code has adapted it to take on much more complex geometries as well as allow the implementation of boundary conditions previously unavailable to them. Now with ARCHER, the larger test cases are looking at around ten million grid points. "This is really interesting for us because you can see how different mesh points relate to each other," Efraimsson explains, "and also because we are solving a big linear system of equations."

Efraimsson is enthusiastic about the results that have been achieved so far, results she is certain are a product of the good working relationship between her team, KTH's computing centre and the people at PRACE. "It should not be underestimated because it makes things easier and means you can focus on the things you want to focus on," states Efraimsson. "There is a lot of positive energy around the results that we have had."

Although pleased with the opportunity to explore the methodology and the code on ARCHER, one area that still eludes Efraimsson's team is the investigation of background flows. In the future they will be able to add to WEM the ability to solve acoustic fields while a background flow is going through the domain. In fact, it has already been done for the smaller test cases, so Efraimsson knows that the method works. Implementing it in a system like ARCHER, the code need not be scaled to include background flow, but there is definitely some programming work that needs to be undertaken. "That is one thing that we would really like to do," states Efraimsson. "It is our main goal right now, and we are very curious to continue and see what happens in the next steps."

### For more Information

www.ave.kth.se/avd/aero

### Core hours

This project was awarded 5 million core hours on ARCHER at the University of Edinburgh, United Kingdom

### Publications

1. C. J. O'Reilly, "A wave expansion method for acoustic propagation in lined flow ducts". Applied Acoustics, 90:54–63, 2015.
2. L. Lundberg and R. Futrzynski. "Parallelization of a wave expansion method code with MPI and C++. PDC Summer School Report", KTH, 2012.
3. F. Majić, G. Efraimsson and C. J. O'Reilly. "Aerodynamic performance of the adaptive nacelle inlet". 33rd AIAA Applied

# Understanding the genetics of Autism

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental disorder that affects one per cent of the population. Next generation sequencing has advanced our understanding of the genetics of the disease, which we need to develop effective treatments, but most of the genes involved in ASD remain unknown. iHART is using whole-genome sequencing data to change that

In order to better understand Autism Spectrum Disorder (ASD) and develop effective treatments, it is essential to understand the genetics of the disease. To meet this challenge, the Hartwell Foundation has launched one of the largest worldwide initiatives to help characterize the genetic basis of ASD, called the Hartwell Autism Research and Technology Initiative or iHART (http://www.ihart.org/). The project will generate open-source, whole-genome sequencing data for approximately 1,000 ASD families (5,000 individuals) and advance ASD research and treatment. In order to detect de novo and inherited genetic ASD risk variants with high sensitivity, the research team, led by Drs Daniel H. Geschwind (University of California Los Angeles) and the iHART Director Dennis P. Wall (Stanford University), are applying a novel strategy by using SMuFin, a reference-free approach that can detect genetic variants by directly comparing two genomes and identifying differences. In these ASD families, SMuFin is used to directly compare genomes between all affected and unaffected children and their corresponding parents.

With its use of a large-scale, whole-genome sequencing data set and the effectiveness of the method proposed for detecting genetic variants in ASD families, this PRACE project aims to characterize disease-associated genetic variants, identify novel risk genes and gain comprehension of the biological pathways affected in ASD. Most of the families participating in this whole-genome sequencing study include multiple individuals affected with ASD. This is an important feature, as one of the main research analysts, Dr Laura Perez-Cano, explains: "Previous large-scale sequencing studies were performed on simplex families, meaning only one affected child, and no previous history of ASD, and only included the protein-coding parts of the genome. These studies revealed extraordinary genetic heterogeneity in ASD, predicting the involvement of hundreds of risk genes, none accounting for more than one percent of ASD cases. What became important, therefore, was the need to expand our knowledge of the genetic risk factors for ASD."

In order to develop effective treatments it will be necessary to better characterise the genetic causes of the condition and, given its heterogeneity and complexity, it is necessary to sequence a larger number of individuals and to include the whole genome. "Another important challenge is to apply effective methods to detect genetic variants from raw sequences," adds Dr Perez-Cano. "This is one of the most complex analyses of genomic data."

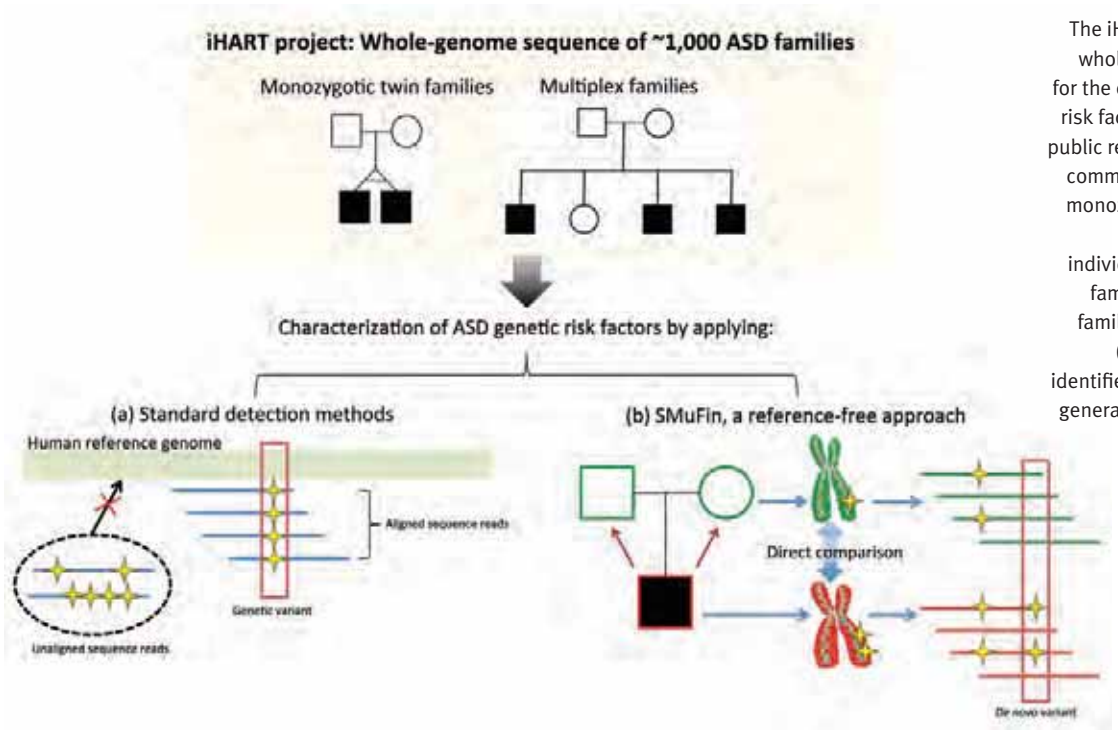
It is this complexity that requires high-performance computing. "The analysis that we are performing is computationally very demanding,"

Two of the main iHART research analysts, Drs Laura Perez-Cano (right) and Elizabeth K. Ruzzo (left), both postdoctoral researchers in Dr Geschwind's laboratory at University of California Los Angeles.

continues Dr Perez-Cano. "And this is where we are taking advantage of PRACE resources. Without these resources it would be much more complicated, if not impossible." So far, the project has been heavily focused on data generation and processing. Before being able to look for novel ASD genetic risk variants, all the sequencing data needs to be processed. Typically, the first step in this task is to align the short sequencing reads to the human reference genome and then to detect genetic variants that defer from this reference genome.

"Standard strategies depend on the alignment of the short sequence reads that result from next-generation sequencing techniques to the human reference genome, using the human reference genome as a template to be able to map these short pieces of DNA sequence and to know which regions of the genome they represent," explains Dr Perez-Cano. "However, sequence reads supporting genomic regions that are very different from the human reference genome are difficult to align and so we lose the ability to detect these genetic variants. So, as well as using standard detection methods to identify genetic mutations, we also use a reference-free approach, called SMuFin, originally developed by the group of Professor David Torrents to detect somatic mutations in cancer.

This complex work has been performed using the 9 million core hours awarded the project on MareNostrum III, the supercomputer located at the Barcelona Supercomputing Center, where a direct comparison of sequencing data from ASD patients and their family members enables the detection of all sorts of genetic variants, including large chromosomal rearrangements. "We apply this method




The iHART project will generate whole-genome sequence data for the discovery of novel genetic risk factors for ASD and create a public repository for the scientific community. Families containing monozygotic twins and families containing more than two individuals with ASD (multiplex families) will be amongst the families investigated by iHART (top). Genetic variants are identified using a) standard next-generation sequencing methods reliant on the human reference genome and b) a novel approach called SMuFin which directly compares affected child to mom/dad to increase sensitivity in the detection of genetic variants.

to directly compare sequencing data between the children and their corresponding parents. Given the similarity of their genomes, this strategy improves the detection of de novo and inherited complex genetic variants," concludes Dr Perez-Cano.

"By analysing whole-genome sequence from these individuals we have been able to identify some potentially damaging de novo mutations, present in the affected children but not in their parents," says Dr Perez-Cano. "Interestingly, some of the variants we have identified are in genes that are infrequently mutated in the population but were previously reported to carry de novo mutations in ASD patients. At this point, we are collecting additional evidence for some of these genes as novel ASD candidate genes."

"On the other hand," she continues, "we have also generated some preliminary results from the analysis of families containing monozygotic twins. We have currently identified somatic mutations in monozygotic twins with significant phenotypic discrepancies, including differences in the levels of intellectual disability or the severity of the disease, but also monozygotic twins where only one of them has autism. This is still an ongoing analysis, but we think this could be potentially very informative."

"Usually, the identification of causal genetic variants is complicated because a human genome has around 3.5 million single nucleotide variants. In contrast, the identification of variants causing phenotype differences in monozygotic twins takes advantage of the fact that they are almost genetically identical," she concludes. "We have started the process of identifying inherited risk genetic variants in families with multiple affected individuals. We expect a difference in the genetic architecture of ASD in families with only one affected individual (simplex families) as opposed to families with more than one affected individual (multiplex families). In simplex families we already know about the role of de novo variants in ASD risk, whereas in multiplex families we expect inherited variants to play a more important role." Dr Perez-Cano expects the first round of sequencing and analysis to be finished by the end of 2015, which will cover around half of the families initially planned. "This is definitely a cutting-edge research project in the genetics of ASD," she concludes.

As well as these scientific goals of the project, iHART is also looking to create a public repository of ASD data that will empower the global scientific community to advance ASD research and treatment. With these two main aims, iHART is expected to have a huge impact. In addition to the potential advancement in the genetics of autism, the work will serve as a landmark for the study of other complex diseases and investigations using whole-genome sequence data.

## For more information

http://www.thehartwellfoundation.com/index.shtml
http://www.ihart.org

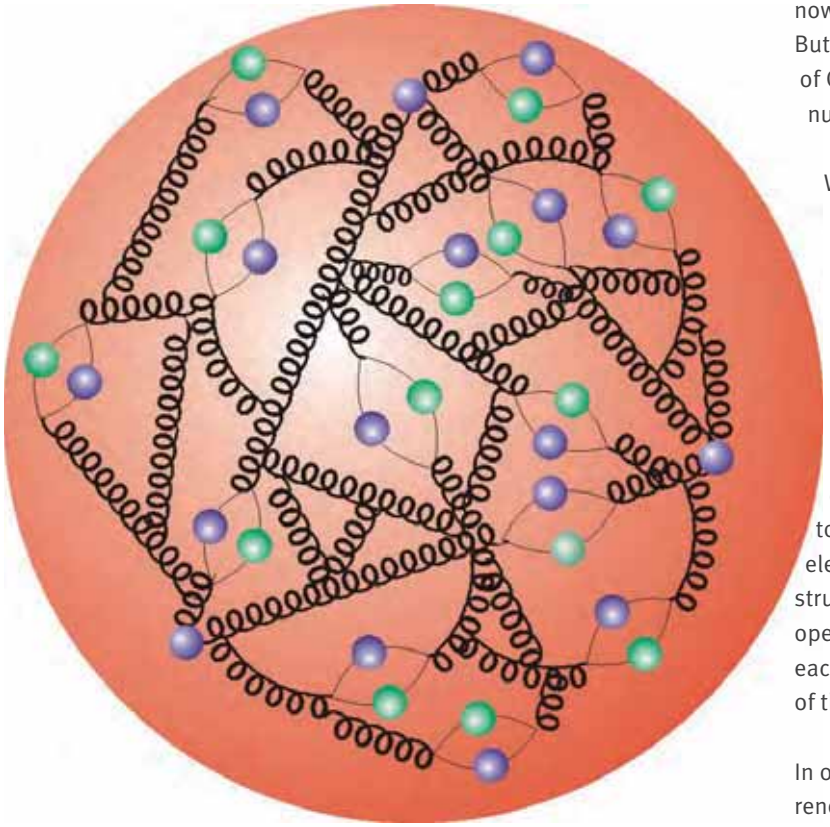
## Core hours

This project was awarded 9 million core hours on MareNostrum III at the Barcelona Supercomputing Center, Spain

## Publications

Laura Perez-Cano, Elizabeth K. Ruzzo et al. "Identifying genetic ASD-risk factors using whole-genome sequencing of 5,000 samples." UCLA CART retreat poster session (2015)

# Diving into the heart of matter



Using the FERMI supercomputer at CINECA, **Dr Mariane Mangin-Brinet's** latest research puts nucleon physics under the rigorous scrutiny of lattice QCD in an attempt to calculate the nucleon matrix elements, a move that contributes to our understanding of nuclei cohesion and structure of subatomic particles

Time and again, investigations by particle physicists into the electromagnetic, strong and weak interactions that govern elementary particles have lent firm support to the Standard Model theory. Concerned with strong interactions, the theory of quantum chromodynamics (QCD) within the Standard Model aims to elucidate the interactions between the elementary particles that carry a colour charge; quarks and gluons. While various approaches are used in the efforts to solve QCD, the choices narrow down if you want to get inside and explore the structure of matter. In this case, the usual weapon of choice is lattice QCD.

Discretising QCD onto a four-dimensional lattice is perhaps, to date, the only rigorous method for solving QCD, capable nowadays of reaching accuracy that rivals the experimental data. But although it has become a precision technique for a range of QCD observables, it remains an open challenge to calculate nucleon matrix elements.

Working to meet that challenge is Dr Mariane Mangin-Brinet, a first grade CNRS researcher (CR1) at the Laboratoire de Physique Subatomique et de Cosmologie (LPSC) in Grenoble, France. Although Mangin-Brinet's research has in the past dealt with cosmic ray physics, today she is entirely devoted to QCD, with her recent attentions focusing on nucleon matrix elements and non-perturbative renormalisation constants.

In lattice QCD, a method of statistical physics is used that computes the average values of a chosen operator in order to extract a chosen observable. "What we mean by matrix elements is that we choose the operators which describe the structure of the nucleon," explains Mangin-Brinet. "We can build operators which represent the fraction of momentum carried by each quark inside the proton and then compute the average value of this operator, which is the nucleon matrix element."

In order to do this, however, first you need to compute the renormalisation constants that are involved in the computation of matrix elements. Renormalisation is an essential ingredient of lattice QCD that enables comparisons between lattice computations and physical results. Being able to perform accurate calculations on the nucleon structure puts QCD theory through its paces. Calculations either agree with experiments and once again give credence to the Standard Model, or a discrepancy is found. "Once it is certain that such a discrepancy is due neither


Dr Mariane Mangin-Brinet

to a computational or experimental uncertainty," states Mangin-Brinet, "then you really find some sign of new physics."

Lattice QCD is not quick. The first step on the road to calculating the nucleon matrix elements is to compute the propagators of the gluon fields – large matrices that give information about what happens to a quark when it goes from one space-time point to another. Calculating these propagators is the most time consuming phase in a time consuming process, and it takes a Tier-1 supercomputer at least to handle the information contained in them. Through PRACE, Mangin-Brinet was granted 468,000 core hours on FERMI at CINECA, a world class system that has proved extremely useful. Equally important is Mangin-Brinet's involvement with the European Twisted Mass Collaboration (ETMC). It was by using gluon field configurations generated by the ETMC that Mangin-Brinet has been able to compute the quark propagators and to extract renormalisation constants.

*"Only by using PRACE's HPC resources have the researchers been able to calculate the propagators of the quark fields"*

The result? "Thanks to all the researchers who have helped, we have calculated this non-perturbative renormalisation constant and this was exactly the aim of the project," Mangin-Brinet. enthuses. "We obtained the accuracy we wanted and we have studied all the systematic sources of error." Now, with this critical factor in the operation of lattice QCD positively pinned down, it can eventually be used to calculate the nucleon matrix elements.

It is something of a double win for the project as Mangin-Brinet's team had also been developing a new method to get rid of hypercubic lattice artefacts. Though its application to renormalisation constants was not its debut, it was the first time the method had enjoyed a lot of success. Subsequent use has since demonstrated its value elsewhere on other types of observables and coupling constants. "We have developed a really interesting and rigorous method. Having access to the CINECA GPUs was undoubtedly a decisive advantage in demonstrating its success," states Mangin-Brinet.

This research is far from over, however. The gluon field configuration generated by ETMC is now over three years old and not representative of physical quark mass because it is only very recently that collaborations have been able to do real calculations with real light quark masses. Now that ETMC is reaching the physical quark mass, Mangin-Brinet would like to do exactly the same research with the new state-of-the-art and rid their calculations of more systematic errors.

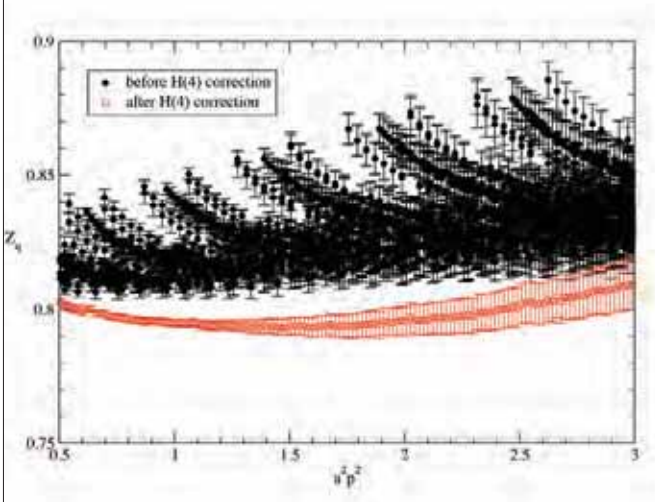



Figure shows the illustration of our method to correct for hypercubic artefacts. Black curve displays the bare quark renormalisation constant as a function of momentum, before corrections, and exhibits a typical "fishbone" structure characteristic of hypercubic artefacts. Corrected results are shown in red.

There is more than one route to take though. While the project specifically concerns nucleon matrix elements, the results are not so confined. Nucleon physics has been subject to a lot of measurements and experimentation, making the comparison of lattice and experimental results a cross-check between two computational measurements. In pion physics, where a lot less data has been gathered, this is not the case, and Mangin-Brinet would like there to be a lot more. In particular, she wants to use lattice QCD to form predictions concerning the momentum of a pion's quark to obtain a value, the idea being to push physicists in their experimentation to start making measurements and comparisons.

However challenging the goals may be that Mangin-Brinet wishes to pursue, access to HPC resources ensures that her work at the LSPC in Grenoble and collaborations with ETMC can continue to rigorously test the theory of quantum chromodynamics.

### For more information
http://lpsc.in2p3.fr/mariane

### Core hours
This project was awarded 0.48 million core hours on PLX @ CINECA, Italy

### Publications
1. "Renormalization of quark propagator, vertex functions, and twist-2 operators from twisted mass lattice at Nf=4", Phys.Rev. D91 (2015) 11, 114507
2. "Renormalization constants for Nf=2+1+1 twisted mass QCD", PoS LATTICE2014 (2015) 284

# The limits of control

The ITER project aims to get world's first commercial nuclear fusion reactor up and running before 2050. **Dr Marina Becoulet** is leading a large, international effort to understand the physics at the heart of what promises to be the largest device of its kind

In 2010 construction began on what is to be the world's first commercial nuclear fusion reactor, the ITER tokamak. Twice the size of the largest tokamak operating today, ITER is the result of a long running and immense international collaboration to design a device for nuclear fusion that produces more power than it consumes. While the current record for energy release stands at seventy percent of input power, for every fifty megawatts (MW) received by ITER, 500 MW will come out.

Being the biggest of its kind, however, the physics behind tokamak nuclear fusion is not yet certain for ITER. Tokamaks operate by employing strong magnetic fields to hold plasmas in high confinement but with this you get magnetohydrodynamic (MHD) instabilities. Although present day tokamaks are built to avoid many of these instabilities, some you can only try to control. Driven by steep pressure gradients and occurring at the plasma edge are instabilities known as Edge Localised Modes (ELMs). While these are not a major concern for tokamaks today, ELMs are not yet fully understood in the context of ITER's ambitious scale.

*"ITER is the result of a long running international collaboration to design a device for nuclear fusion that produces more power than it consumes"*

Coordinating efforts to elucidate the physics of ELM instabilities is Dr Marina Becoulet, a researcher with the Institute for Magnetic Fusion Research (IRFM) at CEA's Cadarache Centre in France. "What we are trying to do," explains Becoulet, "is build on present knowledge to understand ELMs and test the methods of control."

Predicting these for ITER is a challenge. As well as being the biggest machine of its kind, the plasmas confined in ITER will be the hottest yet at 150 million °C, ten times hotter than the centre of the Sun. Moreover, the methods for controlling and mitigating ELMs are not well known. To make these predictions Becoulet uses JOREK code, a nonlinear 3D reduced-MHD code designed to simulate MHD instabilities in realistic tokamak geometry. Computationally demanding in itself, it also presents some logistical challenges for a project that moves around the world. "With each new system you have to install the code again and test it, and that takes time. This time it took us months," recalls Becoulet.

Through PRACE, Becoulet's team has been awarded 12.2 million core hours on Tier-0 CURIE system in France hosted at GENCI @ CEA. Despite installation delays, however, the project has been a resounding success. "It was very nice this time and it worked very well," says Becoulet, "and what we are doing with this code is very practical and realistic. Some parameters are still limited but the physics is now very close to the real experiments."

Without controlling MHD instabilities, the ITER would only survive a few rounds at full power. There are, however, several methods for controlling and mitigating these ELM instabilities.

The first method, and Becoulet's specialist area, is to apply resonant magnetic perturbations (RMPs). "What we do is apply small magnetic perturbations to destroy a little bit of magnetic confinement at the plasma edge," explains Becoulet. Simulating this technique for the JET tokamak in the UK and ITER parameters, mitigation was

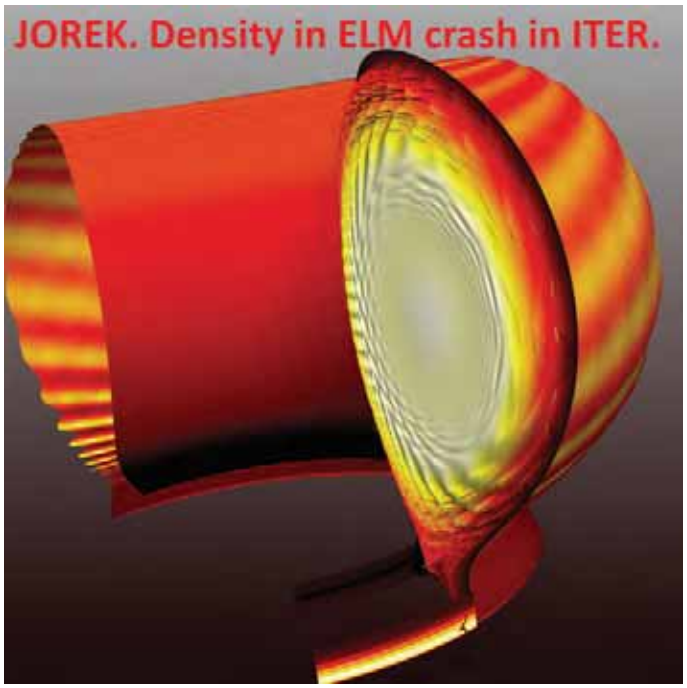



Fig.1. Density and heat flux on the divertor plates (bottom) in ELM crash in ITER.

demonstrated in both cases and in JET the complete suppression of ELM cycles was achieved. In essence, RMPs creates small relaxations meaning that you are no longer going to highest-pressure gradients. Discovering how this mechanism actually works brings the modelling even closer to experimental observations.

Another approach is to inject very small pellets of deuterium, one of the fuels used in nuclear fusion. Each injection triggers a very small crash at the plasma edge. With the JOREK code Becoulet now has a new and more realistic model of pellet ablation, able to describe the interaction of the pellet cloud with the changes it causes to MHD activity. "We have discovered the minimum size of pellets for injection and velocity, real numbers ready for ITER to use," enthuses Becoulet.

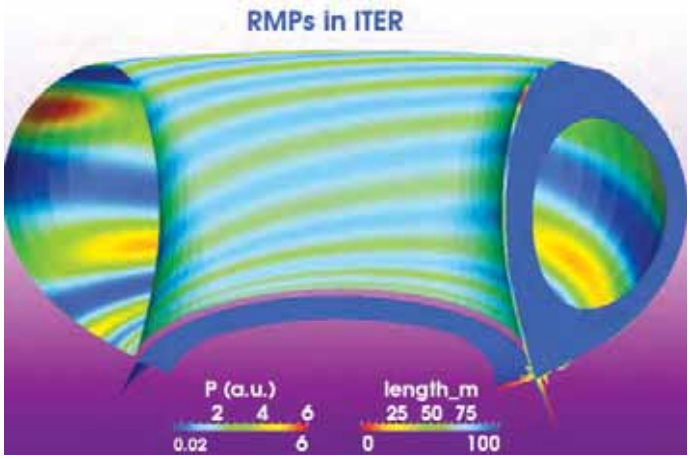



Fig.2. 3D magnetic topology at the plasma boundary with Resonant Magnetic Perturbations (RMPs) in ITER.

Alternatively, you might choose to work with an entirely different plasma regime. In quiescent high-confinement mode (QH-mode) plasmas, ELMs disappear and are replaced with continuous MHD activity taking the form of very small crashes at the edge. "This was the first principle modelling to explain it," Becoulet states. "Before this project no one really knew what it was and why it behaved this way." What it does is drive an external kink-mode which sits constantly at the edge so the plasma never goes toward a large crash.

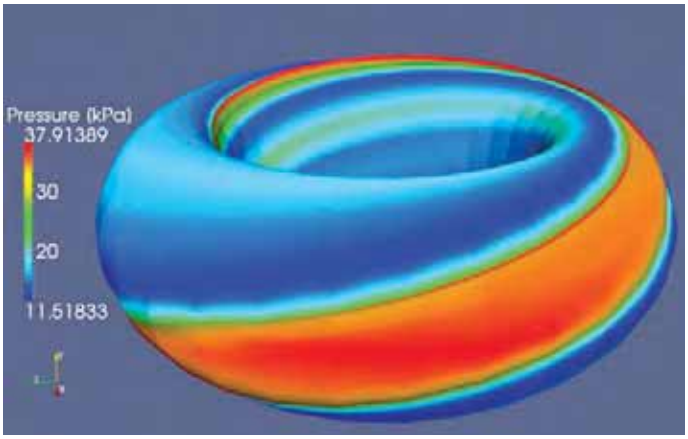



Fig.3. Pressure perturbation caused by pellet injection in DIII-D(US) tokamak.

But what happens when a global instability arises? In these disruptions you could lose the whole confinement of the plasma, releasing huge and destructive amounts of energy. By choosing the right regime this can be avoided, but just in case things go wrong there is always massive gas injection (MGI). The most promising method for disruption mitigation, MGI injects cold gas to cool the plasma, effectively creating a mini disruption. The project's modelling produces observations from current tokamaks which can be used to design ITER's MIG mitigation system, as Becoulet explains, "from where you can do it, what gas you should inject, at what velocity, all these things can be optimised from this modelling."

This has really been the first principle modelling to see if things correspond to experiments in a qualitative way. "This project was really exploratory because when we started we didn't know if we would discover anything or not," states Becoulet. "Fortunately, despite limited parameters, we discovered a lot of things and we are very happy."

To really get the ITER project on its way Becoulet is keen to bring some new subjects to the table and some new MHD instability issues, while continuing further with the themes of this project. For these she is planning a more quantitative approach. Currently at the limits of what the present version of JOREK can do, much needed development is on the cards first. "The main line of the next phase is to go towards the more practical, more experimental comparisons," Becoulet explains. "We have only touched upon some things and now we should be more confident to go further."

## For more information

http://jorek.eu

## Core hours

This project was awarded 12.2 million core hours on CURIE @ GENCI@CEA, France

## Publications

1. Huijsmans, G.T.A.et al. "Modelling of edge localised modes and edge localised mode control", Physics of Plasmas 22 (2015) 021805
2. Becoulet M et al "Mechanism of Edge Localized Mode mitigation by Resonant Magnetic Perturbations" Phys Rev Let, 113 115001(2014)
3. Orain F. et al "First simulations of multi-ELM cycles in tokamak X-point plasmas" Phys Rev Let, 114, 035001 (2015)
4. Orain et al "Non-linear MHD modeling of multi-ELM cycles and mitigation by RMPs" , Plasma Phys Control Fusion, (2014) 014020
5. S. Futatani et al. 'Non-linear MHD Modeling of ELM triggering by Pellet injection in DIII-D and implications for ITER', Nuclear Fusion 54 073008 (2014)

# The weather forecast

Research into the physical phenomena of space weather has bumped against the limitations of magnetohydrodynamic (MHD) simulations, but steady advances in supercomputing have helped **Minna Palmroth** develop a new simulation that can model the physics of space weather at an unprecedented resolution

Solar winds describe the supersonic flow of highly charged particles that are emitted from the Sun's upper atmosphere. Carrying with it the solar electromagnetic field, these waves of plasma trigger the physical phenomena we call space weather; variable environmental effects occurring in the near-Earth atmosphere that range in scale from a few kilometres to hundreds of thousands and in time from milliseconds to years.

Violent eruptions can lead to prolonged space weather disturbances that impact both space- and ground-based technologies such as spacecraft, satellites, GPS and other telecommunication systems. Space weather has also been known to disrupt critical ground-based infrastructures, most notably when power-grid failures led to widespread blackouts in Quebec in 1989, and later in Malmö in 2003.

*"Hornet is four times more powerful than its predecessor and is fully capable of performing the computations needed for the simulation"*

But what if space weather disturbances were as predictable as terrestrial weather? Until recently, the state-of-the-art has not allowed much headway in efforts to forecast the impacts of solar winds but now, thanks to scientists at the Finnish Meteorological Institute (FMI), we are entering a new era of space weather modelling.

Back in 2007, Minna Palmroth received a starting grant from the newly established European Research Council (ERC) to begin work on VLASIATOR. The six-dimensional Vlasov-theory based simulation was developed to address the physics of space weather that are consistently missed by magnetohydrodynamic (MHD) simulations. MHD is good for modelling on a small scale, but accurate, self-consistent modelling of space weather must work on a much grander scale to include solar wind, the entire near-Earth region of space and the ionosphere. "At the time no one actually believed in this work," recalls Palmroth. "Most people thought that we had set our ambitions too high."

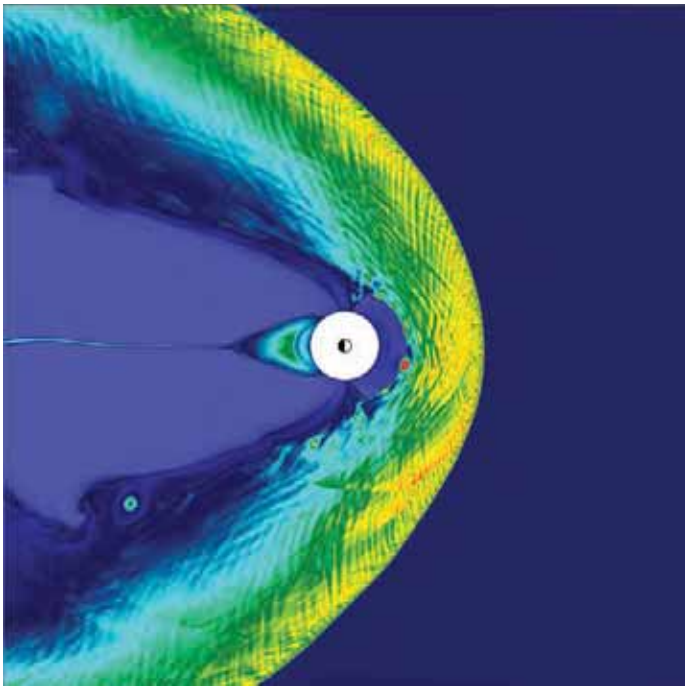
A research professor at FMI and VLASIATOR's principle investigator, Palmroth has steered the project right from its very beginnings when it was just a bold idea. Its fundamental objective is to explore the physical phenomena that are considered most crucial to understanding the behaviour of plasma.

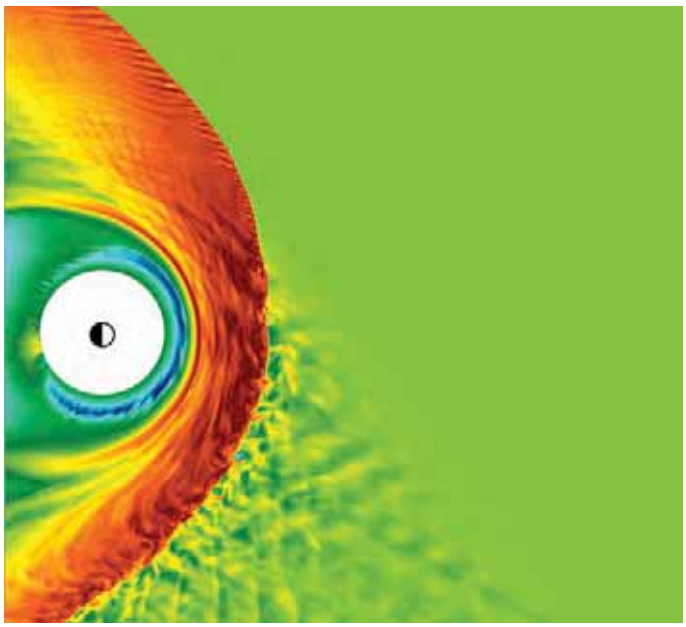
MHD simulations treat the environment as a fluid. Their accuracy flounders at a global scale because MHD approximates plasmas at a single temperature which, as Palmroth states, is not the case: "There are many different temperatures of plasma; cold plasmas from the ionosphere, for instance. Different temperature plasmas are at the heart of space weather."

As a result, the modelling communities and the in situ communities have diverged somewhat, with MHD unable to properly explain the phenomena observed in measurements taken by local spacecraft. With VLASIATOR, the electrons are magnetohydrodynamic fluid but by representing ions as distribution functions it is able to account for multiple plasma temperatures and avoid inaccurate approximations. The processes of space weather that are not governed by MHD are therefore finally beginning to be understood.

For a while, VLASIATOR enjoyed life as a kind of toy model at FMI where the computing facilities consist of two thousand cores. In order to get good results, however, the simulations need to run for days and sometimes weeks which is impossible to do on machines at the smaller end. In order to meet the colossal computational challenges that the simulation poses, PRACE awarded the project 24.1 million hours on Hermit, a Tier-0 system housed at the High Performance Computing Centre (HLRS) in Stuttgart, Germany.

Towards the end of 2014, Hermit was replaced with Hornet, HLRS' new CRAY XC40 supercomputer. Possessing over 100,000 cores,





When encountering the Earth's magnetic field, the solar wind has to flow around the obstacle. A bow shock forms, along with other perturbations and waves. By varying the orientation of the simulation and the solar wind parameters, VLASIATOR simulations help to understand the physics behind space weather in an unprecedented way.

Hornet is four times more powerful than its predecessor and fully capable of performing the massively parallel computations needed for VLASIATOR to work. Of course, the team behind these simulations aren't using the full complement of cores but, as Palmroth's remarks suggest, their allocation appears to be more than adequate: "Hornet is an absolutely beautiful machine, it is giving us incredible results."

Efforts to elucidate the dynamics of plasma behaviour are centred on three phenomena in particular: reconnection, shock and acceleration. Palmroth has a method to help illustrate the moment when plasma comes into contact with a planet: "Picture a rock in a river. The Earth is like a rock in the stream of solar wind." When the solar wind encounters the Earth's magnetic field, a bow shaped boundary, like water flowing around a rock, is formed. It is this interaction and the events associated with it that dominate the investigations into space weather physics.

Magnetic reconnection is the process that allows the transfer of energy and mass between different magnetic domains, such as when solar wind plasma crosses a boundary - the magnetopause - into the Earth's magnetosphere. It is thought that this barrier-breaking is what leads to substorms in the magnetosphere and solar flares.

The electromagnetic fields occurring at shocks and in reconnection regions are both associated with particle acceleration, precursors to some of the events that are most harmful to spacecraft. Using VLASIATOR, Palmroth is looking to use the data generated on reconnection and shocks to help evaluate the energisation and paths of particle acceleration.

These runs are the world's first self-consistent and semi-global attempts to explain the science of plasma reconnections, shocks and particle acceleration in a holistic manner. As greater accuracy at larger scales has become increasingly important in furthering space weather research, pure MHD simulations have struggled to meet demands. Without the rapid technological advances that have taken place in supercomputing, Vlasov-theory based simulations might still be little more than a toy model. Through systems like the Hornet at HLRS, however, VLASIATOR is instead simulating the physics of space weather at unprecedented quality.

Far more complex than previously thought, space weather phenomena that had only been observed by spacecraft measurement are now being seen with VLASIATOR, giving scientists like Palmroth the chance to unravel the mechanisms behind such phenomena and put them into a larger context. In the future, instead of experiencing power-grid failures, we might be preparing for them.

## For more information

http://vlasiator.fmi.fi

## Core hours

The project was awarded 24.1 million hours on Hornet at the High Performance Computing Center Stuttgart (HLRS)

## Publications

1. 2015
Kempf, Y., Pokhotelov, D., Gutynska, O., Wilson III, L. B., Walsh, B. M., von Alfthan, S., Hannuksela, O., Sibeck, D. G., Palmroth, M., "Ion distributions in the Earth's foreshock: hybrid-Vlasov simulation and THEMIS observations." Journal of Geophysical Research: Space Physics, published online. doi:10.1002/2014JA020519, 2015.

# Getting in safely: new designs in drug delivery

**Dr Paraskevi Gkeka's** research into nanoparticle-cell membrane interactions at the Biomedical Research Foundation - Academy of Athens (BRFAA) is making vital contributions to advancing the field of drug delivery design in biological systems


Dr Paraskevi Gkeka

You only need to put on your clothes or apply sun cream to come into contact with nanoparticles (NPs). Increasingly used in the manufacturing process of a wide range of products, NPs can be found anywhere from skin cosmetics and paints to the performance enhancing coatings of ships and aircrafts.

Nanomaterials can readily end up inside the body of an organism due to their small size. If they aggregate, they get bigger and become more difficult for the body to excrete and may end up accumulating in organs like the liver, where they can pose an extremely toxic threat. However, if NPs are designed to reach specific sites (such as cancer cells) intentionally, they can revolutionise the field of drug delivery as a promising new method for targeted tumour destruction.

Dr Paraskevi Gkeka is a postdoctoral researcher at the Center of Translational Research in BRFAA, working in Dr Zoe Cournia's lab. Other collaborators in the project include Dr Apostolos Klinakis from BRFAA, Professor Klaus Liedl from the University of Innsbruck, Dr Lev Sarkisov from the University of Edinburgh, and Professor Ioanna Zergioti from the National Technical University of Athens. The team's latest research focuses on the potential cytotoxicity of nanomaterials as drug delivery vectors. "Our two main objectives are to study the aggregation mechanisms as well as the interactions between NPs and the cellular membrane," states Gkeka. "This way we can assist in the design of nanoparticles with reduced toxicity and tailored functionalities such as direct cellular entry."

In order to study these types of interactions and effects, an in silico approach is needed in the initial steps of the drug delivery system design, as Gkeka explains: "The systems we are focusing our research on consist of several million particles, making the use of very large computing facilities a necessity." Without such facilities, one would need to design unfeasibly expensive experiments to test the NP systems. Through PRACE, Gkeka and Cournia are running molecular simulations using 8.5 million core hours on CURIE, a Tier-0 system hosted by the Grand Équipement National de Calcul Intensif (GENCI) in France. "We have been able to run several large scale simulations so far," says Gkeka, "and although we are still in the early stages of this project, we have already generated several promising results."

*"The systems we are focusing our research on consist of several million particles, making the use of very large computing facilities a necessity"*

One of the first steps into assessing nanoparticle cytotoxicity is to study their interaction with the cell membrane. Essentially, what the team is investigating is whether the membrane is affected or even disrupted by this interaction, in the process of allowing the nanomaterial to be internalised inside the cell. The goal of the study is to investigate the mechanisms of NP internalisation through the cell membrane, which are in turn affected by the size, shape, surface chemistry and charge of the NP.

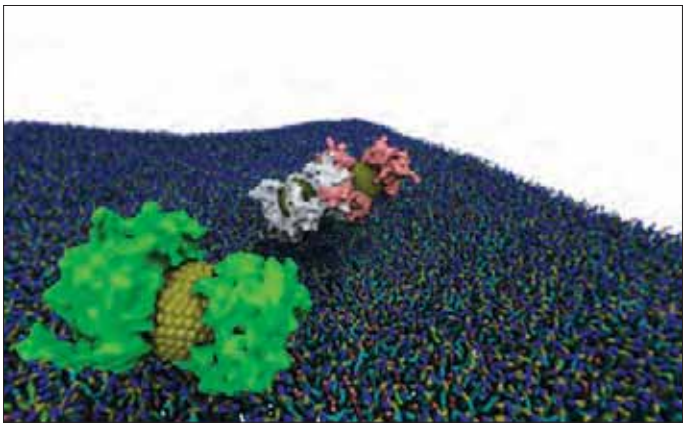

Dr Zoe Cournia

An additional factor influencing these interactions concerns the NP coatings as potential tunable drug delivery vectors. Thus, Gkeka's

simulations aim to study a variety of systems coupling NPs with multiple peptides and ligands to analyse their effect on cytotoxicity and NP-cell membrane interactions. The team's goal is to use these studies to elucidate the link between the type of chemical groups on the NP surface and their toxicity and drug delivery efficiency. In other words, to identify which ligands and which arrangements of ligands correspond to toxicity and/or effective cell membrane translocation. "The ultimate scenario," Cournia explains, "is to design a coating that helps the NP not to be cytotoxic and to enter the cell without disturbing the cell membrane."

*"Using PRACE HPC resources is critical to our work, as we can computationally screen a large number of NPs"*

Although still in the early stages, Gkeka has already run ten simulations to explore the behaviour of NPs covered with polyethylene glycol (PEG) ligands. By attaching a PEG ligand to the surface of the NP, one can reduce NP aggregation as well as improve other physicochemical properties of the system, as has already been shown experimentally. When NPs enter the body, they have a tendency to attract other biological entities, which build up on the NP surface and create a corona, a process known as the 'corona effect'. Both aggregation and the corona effect should ideally be avoided and PEG ligands aid in alleviating these processes. While still in the process of analysing their results, Gkeka has managed to pinpoint the optimum size of the PEG molecules needed for a specific NP used by the experimental collaborators in the project. Available as small, medium or large molecules, only a few PEG sizes allow you to avoid aggregates, while successfully translocating across the cell membrane. As Gkeka recalls: "I was recently excited to inform a colleague that a medium-sized PEG molecule was the best that I could recommend for her research."



Snapshot from a simulation with three PEG-covered nanoparticles interacting with a model cell membrane. The nanoparticles' core is shown in ochre and the PEG tails are shown as surfaces coloured green, grey and pink for the three different nanoparticles. The POPC and DPSM lipids of the model membrane are shown in licorice representation (Colours: glycerol group = blue and phosphate group = ochre) while cholesterol is represented as pink van der Waals spheres. Water is not shown for clarity. The image was generated with VMD and GIMP.

But while the team's research carries on, investigations into another system have already begun. A cell penetrating peptide known as Pep-1 has previously demonstrated its ability to translocate across the cell membrane and deliver biological cargos of various sizes inside the cell. Gkeka and Cournia's simulations aim to see whether NPs can be functionalised with Pep-1 in order to improve cell penetration without damaging the cell membrane.

Further systems to be simulated include a linear polysaccharide called chitosan that has shown great promise experimentally as a vector to be used in drug delivery. "The final system we wish to study is one specific NP that combines all the three components; polyethylene glycol, Pep-1 and chitosan," explains Gkeka.

The completion of these simulations, however, is just the first phase in a rapidly evolving and very promising project. These studies are part of a large consortium entitled NANOTHER (Magnetic Nanoparticles for targeted MRI therapy) funded by the Greek Secretariat for Research and Technology, which involves experimental and theoretical scientists from a variety of disciplines. With the team's results deciding the eventual design of these NPs as drug delivery vectors, it will require experimentation to test their potential in reality. "In the framework of the consortium, we are going to perform experiments using breast cancer cell lines available here at BRFAA," says Gkeka, "These experiments will provide crucial information about whether the functionalised NPs conjugated with a known anti-cancer drug have any effects on these cell lines."

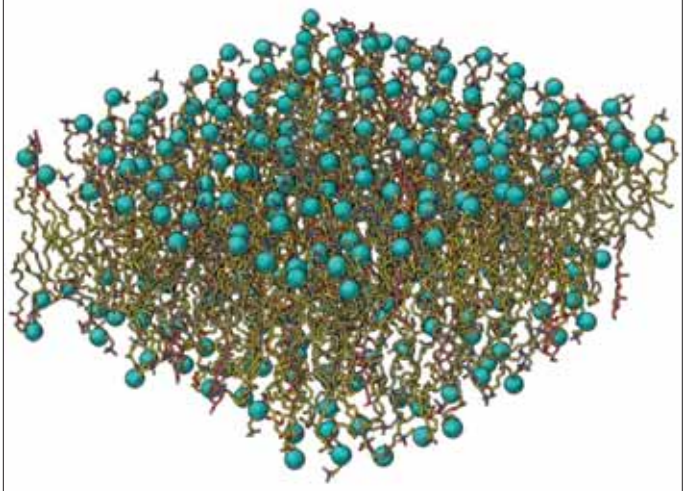
HPC is an especially powerful tool in this area of research. Not only are these systems comprised of several millions of particles, but also the number of different combinations and arrangements of the NP coatings adds a considerable amount of complexity to an already hefty workload. "Using PRACE HPC resources is critical to our work," Cournia explains, "as we can computationally screen a large number of NPs to understand which ones should progress to the experimental stage."

"So far our simulations have proven to be extremely helpful and we expect even more promising results," says Gkeka. Providing the most realistic descriptions of NP-membrane interactions to date, this research is guaranteed to push the envelope of drug delivery vector and agents that have the potential to enter the clinic.

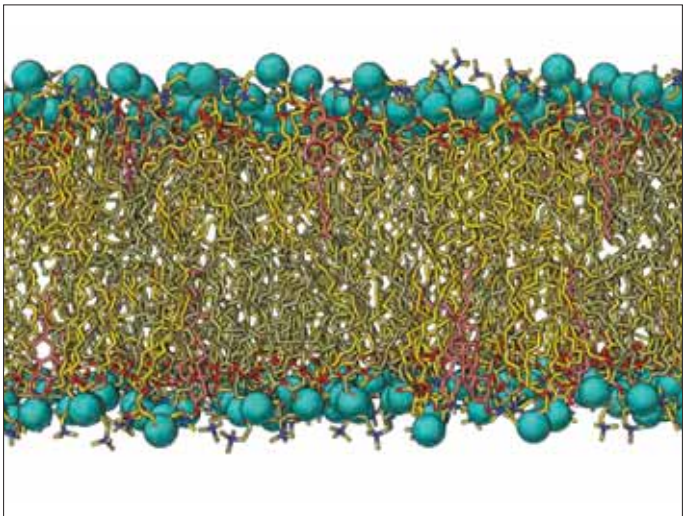
**Core hours**
The project was awarded 8.5 million core hours on CURIE TN @ GENCI@CEA, France

# Optimising gene therapy

Gene therapy is considered amongst medical experts to be the greatest hope for treating serious health issues ranging from cancer to genetic disorders. **Dr Roberta Galeazzi** and her group from Università Politecnica delle Marche are using PRACE resources to elucidate the most effective nanovectors for delivering this novel and potentially revolutionary treatment.



Structure of mixed composition bilayer containing DOPC and crown ether 15C5L' lipid (5%) after 100 ns molecular dynamics (cyan balls represent phosphate of DOPC lipids)



Structure of mixed composition bilayer containing DOPC (yellow) , POPC (brown) and CHOLp (in salmon) after 100 ns molecular dynamics (cyan balls represent phosphate of DOPC lipids

Recent progress in nanotechnology has triggered a surge of research into site-specific drug and gene delivery, which have gained wide acknowledgment in contemporary DNA therapeutics. Gene therapy is now considered a promising approach for the treatment of a wide range of diseases such as cancer, AIDS, and neurodegenerative and cardiovascular pathologies and is expected to be of paramount importance in the treatment of genetic disorders.

Today it is widely accepted by those working in this rapidly developing field, that the main problem that needs to be settled in order to begin the full practice of gene therapy is the availability of vectors or methodologies that can transport DNA inside of cells efficiently, selectively and safely for patients. Consequently, many researchers are currently trying to synthesise new vectors or optimise existing options. Of all the potential vectors so far, cationic liposomes are the most studied, although inherent cytotoxicity that causes negative effects on cells and the low stability of their complexes with plasmid DNA in serum are serious drawbacks and limit their application. The search for more stable and more efficient vectors therefore continues.

Neutral liposomes represent a good alternative. They are formed by zwitterionic phospholipids DOPC and DOPE and are non-toxic and

*"Using supercomputers we can investigate inherent stability and how stable a complex is with DNA"*

more stable in serum than cationic liposomes, but only a limited number of studies have been carried out on them so far because of the supposed instability of their complexes with DNA. Dr Roberta Galeazzi and her group from Università Politecnica delle Marche in Italy have been studying neutral liposomes, i.e. nanovectors that have been demonstrated in in vitro experiments to form stable complexes with plasmid DNA in the presence of bivalent metal cations (Ca, Mg, Mn) and to transfect this material to cells.

"In order to achieve our objectives in a fast and safe manner, we decided to carry out some in silico investigations," says Galeazzi. "Using supercomputers we can investigate inherent stability and how stable a complex is with DNA." The researchers were awarded 3 million core hours on PLX at CINECA.

The main objective of the project is to generate insights into the biophysical properties of liposomal gene delivery systems containing new synthetic lipids lacking in positive charge but acting

as effective cationic lipids. "We want to test the properties in order to define good nanovectors for gene therapy," explains Galeazzi. The researchers are studying neutral synthetic vectors containing lipids functionalised with groups able to coordinate bivalent metals and to form stable complexes with plasmidic DNA. The aim is to optimise the structure of the chelating agent lipids with different polar heads that have been synthesised. These include lipids functionalised with crown ethers, lipids functionalised with polydentate ligand containing nitrogen donor atoms, and anionic lipids derived from malonic acid. All the synthetic amphipatic lipids are mixed with commercial zwitterionic lipids (DOPC or DOPE) in different percentages and used in the preparation of multilamellar liposomes.

*"Furthermore, we have also found that the salt is very important. The salt plays a crucial role in stabilising the nanovector"*

Then, the mixed DOPC/DOPE based membranes containing the new synthesised functionalised lipids are studied using molecular dynamics simulations in order to elucidate the molecular organisation of synthetic neutral lipids into liposomes, their size, and how their rigidity influences interactions with cells. All these simulations of the lipid bilayer are carried out at the atomistic level since this is the only way to understand the parameters that influence such organisation. The concentration of both the synthetic lipids and the salts was varied. Different types of salts were also tested, with monovalent and divalent varieties being used in order to find the best fit.

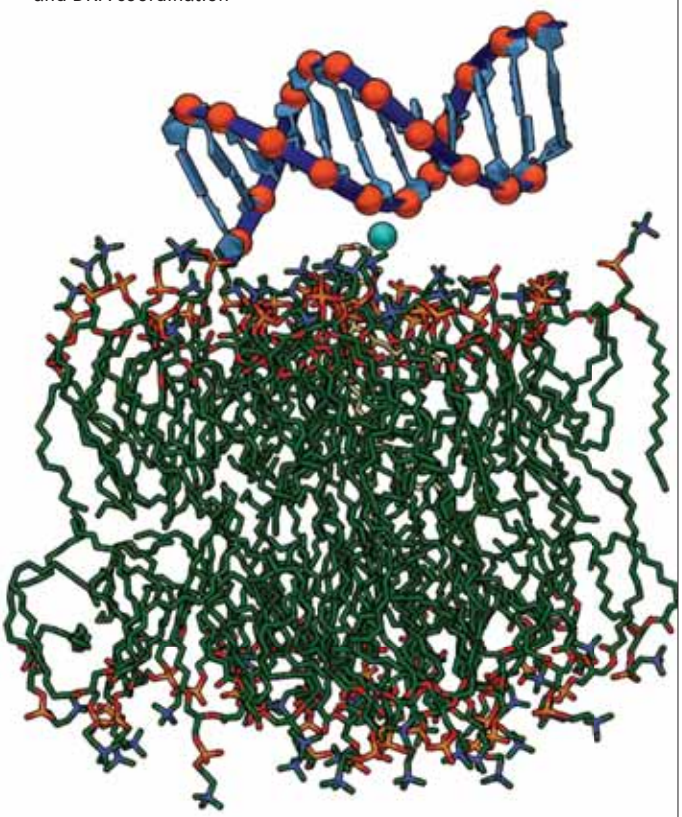
Results so far have been promising. "The GROMACS molecular dynamics package was scalable for the platform we used and allowed us to obtain some excellent results. We have found that there is an optimal concentration of synthetic lipids, which was somewhere in the middle of our range. The layer becomes stable and has good ability to complex with the cation at around 16 percent.

"Furthermore, we have also found that the salt is very important. The salt plays a crucial role in stabilising the nanovector. We saw that bivalent cations had the most stabilising effect and were also more efficiently complexed by our compounds, the lipids functionalised with crown ethers. There was also a particular dimension of the crown ethers that functionalised well."

The results will be used to reproduce biophysical experimental data, such as the single lipid molecular areas, and the influence of the salt nature and concentration into the bilayer organisation and structure, and others which can deeply influence the ability of the synthetic membrane to organise in liposomes and thus strongly interact with DNA – an essential requisite to be a good genetic vector.

Overall the team is happy with the results, and the next steps will be to continue with both in silico and in vitro studies. "So far, our model and the results we have obtained are in good accord with the physical data we have, which means that our model appears to be working well," says Galeazzi.

Mixed composition bilayer containing DOPC and crown ether 15C5L' lipid (25%) after 100 ns molecular dynamics: calcium ion and DNA coordination



## For more information

www.disva.univpm.it/content/laboratorio-di-modeling-molecolare-e-bionanotecnologie

www.disva.univpm.it/content/molecular-modeling-and-bionanotechnology?language=en

## Core hours

The project was awarded 3 million core hours on PLX at CINECA, Italy

## Publications

1. R.Galeazzi, P. Bruni, E. Crucianelli, E. Laudadio, M. Marini, L. Massaccesi, G. Mobbili , M. Pisani, "Liposome-based gene delivery systems containing a steroid derivative: computational and small angle X-ray diffraction study", RSC Adv., 2015, 5, 54070

# Modelling oceans at the mesoscale

As oceanographic observations improve a far more detailed picture of global ocean dynamics is emerging, a picture that today's models are unable to accurately represent. **Dr Simona Masina** is working to reach exceptional resolutions in ocean modelling to realise accurate short term forecasting of the global ocean

Our understanding of the ocean is changing. Once perceived as a global process characterised by large, smooth jets and currents, it is now clear that from the deep ocean to the continental shelf, its defining feature is turbulence. Only in the last few decades short-term ocean forecasting has really started to develop, and today's models are not capable of representing the ocean processes that are occurring at smaller scales.

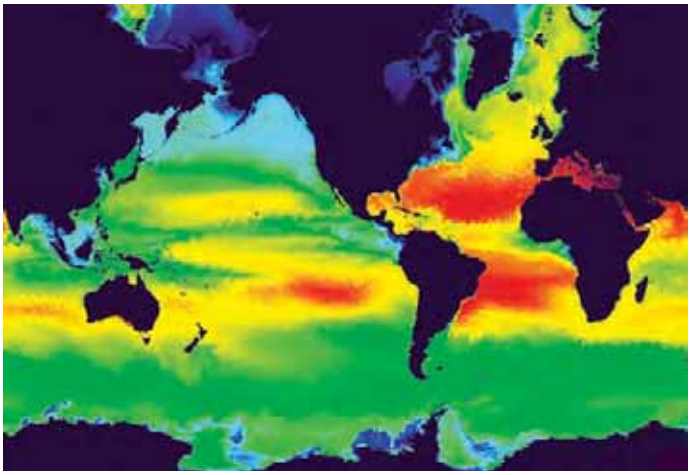
Meanwhile, there is an increasing need in the maritime, fisheries and energy production industries for access to reliable information about marine systems to help sustain the usage of coastal resources and mitigate the effects of global change on the ocean. To meet these needs, short-term forecasting systems are being developed to cover all the relevant scales and ocean processes at the highest resolutions yet.

Currently head of the Global Ocean and Climate Group and research director of the Ocean Modelling and Data Assimilation Division at Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) in Italy, Dr Simona Masina has over fifteen years experience in global ocean modelling and ocean data assimilation. Primarily interested in the ocean's role in the global climatic system, Masina has further responsibilities lecturing at the University of Venice and is a member of the Italian Oceanographic Commission and the CLIVAR Ocean Model Development Panel.

In 2014, Masina began to develop and implement a global ocean data assimilation system for improving ocean forecasting. In order to improve forecasting, however, you first need to improve predictive capabilities. Thanks largely to satellite data, there is a new image of the global ocean, as Masina explains: "It's a turbulent system, characterised by small eddies and mesoscale patterns that are crucial for transporting energy, momentum and heat to different parts of the ocean."

Achieving a resolution that accounts for the natural variability of the ocean in a model is challenging. The system that Masina is currently developing uses the NEMO modelling framework, an open source community model that the CMCC are both users and developers

Sea ice extent in the Arctic at the beginning of September 2007



Instantaneous ocean surface salinity from the global 1/16° model.

of. To date, the highest resolution for a global implementation of NEMO is 1/12˚, but in order to provide forecasts of global oceanographic parameters for the following ten days, Masina wants to push the model's abilities to 1/16˚. That is equal to a horizontal resolution of 7km at the equator down to 2km at high latitudes, a 25 per cent higher resolution than the one presently used in operational forecasting systems. "The total size of the problem is about four times larger than what is used in actual ocean forecasting systems," states Masina, "so it is a very demanding challenge which cannot be realised in a single year."

*"Running the model on MareNostrum has ensured that it is tuned, validated and ready to use for forecasting"*

Too demanding for the machines at CMCC, at any rate. Masina's team has been able to run the global, eddying configuration of the ocean and sea ice system on MareNostrum, the HPC resource hosted at the Barcelona Supercomputing Centre (BSC) in Spain and was awarded 13 million hours. This phase ensures that the model is tuned, validated and ready to use for forecasting, while the next stage is actually coupling it to a data assimilation system. "This is what we are working on now," explains Masina. "What we already have from PRACE is ten years of the 1/16˚ global ocean model, which will take two or three years to analyse."

This ten year hindcast covers global ocean modelling from 2004 - 2013, giving Masina all the variables needed to assess ocean temperatures, salinity, density and currents. It is a significant period because during this time a revolution in ocean observation occurred, not least due to the inauguration of the Argo system – a fleet of almost 4000 drifting profiling floats that provide real-time data on temperature, salinity and currents. Prior to their introduction, ocean observation data was scant at best, mostly coming in titbits from voluntary and commercial ships during their trips. With this timeframe, the model can be validated against these unprecedented observations. "It represents and simulates all the natural variability of the ocean," says Masina, "giving us the unique opportunity to investigate it properly. This is what we are doing right now."

In particular, Masina started looking at the variability of the Atlantic meridional overturning circulation, a crucial process that carries a lot of heat and significantly impacts the European climate, to see how much the eddies and small scale mechanisms represented in the model contribute towards variability. Due to the 1/16˚ resolution, an almost universal mesoscale eddy field showed itself with far greater strength than lower resolution global simulations are typically able to produce, while the eddy energy agrees on many levels with satellite data.

Although this is just beginning, these results are something of a coup. Satellite observations already show high levels of eddy kinetic energy everywhere when it was once thought to only exist in regions like the Gulf Stream. These areas are just the peaks of such mesoscale processes. "This is the challenge of the next few years: to try to have models that represent mesoscale variability without much parameterisation," says Masina.

In the meantime, Masina intends to keep working on the technical problem of actually coupling the data assimilation system to the ocean model, after which forecasting would become possible. With such high resolutions at high latitudes, it could be an appealing tool for companies who have or are interested in having infrastructures and shipping routes in the Arctic Ocean. But for now, as Masina says, it is all about the model: "These things are next. First we have to be absolutely sure about the quality of the model. If it is not good enough then it will be a complete waste of time to start forecasting."

## Core hours

The project was awarded 13 million hours on MareNostrum at the Barcelona Supercomputing Center, Spain

## Publications

**Technical report**

1. Iovino D., A.Storto, S.Masina, A.Cipollone and V.Stepanov: "GLOB16, the CMCC global mesoscale-eddying ocean." Research Papers Issue RP0247, December 2014.

**Publication under review**

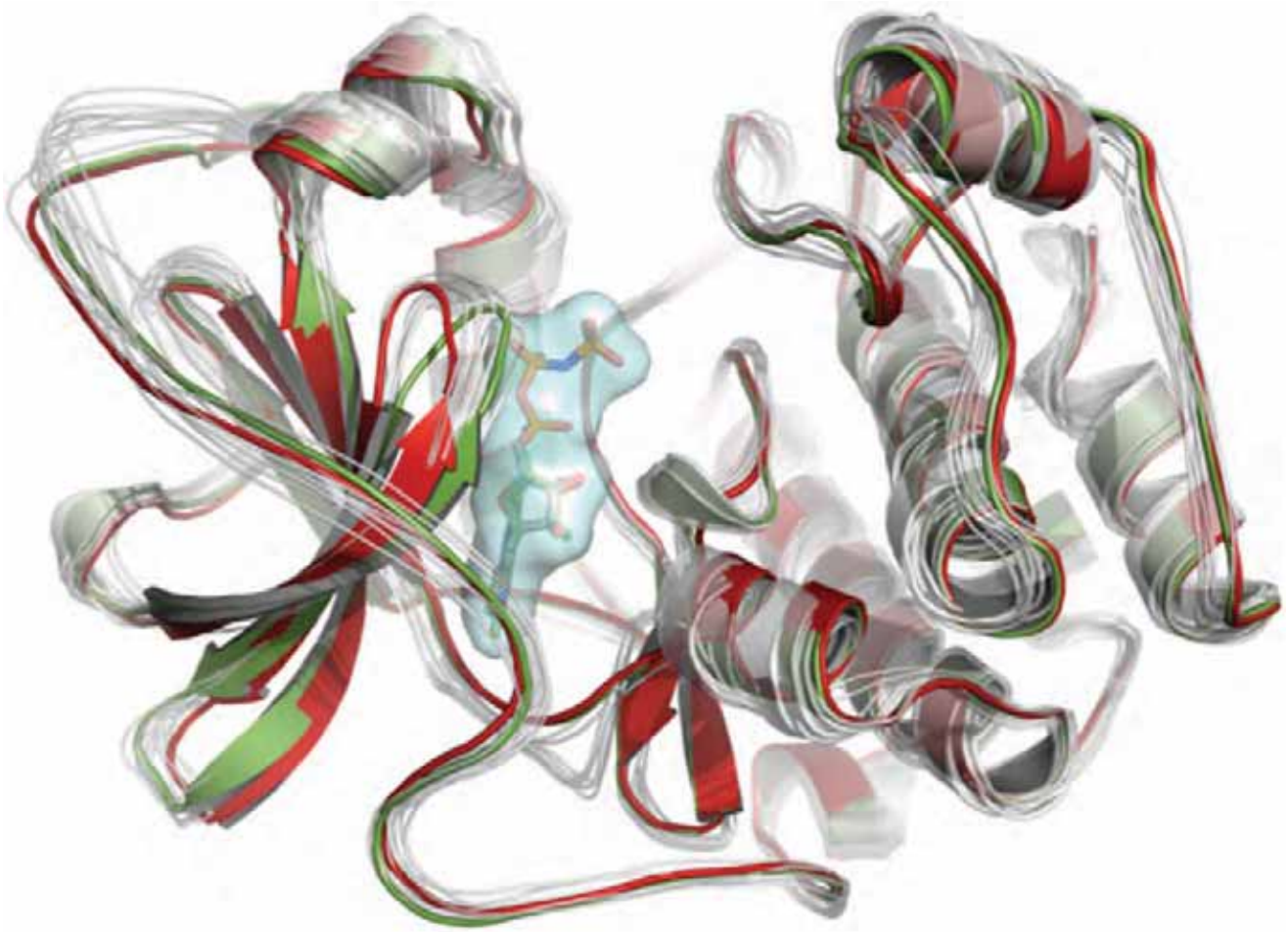
2. Stepanov V. et al.," Atlantic meridional heat and mass transports in models and RAPID observations."

**Publication in preparation**

3. Iovino D. et al.," An eddying 1/16° ocean simulation."

# Cross-talking in drug design

**Dr Teresa Carlomagno** has been working on a method to improve the success rates in structure-based drug design for over a decade. The INPHARMA approach is ready for use, but its scope for development is far from at an end



The pharmaceutical industry has benefited greatly from protein-ligand docking. An important computational tool in structure-based drug design, this molecular modelling technique helps to select likely drug candidates by showing the best way for a ligand molecule to bind to a target protein. The key is to narrow down the choice of poses until a particular orientation provides the highest binding affinity. As such, success in structure-based drug design is dependent upon reliable information on the interactions between ligands and proteins.

Today, however, deficiencies in the standard methods of protein-ligand docking leave considerable room for improvement. Originally conceived over a decade ago, INPHARMA is a new nuclear magnetic resonance (NMR) spectroscopy technique that aims to boost prediction success rates in structure-based drug design.

INPHARMA, or Interligand NOEs for Pharmacophore Mapping, is the product of more than ten years work by Dr Teresa Carlomagno and her research group at the European Molecular Biology Laboratory (EMBL) in Heidelberg, Germany. Recently, they were awarded 0.7 millions core hours on HECToR, a Cray XE6 machine that was the UK's primary academic research supercomputer until ARCHER replaced it in 2014. "Access to this machine through PRACE was very important," states Carlomagno. "The computational effort in what we do is such that the thousand CPUs we have available at EMBL are simply not sufficient."

Protein-ligand docking is computationally exhausting. In conventional docking, flexible ligands are tried against a more or less fixed protein structure. In reality, however, proteins are not fixed in one state. An improvement upon this is ensemble docking

which generates different possible protein structures to try. Starting with one structure, molecular dynamics (MD) simulations allow you to create a series of slightly different versions of the same protein to find the highest binding affinity. It may be computationally demanding but the ability to account fully for protein flexibility makes MD simulations a key asset in structure-based drug design. As the number of structures to choose from increases, though, so does the amount of data produced, thereby adding to the complexity and the time it takes to analyse it.


Dr Teresa Carlomagno

*"Access to HECToR was essential, because the thousand CPUS we have available at EMBL were simply not sufficient"*

With so many structures available it is essential that you have a robust scoring function, a concrete method of selecting the correct docking mode. "In this scenario a scoring function that uses experimental data as well as well calculated energies is very important because it is much more solid than just prediction," explains Carlomagno.

INPHARMA is different because the scoring function is based solely on experimental data acquired through NMR spectroscopy, a far more reliable method of choosing the correct docking mode. This puts Carlomagno's new approach within the framework of techniques that focus squarely on the ligand rather than the protein. NMR techniques that look at the resonances of proteins are high precision methods but they are limited to small proteins. Unfortunately, the bigger the protein molecule the harder it is to detect magnetisation, and so ligands enter the picture. But even then you are still limited to weakly binding ligands. Getting around this requires a new concept.

It all began ten years ago with the first measurements of 'cross-talks' between two ligands. Cross-talking is where ligand A talks to a protein binding pocket by transferring some magnetisation to it, thereby leaving a signature of itself. Ligand A happens not to be such a tight binder and gets off the protein, then ligand B comes along to the same binding pocket and finds the signature left by ligand A. By interacting with the protein, ligand B is able to receive this info and indirectly communicate with ligand A. "It is a little bit like if I went into a room and left a message for you and then you come and read the message," Carlomagno explains. "We never talk to each other but we communicate."

So what can you learn from listening to a conversation between ligands? Cross-talk can tell you about the relative orientation of the ligands in the binding pocket, so if you try ligands A, B, C, D, E and F, for example, you will know that a certain part of each ligand has seen the same part of the binding pocket. This amounts to a lot of information for narrowing the choice of docking modes. "At the time there were many people in the NMR community who would not believe that you were able to see those things," Carlomagno recalls. "Now, in terms of using INPHARMA as an energy function to select docking poses, the method is ready for application."

This may sound simple, but the INPHARMA approach requires a lot of calculation and computing power for the docking procedure. "You might have six or ten million combinations. Then you need to calculate the cross-talk and pick the one that explains the experimental data it is compared against," says Carlomagno. Armed with this information, it is then possible to select how one ligand binds to a protein.

Although INPHARMA has already begun to be used, its availability does not mean development is at an end. "What we would like to do is go one step further. Instead of using the programme data to select docking poses, we want to use it to create a real complex ligand-protein structure," explains Carlomagno. Currently, it is possible to extract information about ligand cross-talk but the protein remains unseen. What if this indirect communication contains some information about the medium that allowed the transfer to take place? The next step is to develop computational procedures capable of retrieving this information. "In this case you would not need ensemble docking anymore," says Carlomagno, "but you would directly calculate a protein-ligand structure. However, this is quite challenging computationally."

Challenging, but not impossible. With access to HPC resources like those provided through the PRACE infrastructure, the next phase of this ambitious project has the potential to bring unprecedented levels of accuracy and success to structure-based drug design.

### For more information
www.carlomagno-group.org

### Core hours
The project was awarded 0.7 million core hours on HECToR at the University of Edinburgh, United Kingdom

### Publications
1. J. Sikorska, L. Codutti, L. Skjærven, B. Elshorst, R. Saez-Ameneiro, A. Angelini, P. Monecke, T. Carlomagno* "Identification of new scaffolds with INPHARMA-based virtual screening" Medicinal Chemistry Communications, 2015 6, 1501-1507

# Ripple effect: controlling hydrogen binding to corrugated graphene

As graphene continues to prove itself as the wonder-material of modern science, research by **Dr Valentina Tozzini** grapples with its remarkable properties that could one day see it revolutionise the field of hydrogen storage

As a zero-emission fuel, hydrogen has become a vital player in the search for renewable, non-polluting energy sources, but efficient storage methods still stand as a barrier to its utilisation. Recent research into the extraordinary properties of graphene could provide the key to hydrogen's viability as a renewable fuel.

Dr Valentina Tozzini is a researcher with the Italian National Research Council's Nanoscience Institute (CNR NANO) and the National Enterprise for Nanoscience and Nanotechnology (NEST) in Pisa. Her work on hydrogen storage looks to exploit the huge surface-to-mass ratio resulting from its 2D monolayer structure, a feature that conveniently means it can react with substances optimally. Coupled with graphene's inherent lightness, its suitability for storing a range of gases for energy purposes appears beyond question. But, as Tozzini explains, it is not so simple: "You cannot store something on a 2D system. You need to have a framework and you need to manipulate it to create specific properties. The problem is how to create these frameworks."

Currently, there are two routes to take that bind hydrogen to graphene. With physisorption, weak van der Waals interactions come into play, which do not break the hydrogen molecule. This is a good way to store hydrogen in its gaseous phase but problems arise when you want to increase the ratio between the stored hydrogen and the graphene. The other way is by chemisorption. Here, chemical reactions form strong bonds between hydrogen molecules and graphene which, amongst other things, prevent it from exploding. However, the kinetics of adsorption is slow because for a chemical reaction you need to break the hydrogen molecule.

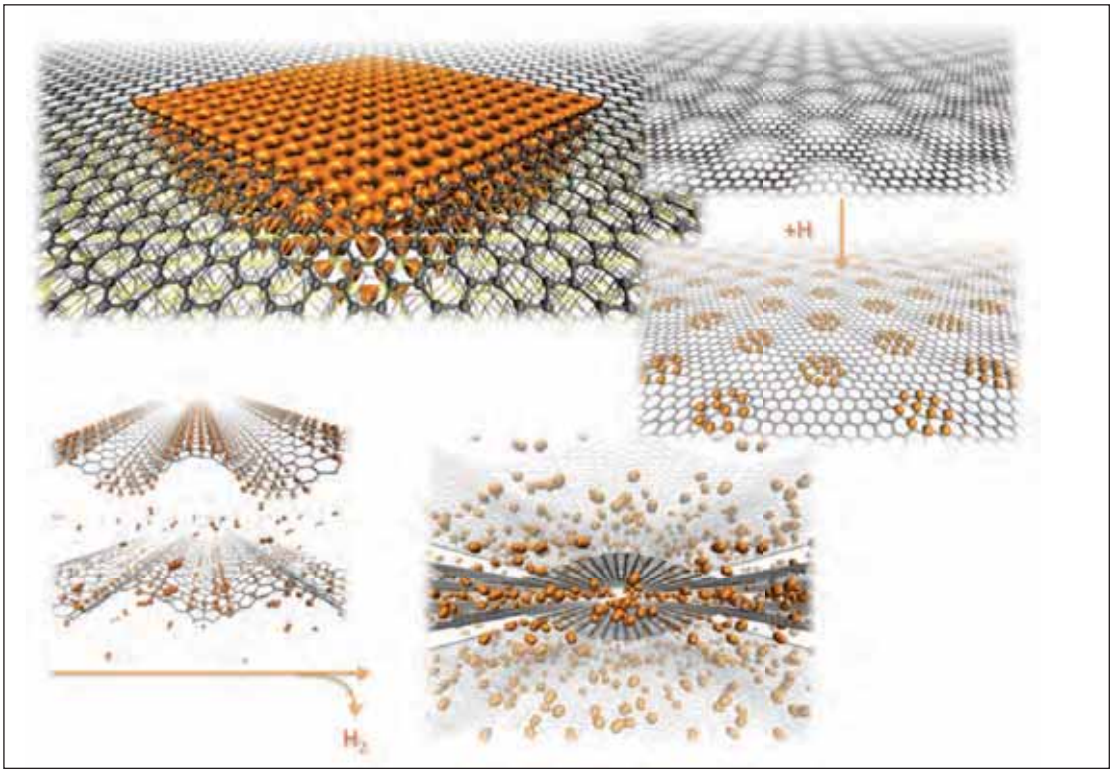
It does not take particularly accurate methods to study physisorption, governed as it is by so-called classical interactions. On the other hand, with chemisorption you need some very accurate methods to perform some very heavy calculations. Through PRACE, Tozzini was awarded 38 million core hours on the FERMI system at CINECA in Bologna, without which it would be impossible to properly analyse the chemical reactions between hydrogen and graphene. "The systems we need to address are very large and go up to 1,500 atoms, so you need to use advanced techniques like density functional theory (DFT)," Tozzini explains.

And the systems have to be large. A simulated system needs to be a replica of the experimental one and, in this case, needs to be large enough to reproduce the sample exactly. Here, Tozzini simulated a pure graphene system to match a sheet grown from a silicon-carbide substrate. Rather than a smooth, featureless sheet, however, Tozzini's graphene is a little rippled or, more accurately, corrugated. This pattern arises because of a mismatch in the lattice parameters between the graphene and the silicon-carbide substrate. "This was very interesting for us because corrugation enhances reactivity of graphene generally," explains Tozzini, "so it is an idea to solve the problem of overcoming the barriers for hydrogen chemisorption."

*"Using the FERMI system has allowed the researchers to properly analyse the chemical interaction between hydrogen and graphene"*

In comparing the results from the theoretical simulations and the experiments, it was observed that hydrogen preferentially binds on the corrugation. Put another way, corrugation actually favours hydrogen binding and could be exploited to design a safe and effective device for storing hydrogen. Furthermore, it may even be possible to develop a method that releases the hydrogen when needed.

Whilst too difficult to realise in experimentation, the simulations on FERMI reveal that hydrogen loses its stability when a concavity is introduced at the attachment site; an instability that ultimately leads




**Pictorial representations of the simulated systems**

**Upper left:** model system of a sample of graphene grown on SiC. The graphene sheet is visible in black, with a portion of its electronic cloud represented as an orange surface. The SiC substrate (Silicon in yellow and Carbon in grey) is visible underneath.
**Upper right:** the rippled graphene sheet (protrusions in lighter grey) and its hydrogenated counterpart (hydrogen atoms in orange)
**Lower left:** wavily rippled hydrogenated graphene and hydrogen detachment upon dynamical curvature inversion by wave passage.
**Lower right:** waves in graphene multilayer with hydrogen embedded.

to detachment. This discovery is potentially an entirely new idea within the field: to design a device for hydrogen storage and release by manipulating the local curvature of graphene. "It is not that easy, of course," cautions Tozzini. "In a simulation you can manipulate everything, but these things are very difficult to do in an experiment."

So how do you manipulate graphene local curvature in reality? Tozzini has proposed several strategies, one of which is to try and attach graphene to a piezoelectric substrate. The idea is that waves generated by the substrate would propagate onto the graphene sheet and dynamically alter its local curvature. Another idea, which diverges from the experimental route, calls for the use of HPC facilities like Fermi. In the simulations generated in this research, local curvature is manipulated by an external electric field orthogonal to the graphene sheet. While it is not yet clear how this happens exactly, the effect itself is quite observable; electrons are moved by the external electric field, which locally define the structure of the sheet. "The details are still under study but this could be a way," states Tozzini. "We have already seen on our simulated system that the external electric field is able to move concavities and convexities on the sheet, so this is a possibility we are investigating."

Before devoting herself to this next phase, there is a small matter of unfinished business Tozzini would like to attend to. There are always unexpected problems in this type of work and as such the project was not entirely completed. "I want to finish and go on with this research which I think is very, very important," states Tozzini. Graphene might be an exceptional material but, as this research shows, it has to be manipulated. It is not currently known which strategies will prove optimal, but by picking up where she left off and proceeding with HPC and experimentalists hand-in-hand, the investigation can begin.

While there are numerous methods of storing hydrogen, efficient and reversible storage is an ever-present issue in chemical techniques. Simulations of preferential bonding and a release mechanism are exciting indications that corrugated graphene could revolutionise hydrogen storage, or indeed the storage of any gas for fuel purposes. "We need to proceed together with experimentalists to make simulations and understand what is happening," states Tozzini. "This is the direction we are going in, which I think is quite fruitful."

## For more information

www.nano.cnr.it/index.php?mod=peo&id=256

## Core hours

This project was awarded 38 million core hours on FERMI @ CINECA, Italy

## Publications

1. A Rossi, S Piccinin, V Pellegrini, S de Gironcoli, V Tozzini "Nano-scale corrugations in graphene: a Density Functional Theory study of structure, electronic properties and hydrogenation" J Phys Chem C 119 7900–7910 (2015) DOI: 10.1021/jp511409b
2. V D Camiola, R Farchioni, T Cavallucci, A Rossi, V Pellegrini, V Tozzini "Hydrogen storage in rippled graphene: perspectives from multi-scale simulations Front Mater" , 2 00003 (2015) DOI: 10.3389/fmats.2015.00003

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