Surviving the Maelstrom Inside ITER

Fusion for Society

The Need for a New Pulsed Power Supply

Press Start

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ATTENTION new readers!

You’ll find many acronyms and terms in this magazine that are most likely foreign to you. Fear not! We’ve highlighted them and provided easy-to-understand descriptions on our website: www.euro-fusion.org/glossary

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This year we have the honour of featuring 11 stories from fusioners who’ve volunteered their time and tales to entertain, enthrall, educate and elucidate you. Each contributor has not only dared to bare their souls, but experienced first-hand the challenges of scientific storytelling, of turning their experiences in the almost unfathomably complex discipline of fusion research and studies into easily digestible, commonly comprehensible and well-baked sound bites.

How very appropriate it then is that our theme for this issue is ‘challenges’. Face them they have. What’s more: working together we are moving the needle. We are ever nearer to reaching that summit, that long promised and distant peak still concealed in the clouds. It’s exciting.

It’s exciting for me, as a science outsider, to read these stories. It’s exciting to learn about what they are doing, the progress they are making, and their multi-cultural, collaborative approach. All of which makes it somehow reassuring... That no matter what road-blocks are in the way, what dead-ends are encountered, fusion research is in the hands of incredibly intelligent, dedicated, enthusiastic and good people who will work inclusively across borders, languages and time zones to figure this fusion thing out and realise on the dream of fusion energy.

You’ll notice the call to vote. It’s your chance to share with these Fusion Writers how their stories impacted you.

Karl Tischler
Editor of Fusion in Europe
magazine@euro-fusion.org
Should citizens be involved as decision-makers in the development of fusion energy technologies? At first you might not think so. After all, how could people with no expertise on this topic meaningfully contribute to the development of such complex technologies?
This year, I set out to study the need and potential for citizen participation in fusion development. I started by engaging with people inside the fusion community (public and private, scientists and communicators), as well as people outside fusion (from politicians to regular citizens). Afterwards, I concluded that fusion energy development both can and should open up to involve citizens as decision-makers that inform the development of fusion energy technologies.

Why I reached these conclusions is firstly a matter of politics. I’m a student of the social sciences, and a salient topic in this field is the social and political nature of scientific knowledge and the technologies into which this knowledge is invested. This is counterintuitive: we like to believe that science is objective, and that technological innovation follows a pre-determined and linear path of progression as science reveals more and more about the nature of reality. Such assumptions are evident in claims that fusion is the ‘holy grail’ of energy production — that is, an end point on the one-way path of technological innovations for the production of energy.

Yet history defies these assumptions. Scientific investigation and technological development do not follow pre-laid paths, but develop in multiple, unpredictable directions. This is because they are practiced by humans within social networks, and are therefore driven by particular human values, preferences and assumptions about the world and how it should be. For this reason, the social sciences consider science and technologies to also be social and political, which is a realisation that encourages us to question why we limit scientific and technological decision-making and governance (how we decide how a technology develops) to technical experts alone.
In this regard, there have been calls to democratise decision-making processes in technological innovations by opening them up to citizen participation so that the developmental trajectories of these innovations can be collectively determined and guided towards socially desirable ends. These calls make the case for citizen participation on the basis that those who may be affected by, and who often fund (through taxes) such innovations should have a say in the way they are developed. Moreover, collective decision-making would make these innovations more robust and accountable when faced with the prospect of unforeseen consequences arising from the introduction of new technologies into society.

Following these calls, experiments with citizen participation in technological decision-making have been conducted in matters from geoengineering to nanotechnology, and even for asteroid redirection missions at NASA. Under the supervision of scientists and engineers, these experiments informed groups of citizens on genuine developmental problems, allowing their responses and reasoning to influence experts tasked with making the final decisions. Despite the inherently complex nature of the issues involved, these experiments found citizens’ responses to be highly insightful and valuable. They were able to contribute to the direction of technological development whilst moving scientists and engineers to question the underlying values motivating their decisions, and to consider the wider social implications of their technical choices.

The reason citizen participation experiments are successful in this way relates to social science’s observation that science and technologies are social and political. Because this is so, the decisions made in technological innovations are rarely entirely technical; they have social elements, too. For this reason, a variety of citizens, with varied experiences, expertise and ways of looking at the problem at hand, produces a greatly enriched decision-making process that counters the blind-spots of technical experts. On this basis, science as a whole — and fusion in particular — should move away from models of engagement that treat the public as a passive audience. Instead, moves should be made towards participatory models that enable the public to meaningfully influence developmental decisions and trajectories. Fusion should be democratised.

Achieving this is a huge challenge. Technological innovations (fusion included) are firmly rooted in the assumption that development processes are purely technical domains in which scientists and engineers (as the only valuable decision-makers) pursue technically optimal solutions. Democratising fusion requires re-orienting this assumption so that the aim of development is not to produce a technology that is technically perfect, but one which is responsible, desirable and accountable to the society into which it is to be introduced, and to which the technology ultimately belongs. This means shifting from the pursuit of technically-optimal solutions determined by a handful of technical experts, to workable and equitable solutions determined collectively. As a technology intended for the benefit of everyone in society, it is incumbent on fusion to experiment with these practices.

Democratisation however, should not be approached as a reluctant concession on the part of those currently developing fusion technologies. Instead, citizen participation promises insightful surprises and enriching engagements that would broaden the potential of what fusion energy could look like and how society could relate to this exciting and ground-breaking technology. Through my research, I gained an overwhelmingly optimistic sense that fusion could become a model for a way of doing technological development that is more engaged, integrated and democratic. Participation presents an invaluable opportunity to bring fusion into intimate relation with the public at a time when the technology is of growing importance.
The history of mankind has been always filled with confrontation. What students are taught in History class mostly deals with the evolution of a certain group of people and how they faced other groups of people in order to survive and prevail. After the end of World War II last century, this trend has changed, especially among European countries. During the last years, we have enjoyed the most peaceful period in history. The closer attachments and dependencies developed among countries due to globalisation are partly responsible. And these international connections are the backbone of the fusion initiative.

Alejandro Vázquez Cortés
Nationality: Spanish
Currently working at: Karlsruhe Institut für Technologie (KIT)
@alevazcor
linkedin.com/in/alejandro-vázquez-cortés-b91b03122

I am a PhD student working on the DEMO fuel cycle. I have a degree in Energy Engineering that helped me to realise the advantages of fusion. I come from Spain and since I’ve been living in different cities in different countries I feel like I belong anywhere. Still I try to go back to my hometown as often as possible. I never say no to an evening with beer and tapas with good friends or a spontaneous road-trip.
Just like the promise of a fair civilisation (in the sense of an advanced stage of society) is the great gift of globalisation in terms of social development, the promise of fusion energy is the great gift in terms of scientific development. However, the research required in order to turn this promise into reality takes a lot of manpower, investment and resources. During the second half of the 20th century, many countries tackled this challenge, but only their combined research efforts have led to our current state. No individual entity could have carried out this amount of high quality research by itself, making fusion research part of the glue that leads to globalised development. The fact that the fusion initiative intends to tackle the problem of greenhouse gas emissions coming from baseload power generation further emphasises its worldwide importance. The ultimate goal of fusion research is the improvement of the wellbeing of mankind, which is the most fundamental and important goal of scientific development.

The successful collaboration of scientists coming from numerous cultures, diverse backgrounds and different mindsets pursuing a common goal together serves as a great example for the rest of the world to follow. Of course this is not a perfect partnership! Scientists are human after all. This presents a challenge to the success of any project, and the fusion community is no exception. Nevertheless, science provides the best environment to overcome those obstacles, and it gives us the means to move forward towards a just and inclusive global civilisation.

One example of this is the formation of the ITER project in 1988, which was a result of the USA and USSR’s joint statement for international cooperation in pursuing controlled thermonuclear fusion as a source of energy. Nowadays, the research centres involved in ITER face the challenge of adapting foreign scientists to local working practices and customs. The differences in customs can be seen during the simple act of having lunch. In Mediterranean countries people go for lunch way later than in Northern European countries, so researchers working abroad have to adapt to new local habits in order to thrive. And as a good example of differences in work practices, I think of the subtleness of interactions with Japanese colleagues when working on a project together. By European standards, they are not direct enough when reviewing a project.
The ITER project is, therefore, the best example of what I am trying to tell. It took several years just to figure out where it would be located. Its multiple partnership nature entails this sort of situation, because the importance of the project makes each individual partner wanting to get the best possible outcome from it. Therefore, the expertise given by each part differs from one another, and everybody would like to have it their own way. Despite this, it has become a ground of mutual understanding and work towards a common goal.

Something I have personally experienced is the huge variety in units of pressure currently used by scientists from different countries (e.g. Pascals, milibar or Torr). As a result, it is sometimes challenging to speak to different scientists about pressures ranges. You are more worried about correctly converting the units instead of focusing on the discussion.

In the case of the ITER project, the different parties have conceded much, so that the best joint feasible strategy is adopted. In so doing, the multicultural background of the ITER workforce has become the greatest asset of the project. Having several perspectives for the same problem actually ensures the application of the best-suited solution. ITER will be a success because of, and not in spite of, the differences among the partners.

I have realised that certain common backgrounds really help people to collaborate, concede, and trade shoes with their partners. I’ve experienced first-hand how international educational programmes, such as the FUSION EP Master (of which I am an alumnus) are a very effective tool to get people used to working together. The students come from all over the world and have different backgrounds in physics (scientific discipline) and engineering (technological discipline). A fusion-dedicated Master’s Programme brings all of them together and gives them a shared experience and common ground. At the same time it allows for the exchange of ideas and experiences, and the pursuit of diverse research paths that the fusion field can offer. By the time these students finish their studies, they have acquired an extensive network of young scientists around the globe.

Fusion is therefore more than a scientific pursuit. Its research is becoming a promising example of what international collaboration can achieve. It’s something of which the rest of the world should take note and imitate.
I am an industrial engineer with 20 years of experience in measurements of large volume components for nuclear fusion. Since I moved from a private company to EUROfusion’s Italian Research Unit, I was keen to be part of the fusion family, to build a better future for everyone. Nowadays, with Fusion for Energy and EUROfusion, the start of fusion energy is a fact to me now.”
Italo’s reply is immediate. “Because we can take advantage of the nuclear activity at this site. We can use the neutrons it generates to make tritium and in so doing make a very efficient shield for the outside world.”

“Ok. But why should we care about tritium?”

A worldwide expert in tritium breeding blanket technology, Italo continues, "As you know, a tokamak fusion reactor uses two hydrogen isotopes as fuel: deuterium and tritium. It also uses helium as a refrigerant for its superconductive magnets. Helium reserves are low due to the numerous superconductive magnets being produced and used by the growing number of fusion power plants. And while each tokamak generates tritium, the quantity produced is only enough to cover the reactor’s own needs. To start up a new fusion reactor we therefore need an external tritium source. And nowadays the only source is a particular type of fission reactors, the CANDU reactors, which are being progressively shut down...”

“To be absolutely clear: despite being an isotope of hydrogen, tritium has a half-life of 12.3 years, meaning it is not found in our topsoil.”

“In fusion reactors, tritium and deuterium are fused together producing helium and a spare neutron which has a lot of energy. This neutron is so powerful that if it encounters a lithium atom it will divide it into two lighter atoms: tritium and helium. This encounter is the purpose of the Tritium Breeding Module which surrounds the plasma of a fusion reactor. Afterwards, the two new atoms that are produced in different proportions are filtered and extracted from the lithium-based substance (possibly a lithium-based alloy in liquid form) of the breeding blanket and reused by the fusion reactor itself... It may sound easy but is extremely difficult in practice.”

After Italo completed his explanation, someone from the audience asked, “But isn’t the technology to do so not yet on the market and won’t it cost a fortune to develop and install?”

In response, Italo offered attendees a simpler explanation. “The Breeding Blanket technology is already present today in fusion reactors. It works similarly to the lungs in the human body. Just like the blood cycles through the lungs, exiting them enriched with oxygen, the liquid lithium-based alloy enters the blanket and comes out enriched with tritium and helium, all thanks to the energetic neutrons created by a fusion reaction.”

Noticing people’s excitement and wanting to fuel their fever, Italo added, “In fact right now a drone with special scanning equipment is flying above Chernobyl’s Reactor 4 and Alex the Beef, one of the best metrologists on the market, is going to make a digital reconstruction of the site.”
The conference continued with lots of discussions and brainstorming. In the days that followed, Italo's idea gained a lot of support. Two years later, it went on to receive support at the international level in the form of funding.

... 20 years later ...

Today the Tritium Breeding Sarcophagus (TBS) will be installed. All operations are directed by Mr. Alfred Bigdoor, an experienced and well-known nuclear engineer. The huge half sphere, a jungle of pipes, is ready to be fit onto the site. It resembles a giant ice cream spoon, but instead of scooping up ice cream it will be collecting neutrons.

From a nearby building, hot lead-lithium alloy will be pumped through the TBS like blood through veins. Geiger counters are ready to measure the tritium inside the returning lead-lithium line at the processing station. Additional counters outside the TBS but still within the shield will check if the sarcophagus' shield activity provided is effective.

The radioactive counters located around the site are buzzing like crazy when Alfred gives the sign to start the flow of liquid lithium inside the TBS. Minutes later these external counters stop their buzzing pitch and begin giving off single beeps, a sign that the radiation level is now at normal levels. The shielding function of the TBS is a success!!

Meanwhile, the Geiger counters inside the filtration area start to buzz without pause. It's a clear sign that tritium storage has begun.

“It works! It works!” screams Alfred. Emotions are running high. “Has the helium and tritium filtration begun?” he asks his main collaborator.

“Yes, we have started accumulating helium and tritium,” comes the answer.

“Bravo, well done!!”

Alfred calls Italo to share the results. What once was a threat to both the environment and mankind has now become a source of fuel for fusion power plants. After a month of irradiation and filtration, enough tritium is collected to meet the needs for a brand new fusion reactor in the UK.

It’s a happy turn of events. In the end, even the devil is an angel!
USING STORYTELLING TO TEACH FUSION IN THE CLASSROOM

How do we teach ten-year-old students a complex topic like fusion? Being a teacher for 23 years, I like to take on new challenges and tasks that appear impossible to other teachers.

Patrícia Raposo-Weinberger
Nationality: Portuguese
Currently working at: Graz International Bilingual School, Austria

“ I am an experienced Physics and Chemistry teacher with a master in sciences. Passionate enthusiast about my work, active developer of educational projects (STEM) and interdisciplinary projects with a strong cooperation with industries and universities.”
To spark the enthusiasm of students and build the new generation of scientists, we have to start at a very young age. I advocate that physics can be taught to students at any school age (even Kindergarten) and I try to make that a reality in my lessons.

There are many strategies that a teacher can use. For me, the best approaches are performing experiments and storytelling. Both strategies are quite powerful tools to hook the students’ interest in physics and science in general. Experiments offer a more hands-on approach to complex scientific topics, whereas storytelling attracts the students when the narrative is challenging, creative and relates to their daily life.

We started our physics lessons at the start of the school year: a new subject for almost all students and in a new language (English). Teaching in an international school and having students with a multicultural background is a complex challenge: how do we accommodate the previous knowledge from our international students? And how do we address complex topics like fusion?

"I have not failed. I've just found 10,000 ways that won't work."

Thomas Edison

Storytelling is an powerful tool. When we talk about famous physicists, I start with the example of Madame Curie. First, because she won two Nobel prizes in areas students perceive as difficult and male-dominated. Second, because hers is a wonderful example of perseverance, hard work and dealing with failure. A difficult and important lesson for the students is that being a scientist is to fail one hundred times to succeed once. Like Thomas Edison wonderfully stated about his work with the light bulb: One strategy is to have the students assume the role of storytellers and discover more about scientists like Faraday, Ampere or Tesla in the process. This strategy of humanising science makes the student understand that all of us have the possibility to be the next Volta or Joule if we put in the hard work and constantly develop our knowledge. It also teaches the importance of team work in science, to think critically and to always ask why. These social skills are relevant to all areas, not only physics.

Thanks to storytelling, I have students who now know that the Celsius scale was not invented by someone named Celsius, that Fahrenheit “improved” the temperature scale proposed by Römer, and that Faraday had no formal education but became one the most important scientists in the field of electromagnetism.

Personal stories also have an important role when it comes to learning physics. Sharing them in the classroom is an important tool for introducing new concepts and definitions using daily life situations and examples. Storytelling builds a bridge between facts and understanding, and it debunks difficult concepts and definitions in physics. Last year we participated in the European Space Talks (ESA) and we discussed future missions to Mars with Member of the Board of the Austrian
Space Forum Mr. Willibald Stumptner, and analog astronaut (a person who conducts activities in simulated space conditions) Mr. João Lousada. The students found their personal stories about the troubles of trying spacesuits in a desert mission and the personal struggles of becoming an analog astronaut to be the most interesting ones.

Bringing the scientist to the classroom and listening to their stories is another powerful tool for building scientific knowledge. Do the students remember all the scientific concepts discussed during the workshop? Obviously not. But a foundation was built during the workshop and it is the role of the teacher to use this momentum to develop the students’ interest in science.

Space exploration and future energy sources are excellent approaches to tackle the topic of fusion in the classroom. It starts with a picture of our Sun and, of course, the famous picture of the black hole, along with the story behind this image and the cooperative and astonishing work to make it a reality. These two pictures are the beginning and the end of an astonishing cosmic journey: the life cycle of a star. Nebula, supernova and black hole images have a powerful role in this story. Concepts of energy, temperature, heat and energy transfer are presented and discussed. Even Japanese anime character Dragon Ball’s son Goku can be referenced to introduce and explain the concept of fusion. Finally, astronomy and space exploration are exciting and current topics that engage students in creative visual storytelling for science.

Storytelling can be used to introduce a topic, to illustrate a law or a theory, and to attract less-motivated students. Never underestimate the power of a good, simple and enthusiastic story and its effect in students’ interest for physics. Starring Newton’s Apple or introducing Lord Kelvin’s crazy experiments, this physics story is definitely to be continued...
AN ALUMNI PERSPECTIVE
ON THE CHALLENGE OF FUSION EDUCATION

FUSION-EP is so much more than just the graduation certificate from eight universities. Picture: edited by Tobias Jesche based on a photo by Brett Andrei Martin on Unsplash

Developing fusion as an energy source has been compared to the construction of a cathedral. It takes generations, and each milestone builds upon decades of ideas, mistakes and dead ends. Today, the physics of fusion machines must be passed on to the up-and-coming scientists who will exploit ITER. At a later stage, a new generation of engineers will use the knowledge gained from ITER to plug in the first DEMO pilot plants. The fantastic complexity of fusion devices necessitates collaboration among experts from different communities, each with their own backgrounds and perspectives. Rising to the challenge of commercialising fusion energy will demand goal-driven leaders with multidisciplinary training, sharp communication skills and keen cultural sensitivity.
An adequate curriculum should attract students with a talent for experiments as well as those gifted with computer modelling abilities or an instinct for theory. Let them upgrade the control system of a probe on a small stellarator or turn the MHD (magnetohydrodynamics) equations inside out. They will pour their heart into it and might even remember their lessons after the exam! Combined training and teaching activities organised among university partners, associated research centres and the industry can offer such opportunities and a variety of hard skills up for grabs. However, facing too many options, fusioneers often struggle to make informed career choices. At the crossroad of research areas, a solid knowledge basis is needed to connect the dots. To this day asking graduates how they selected a thesis usually leads to the answer: “I don’t know. It seemed fun.”

Enthusiasm is essential but not sufficient. Newcomers need explanations, discussions and feedback to form their own concepts. However, the courage to share their thoughts with senior colleagues, or even peers, does not come naturally to everyone and is continuously eroded by instant messaging and social media. Proper training in the preparation and oral defence of their work before small expert groups or large audiences is thus crucial and goes beyond reading and writing: concluding the Q&A of a presentation on magnetic dynamos, a teacher once asked me what could cause the Earth’s magnetic field to change polarity. Embarrassed, I offered a guess but confessed my ignorance. “This is the right answer,” he said with a smile, “no one really knows”.

In an international team where people collaborate on distant pieces of the same puzzle, communication can be tricky. The ITER project is a perfect example. Consider a Japanese software engineer politely telling a German physicist that their work needs improvement. The German might understand indirect criticism as a compliment! And while English is the starting point, notions of other languages and cultural references can greatly improve mutual understanding. No book, classroom or internship can replace life-experiences such as collectively suffering over school assignments or the taste of success upon completing a joint training exercise. Everyday activities like cooking, watching movies or visiting a classmate’s hometown also help us to grow out of our comfort zones, and to cultivate trust and empathy.

But intercultural communication is never easy, especially at first. How does a European woman react when her Middle Eastern male colleague refuses a handshake? How does the latter feel among classmates sharing intimate stories over a bottle of wine? These seemingly innocent questions represent major concerns in the day-to-day management of large fusion laboratories.

The complexity of fusion research presents a considerable challenge in terms of knowledge transfer to the ITER Generation of physicists and future DEMO engineers. The lessons learned over half a century of fusion research are not only scientific and technological. Mutual trust and creativity in dealing with the shifting sands of international projects are just as important. Educating the next generation of fusion scientists and engineers therefore needs a high-level research-driven curriculum with a well-integrated language and cultural experience.
The European Master in Nuclear Fusion and Engineering Physics (Fusion-EP) started in 2006, after the decision to build ITER in Europe. Fusion-EP is based on existing EU research on education networks. The core partners are from Belgium, Czech Republic, France, Germany, and Spain. Besides the ITER International Organization, there are several academic and research associate partners from the EU and abroad. As of 2019, two hundred alumni form the global network of Fusion-EP (31% Europe, 69% international). Three out of four graduates pursue doctoral studies in the field of fusion science and engineering. They provide a solid foundation of researchers and leaders for the further development of fusion. Moreover, these graduates know each other and have a sense of belonging to a group that has been provided a unique opportunity. Many of them, in return, make it a point of honour to provide similar opportunities to younger students.

**Fusion-EP in a nutshell:**
- A two-year International Graduate Programme in Fusion Science and Engineering.
- A well-integrated language and cultural experience in Europe and abroad.
- Hands-on training at the WEST, COMPASS and GOLEM tokamaks.
- A global network of scientists and engineers trained for ITER, DEMO and beyond.

More information at www.em-master-fusion.org
Alexis Devitre
Country: Canada
Status: PhD: Nuclear Aging of REBCO Superconductors, UGent (BE) based at MIT (US)

Fusion could be a role model for globalised educational standards.

Robin Somers
Country: Belgium
Current status: Management Traineeship, Proximus (BE)

Did you know hello in Spanish is Hola and not Ola? They don’t pronounce the h!

Veronika Klevarová
Country: Czech Republic
Status: PhD: Disruption Studies, UGhent & LMU (BE&DE) based at IPP Garching (DE)

Fusion is the 42 of the energy sector and coffee is the ultimate 42 to those engaged in the fusion research.

Francis Albert
Country: India
Status: MSc: Turbulence during ELM suppression by Magnetic Perturbations using the GENE code, IPP Garching (DE)

Splendid time to solve a challenge together.

Johannes Lips
Country: Belgium
Status: MSc: Antenna Design for Multi-reflectometry Diagnostics, Université de Lorraine (FR)

Don’t forget the planet.

Contact us!
AskUsAlumni@gmail.com

Vote for Alexis & the Fusion-EP Team’s article here:
www.euro-fusion.org/vote
Antonio Magnanimo
Nationality: Italian
Currently working at: Max Planck Institute for Plasma Physics (Max-Planck-Institut für Plasmaphysik, IPP) in Garching near Munich, Germany

“Since when I was a master’s student I have always been interested in nuclear fusion technology. Actually I am a PhD candidate at Max-Planck-Institute for Plasma Physics, where Germany’s biggest nuclear fusion experimental reactor is located. Despite the fact that fusion energy could significantly contribute to the health of our planet, this technology is still unknown by most people. That’s the reason why I decided to give my contribution in promoting fusion in ‘Fusion in Europe’ magazine. As an electrical engineer, I am involved in the power supply design for fusion devices and in this article I explain the main challenges of providing the electrical power required by these huge machines.”

Nuclear fusion is the process the powers the sun and the stars, making life on Earth possible. One of the hardest scientific challenges of the 21st century is achieving such a reaction on our planet to use the heat it produces for electrical energy production.
The most promising kind of fusion reactor is called a “Toka ma k”. It consists of a toroidal-shaped vacuum chamber able to create and contain plasma — the fourth state of matter — at 100 million degrees or more. In order for fusion to occur, the plasma must be kept at these temperatures for sufficient time. Once two particles fuse, the challenge is to harvest the released energy without losing control of the plasma. The plasma is said to ‘ignite’ when it generates enough heat on its own via fusion that it becomes self-sustaining and additional heating systems are no longer required.

As you can imagine, no existing materials can resist such high temperatures. So we must use other ways to “hold” the plasma. One method is to use very strong magnetic fields to stop the plasma from touching the so called ‘first wall’ (or inside wall) of the reactor. Superconducting coils surrounding the toroidal chamber induce strong magnetic fields that shape the plasma. Furthermore, in tokamak machines the plasma current (circular flow) is induced using a transformer that must be charged before an experiment and rapidly discharged during operation.

This sounds great, but how is it possible to provide the great amount of power needed to such a complex system?

I am actually working at the ASDEX Upgrade tokamak — Germany’s biggest tokamak. This machine is operated at the Max Planck Institute for Plasma Physics (IPP) in Garching where three flywheel generators are charged up before the start of a fusion experiment. A flywheel generator is composed by a motor, a big rotating mass (flywheel) and a generator: the motor is connected to the public grid and — taking power from there (up to 15 megawatts) for several minutes — it converts electricity into kinetic energy by accelerating the rotation of the heavy flywheel up to about 1,600 revolutions per minute. The flywheels essentially provide the 450 megawatts power needed to power a fusion experiment, using only the available 15 megawatts of the public grid. Just to give you an idea, this amount of power is equivalent to half of the average power consumption of the entire Munich area.
The oldest — and biggest — flywheel generator (Fig.1) has been in operation since 1973. There are no companies able to produce flywheel generators of this size anymore. This is why it is so important to look into the up-and-coming ultracapacitor technology, with its very high power density, which could be a possible future solution for tokamak coils’ immense power requirements.

ULTRACAPACITOR TECHNOLOGY FOR FUSION REACTORS

Ultracapacitors (a.k.a. Supercapacitors) have been around since the 1960s. They have attracted a lot of attention recently due to their growing use in electric vehicles. Ultracapacitors not only store relatively large amounts of energy but release this energy very rapidly when needed — their primary advantage. Fundamentally, an ultracapacitor consists of two conducting electrodes separated by an electrolyte (usually water), in which a porous separator is soaked. Because the ions that form in the electrolyte fluid can move freely through the separator, they move to the oppositely charged electrode (see Fig.2), forming two Helmholtz double layers. Here’s where it gets even more interesting: the surface of each electrode is not smooth but is padded with activated (porous) carbon. This results in a surface area about 100,000 times larger than an ordinary capacitor.

Two features are the most relevant for fusion devices:
- Power Density: about 10 kilowatts/kilogramme (more than 10 times higher than Lithium-ion batteries)
- Lifetime: about 1 million cycles against the average 1,000 to 10,000 cycles of Lithium-ion batteries.

Now the question becomes: can ultracapacitors power a tokamak’s coils?

For the charging process, due to their very high power density, ultracapacitors cannot just connect to the grid because they require a customised converter to limit the charging current to the desired value. One solution consists in using a ‘boost-converter’ that provides an output voltage greater than its input voltage and limits — through an inductance — the current’s variation.

For a standard ASDEX Upgrade experiment lasting 10 seconds, the TF coils require about 1,400 Switching Modules which is about 60 tons of ultracapacitor modules. This sounds like a lot, but it is much, much less than the 220 tons of the actual flywheel used for powering such coils.

The modular structure makes it easily possible to replace any one of the Switching Modules with a new one, making this MMC-based topology much more reliable and lower-risk than having a single, big flywheel generator.

But no one has ever used this many ultracapacitors all at once before. Hence the purpose of my ultracapacitor PhD project is to realise a small scale prototype of this power supply to demonstrate its validity as a possible replacement of one of the huge flywheel generators of ASDEX Upgrade; such prototype will in-
deed require a very specific power electronics topology that can scale to (almost) any size in future, including future fusion power plants.

This is the first time that anyone tries to bring such a powerful ultracapacitors-based power supply to the fusion field: only small projects have been attempted in the past. Should its feasibility be successfully demonstrated, it could contribute to future fusion power plants possible even starting with DEMO, which will dwarf the ASDEX Upgrade tokamak. Through my work with ultracapacitors, I hope to help bring the fusion dream one step closer to reality.

Fig. 2: Ultracapacitors’ inner structure
Jack Davies Hare
Nationality: British
Currently working at: Max Planck Institute for Plasma Physics, Garching
twitter.com/JackHare16

“ I'm a postdoctoral researcher, working on diagnostics for ITER, the world's next step on the path to a working fusion power plant. I'm passionate about the role of fusion in a post-carbon economy, and it's exciting to be part of a large international project trying to make this a reality.”
How do you build something that can survive for twenty years in the harshest conditions ever created on Earth, with no chance of replacement or repair, and with no test facility to replicate this environment? Welcome to the challenge faced by the designers for ITER, an international effort to create a proof-of-principle nuclear fusion reactor, currently under construction in the south of France. When ITER starts full power operations in 2035, the conditions inside this donut-shaped vacuum chamber will be the most extreme on Earth, with huge magnetic fields, temperatures of hundreds of millions of degrees Celsius, beams of particles close to the speed of light, a bath of intense electromagnetic radiation, and thermonuclear, atom-fusing reactions.
How can we peek inside such a maelstrom and try to understand what is happening? This is where our diagnostics, the senses of the machine, come in. In ITER there will be 50 to 60 diagnostics in many shapes and sizes: from tiny conical probes, to high speed cameras to capture the writhing plasma motion, up to large, powerful lasers to measure the temperature of the plasma.

But in ITER, we don’t simply want to know what the plasma is doing, we also need to use that information to control and stabilise the plasma so that we can sustain the fusion reaction. This is handled by CODAC, the ITER Control, Data Access and Communication system, which considers the vast amount of information coming from the diagnostics, and makes split second decisions on how to control the plasma to keep it stable and how to protect the ITER tokamak device from plasma disruptions which can damage the machine. This places a heavy burden on the reliability and accuracy of the data provided by the diagnostics, made more challenging by the harsh conditions inside ITER which the diagnostics must withstand.

As part of a team at the Max Planck Institute for Plasma Physics in Garching near Munich, I work on the bolometry diagnostic for ITER, a simple diagnostic that’s a bit like a tiny solar panel. Hot plasmas emit light — think about the glow of a red hot poker — and this light cools the plasma down. If the plasma cools too much, the fusion reaction will either not occur or stop. At its most basic, a bolometer is just a tiny thin strip of metal exposed to light from the plasma — the metal absorbs the light, and heats up. This changes the resistance of the metal strip, which we can measure, and from that small change we can work out how much light the plasma emits. There will be over 500 of these detectors surrounding the ITER plasma, so we can build up a picture of where plasma is brightest. CODAC can then use this picture to control the plasma stability and keep ITER running.

Bolometer sensors being loaded into IBOVAC, the ITER Bolometry Vacuum test stand. This vacuum oven heats the sensors to around 450 °C, so we can test and calibrate them in ITER-relevant conditions. Picture: Jack Hare.
A bolometer sensor, with a euro coin for scale. The eight absorbers are arranged in pairs — one of each pair absorbs light from the plasma, and the other one is shielded from the light. By measuring the difference in temperature between these two absorbers, we can determine how bright the plasma is. Picture: Jack Hare.

In order to get enough light onto our bolometers, we have to place them very close to the plasma — some will be peeking out between gaps between the blanket modules, which make up the first solid surface inside the machine that are exposed to the hot plasma. This exposes the bolometers to some of the harshest environments in ITER, but also makes them very difficult to replace. Once ITER reaches full power operation in 2035 and begins to burn deuterium-tritium fuel, it will no longer be possible for humans to enter the vacuum vessel. Any maintenance will have to be done remotely by robots, which makes repairing or replacing components very difficult.

As the information from the bolometers is a key part of the control and safety of ITER, they must continue to function throughout the twenty years of expected operation, whilst sitting in a uniquely hostile environment, bathed in ultra-fast subatomic particles and mind-bogglingly high temperatures. This is difficult to guarantee — there is no environment that can adequately reproduce the conditions in ITER, and so we must test individual aspects of our diagnostic and build in redundancy to guard against failure of some of the bolometers.
For example, one aspect of the ITER environment is the neutrons. These subatomic particles have no electrical charge, so they can escape the strong magnetic fields which confine the rest of the plasma. Travelling at a reasonable fraction of the speed of light, they act like a bowling ball, colliding with the atoms in solid materials and rearranging them, leaving voids and weakening the impacted material. Even when hidden behind the blanket modules, our bolometers will be constantly bombarded by neutrons, which will cause them to weaken and fatigue. Even worse, neutrons can transmute elements — one traditional material used in bolometers is thin gold resistors, which can be turned into mercury by the neutrons. As mercury is a liquid, this is bad news — our bolometer could literally melt and drip away!

We can attempt to mimic the neutron damage expected in ITER using a nuclear fission reactor. We can place a sample inside a fission reactor and expose it to the neutrons there, and then study the damage.
Cooperation. Fitting everything inside ITER is a bit like doing a jigsaw puzzle — from inside the box! Space is limited and extremely valuable, with many diagnostics laid on top of each other. For example, we have to design a tunnel under our bolometers to allow passage for the large loops of wire used to measure the magnetic fields inside the plasma. This means close cooperation with the magnetics team - we have to get this exactly right, or ITER won’t fit together!

Although the conditions are not the same as in ITER, we can try to scale up the damage to understand how likely a given material is to survive. One possible solution is to use platinum instead of gold, which should be more resilient to the neutrons.

As well as these nuclear fission tests, we subject our bolometers to high temperatures under vacuum, compress and stress them to mimic the forces expected during ITER operation, blast them with electromagnetic noise to see how the accuracy of the signal is affected, and spray them with jets of steam to mimic the rupturing of water coolant pipes. These tests feed into our constantly evolving design.

Working on diagnostics for ITER is challenging, with a bewildering array of requirements to fulfil and tight deadlines to meet, set by the ever accelerating pace of construction. In the end, ITER is an experiment. We can do everything we can to try and predict how it will behave, but undoubtedly there will be some surprises! By careful design and prototyping, we make our diagnostic as reliable as possible. But the true test will come inside ITER. Here our bolometer will sit for twenty years while being baked, squeezed and bombarded with neutrons, steadily delivering the data to control and stabilise the plasma within the machine which is the next step on the path to a fusion power plant. It’s exciting to be able to play a small but essential part in such a huge project.
In 2014, Assystem’s engineers in Sunderland, UK, were tasked with developing the world’s largest remote handling system for the ITER fusion project in southern France. The brief was to develop a piece of equipment which had never before existed. Our engineering team knew that this was a frontier that could not be crossed alone; a unique project of this scale and importance would require collaboration and diverse thought from all over the world.

“...As Senior Mechanical Engineer at Assystem’s Sunderland site I led the development of the manipulator arms for the Divertor Remote Handling System at ITER. My article considers how important it was to assemble a diverse team of the best minds in the world in order to successfully create a piece of equipment which never before existed, and which will help ensure fusion becomes a reality.”

Fanny Fouin
Nationality: French
Currently working at: Senior Mechanical Engineer, Assystem (Sunderland); Chair, Nuclear Institute’s North East branch

@twitter.com/fannyfouin
www.linkedin.com/in/fanny-fouin-1b117387
The Divertor Remote Handling System (DRHS) is an essential tool for maintaining the ITER reactor. As the largest fusion prototype ever developed, it is a harsh radiated environment requiring regular maintenance. The only safe way of entering the reactor after it has begun deuterium-tritium operations in 2035 is with a robot.

The challenge for the project team, therefore, was to create a tool that could securely enter the reactor to remove and replace parts on regular basis through its lifetime. The solution would have to be both agile and robust. Without doubt, this was a mammoth undertaking. But it was also an opportunity to work at the cutting-edge of nuclear technology – and who doesn’t want to build a giant robot?!

Assystem set about building a diverse team, not only of individuals, but also with international partners (SMD, Wälischmiller, Axon Cables, RACE, VTT and TUNI) who could contribute a wide range of expertise, and experience across disciplines, geographies, cultures and genders. The result was a core project team of experts from more than five countries, including Spain, France, Italy, Finland, Germany and the UK.

Uniting the team was a shared commitment to a single vision: fusion as a revolutionary source of energy generation. Successful production of large-scale fusion has been elusive for decades, but at ITER this is likely to happen within our lifetimes. The DRHS forms a crucial part of this larger ambition, and the knowledge of its impact was the most significant element in driving towards success and inspiring collaboration.
Creating equipment this complex was no mean feat and required innovative thinking to solve challenging problems. While technical approaches were broadly consistent, there were differences in ways of working and processes which had to be accommodated by all participants on the project. The UK team, for example, learned that their approach was heavily process-led and were encouraged to work more flexibly by adopting alternative and more efficient approaches employed by their project colleagues which may not have otherwise been considered.

From the outset of the project, communication was the key priority. The team regularly worked together over Skype and also scheduled face-to-face meetings once a month, hosted on rotation by the different organisations and stakeholders involved in the DRHS. This gave the team a vital chance to build a rapport, learn about each other’s skillsets, and cultivate a working environment where ideas could be openly discussed and critiqued even when working remotely.

By bringing together a diverse pool of talent, we were able to build this ground-breaking machinery: two large movers which can carry approximately 10 tonne components. The DRHS will enter the reactor vessel during maintenance shutdown periods to remove, repair and replace the 54 Divertor Cassettes (large load-bearing steel structures, approximately 3 metres by 2.3 metres by 0.8 metres each) which are located at the bottom of the Tokamak (device which uses a powerful magnetic field to confine hot plasma in the shape of a torus.)

The movers can operate in small spaces and are equipped with manipulator arms which precisely lock and unlock the cassettes and cut and weld pipes. The range and variety of what this machinery can do is unprecedented in the industry and will set the standard for the future of fusion.
Working remotely and with multiple nationalities also quickly showed up the importance of articulating ideas clearly and precisely. No more relying on implied details! While this meant it sometimes took more time to deliver a piece of work, it also had the effect of raising the quality and ultimately worked to the strength of the project — and taught us all a lesson about patience!

The DRHS is the type of project that only comes along once in a while, but it highlights the advantages to be gained from embracing diversity. Large-scale collaboration certainly presents challenges, but it is also a rewarding and fulfilling opportunity to absorb new ideas, learn from peers and listen to new perspectives. Getting to work on first-of-its-kind technology such as the DRHS as well is the icing on the cake.

Correction: In Dan Clery’s article ‘Outside Insights: Alternative Fusion’ last issue, in the print edition we incorrectly referred to the fusion triple product as “aka Lawson criteria” in the chart description on page 19. This is incorrect. The Lawson Criterion assumes that the alpha particles leave the plasma whereas the fusion triple product criterion correctly takes into account that they are retained and can heat the plasma to ignition.
José Vicente
Nationality: Portuguese
Currently working at: Instituto Superior Técnico, Universidade de Lisboa, Instituto de Plasmas e Fusão Nuclear

“I am a research physicist interested in turbulence phenomena at the periphery of fusion plasmas. My research aims at understanding turbulence measurements using both numerical simulations and experimental data. I am also interested in science policy and societal impact of science and technology as I believe that fusion is a two-way street between scientific and societal challenges.”

It’s Friday evening. A reception at the United Nations brings world leaders together mingling over drinks and traveling plates of hors d’oeuvres. Business would have been conducted as usual if it weren’t for the Arctic wildfires, devastating storms and killer floods spreading in conversations around the room — terrifying climate change scenarios ignited by children protesting outside, demanding for real action from their governments and international policy-makers.
While climate agreements have been made in the past, without changing the energy system based on fossil fuels, warning limits will surely be surpassed and agreements will be broken as energy consumption keeps rising to feed the appetite of an ever-developing world. Children, becoming increasingly educated, will remain rightfully loud as they build their own life expectations.

When the problem is brought to the table and served, well-known solutions established in previously catered events emerge across the room: “reductions on the use of fossil fuels”; “strict carbon emission limits”; “available clean energy sources”. With this sort of buzz in the background, together with the clinking glasses, another voice might be overheard announcing, “Nuclear fusion”.

This is the moment when we from the nuclear fusion research community stand out from the crowd, slightly embarrassed, thinking not of the fusion promise but rather of the challenges still ahead to finally deliver fusion electricity. We are driven to crack the unsolved puzzle handed to us by fusion forefathers Igor Tamm, Andrei Sakharov and the others that followed. Our drive might be the promise for a sustainable energy source, but our focus is on a given specific problem that we individually have to solve.

On the other hand, fusion technology’s contribution to a future global energy supply system is due to meet other barriers. Not just those overcome in laboratories and experimental devices. How significantly can fusion contribute to base load electricity generation once it is part of a given energy mix? The answer may depend largely on the investment cost and opportunity cost at the time of deployment and throughout its operational lifetime. But it will also depend on factors like the existence of strict carbon emission limits (assuming that the depletion of natural resources has not yet had any effects) which could contribute to a stronger market penetration of the technology.

Simply put, an outspoken world with a strong sense of environmental responsibility will support the development and widespread use of fusion electricity. Put down your cutlery and champagne flutes, stop and listen, as one of the biggest challenges fusion faces is being taken on just outside by our own children.

Vote for José’s article here:
www.euro-fusion.org/vote
One of the main challenges facing fusion today is keeping a high-temperature, high-density plasma in the middle of a vacuum chamber and holding it there even as it reaches temperatures that are ten times hotter than in the core of the sun. This may sound impossible. But to me, it’s what I want to help the fusion community solve.
MAGNETIC CONFINEMENT

Figure 1 shows a cross-section of a plasma-filled tokamak with a divertor (the two grey bars) at the bottom. Called a “magnetic field configuration” it is basically the same for any tokamak.

The dotted lines represent magnetic flux surfaces. Although only eight are shown in this picture, in reality there is an infinite number of these magnetic layers sitting within each other (we often use the term “nested”) just like layers in an onion. Since the plasma consists of charged particles, we can control it with these magnetic fields. The particles can move rapidly along one magnetic flux surface (layer), but only very slowly from one layer to another — in other words, they are magnetically confined.

The confined region of the plasma is where the magnetic flux surfaces are “closed” like a ring. Further out are the “open” layers that touch the divertor. We call this region the scrape-off layer. The last closed magnetic flux surface, called the separatrix (the purple line in Figure 1), separates the confined region of the plasma from the scrape-off layer.

The area that interests me is the general region surrounding the separatrix. We call it the plasma edge region (the blue region, purple line and part of the lilac region shown in Figure 1).

THE IMPORTANCE OF THE PLASMA EDGE

With a size of only a few centimetres, in contrast to a total plasma radius of 2 metres in the ITER tokamak, the plasma edge region is very small compared to the overall plasma size — like an eggshell compared to the egg. Despite the fact that the desired fusion reactions do not occur in this region, this area plays a key role in realising fusion on earth, because the processes that do occur within it are of major importance for 1) the overall behaviour of the plasma and 2) the power exhaust process.

Reaching these high temperatures is not the problem. With the push of a button, a fusion reactor can heat a plasma up to 150 million degrees Celsius in temperature in less than one second. The problem is figuring out how to efficiently control this high-energy plasma to keep it from touching the walls of the tokamak except for the divertor, which is used as the exhaust point of the reactor.
For ITER the foreseen heating power is 50 mega-watts — the power equivalent of 500 car engines or 25,000 hair dryers. Moreover the desired goal for ITER is to use this 50 megawatts heating power to generate 500 megawatts of power released by the resulting fusion, which corresponds to a power amplification factor of \( Q = 10 \).

Because we do not want the machine to continuously heat up, the challenge becomes removing the 550 megawatts (50 megawatts heating plus 500 megawatts fusion power) from the tokamak chamber. This means: What goes in has to go out.

But how can we remove power from a nuclear fusion device?

80% of the fusion power (400 megawatts) is carried by the fusion neutrons. As they are electrically neutral, they do not interact with the magnetic field cage and are therefore distributed evenly over all wall components. The same holds true for the generated photons (light emitted by the plasma), which carry a total power of 40 megawatts to the wall. These two parts are not the problem. Heat exchangers placed behind the first wall use them to generate electrical power.

The first important role of the plasma edge region is to set the boundary for the hot core plasma in the confined region (the yellow, orange, red and pink regions as Figure 1). It surrounds the burning plasma and acts like a shield between it and the reactor walls.

In the plasma edge region, the gradients (changes in a given direction) of temperature and density are very steep — i.e. the properties change fast over the radius. The combination of the width of this layer and its gradient defines the boundary to the plasma core. We have found that the higher the core boundary temperature is, the better the conditions will be for fusion to occur in the plasma core.

Think of the plasma edge region as the insulated outer walls of a heated house. With no insulation and open windows, the heat flows right through the walls. In this case, the temperature gradients in the outer wall region are low. If we close the windows and insulate the walls, the temperature in the wall region — from just inside the house to just outside the house — changes from high to low over a very short distance. The temperature gradient is now steep. So we can say that the higher the temperature difference at constant heating, the more efficient the thermal insulation of the house.

Back in a tokamak, the insulating properties of the plasma edge region can be explained by transport barriers which can build up just inside the separatrix in the confined region. The better this barrier, the higher the temperature difference and thus the higher temperature and density will be at the plasma core — which makes it more likely that fusion will occur successfully.

The second role of the plasma edge region is to moderate the power distribution in the scrape-off layer and the divertor heat loads. This is still a key nuclear fusion research challenge because the amount of power we are talking about is enormous!

The steady-state operation of a nuclear fusion device is the ultimate goal for an efficient fusion power plant. That means keeping plasma parameters like temperature and density, as well as the fusion power produced, constant over time. To sustain and control the fusion process, continuous external heating is necessary.
The challenge is handling the remaining 110 megawatts of power carried by charged particles that slowly move from the hot core to the relatively-cooler plasma edge. Physicists call this process diffusion. Once the particles cross the separatrix and reach the scrape-off layer, they are transported to the divertor. Due to diffusion, some charged particles reach more outward layers before the divertor. The speed of this diffusive outward motion influences the width of the blue area in Figure 1, which is a belt roughly three centimetres wide surrounding the divertor. If all the power in the scrape-off layer was deposited in this tiny region, we would end up with a power density (amount of power per area) of 100 megawatts/square metre. No material can withstand these power loads, as it is higher than if we placed the material directly on the surface of the sun!

This means we have to minimise these power loads somehow. To manage this, we combine two strategies. First we must get rid of some of the power in the scrape-off layer by additional radiation (plasma has to emit additional light, which is...
again homogeneously (equally) distributed over all the machine components. Second we must increase the area in the divertor reached by the particles.

Heat-carrying filaments, which occur in plasma, can help us do this. Filaments are structures several metres in length, which stretch along the field lines. In the cross-section, they appear as a small dot of only a few millimetres in diameter. Comparable to flares in the sun [see Figure 3], they can carry temperature and density radially outwards, speeding up the slower diffusive outward transport of heated plasma particles. In contrast to diffusion, where heat is transferred between particles, heat transported by the filaments is due to the movement of the particles themselves. We call this process “convection”. It is the same physical principal as when you use your convection oven, which uses a fan to move the hot air particles around.

To be able to control these filaments through plasma shaping, fuelling and heating, we need good experimental access to the underlying physics. In other words: we need to conduct experiments to better understand the physics of these filaments and how we can control or at least influence them.

**DIAGNOSTIC ACCESS**

The filaments are turbulence-driven and can move radially outwards with velocities of several kilometres per second. Diagnostic instruments that measure parameters like the temperature and density of plasmas therefore have to deliver a sufficient temporal and spatial resolution (be very quick and able to record all points in the diagnosed area).

In fact, they record one million frames per second to catch these filaments! This is so fast that watching two seconds of a recorded plasma discharge at the standard television framerate of 24 frames per second would take around 22.5 hours — the same as watching all the Star Wars movies back-to-back. This would take too long, so we use atomised and statistic-based analysis tools to catch the occurrence of filaments.

Someday, we hope that these powerful diagnostics, combined with enhanced theoretical models and improvements in materials, will help us control even the hottest of plasmas and harvest the heat energy created by fusion reactions in future devices like ITER and DEMO.

Controlled fusion for electricity production was promised by scientists a long time ago. But now I can see how all the parts are coming together and how the remaining problems are being identified and addressed one after another. I find it so interesting and rewarding to get to work on solving one of the pieces needed to realise the promise and make fusion happen within my generation — the ITER generation.

![Figure 3: Measured plasma filaments at the edge of ASDEX Upgrade (1µs = 1 micro second)](image)

*The purple line is the separatrix.*
EXPLORING EDGE ERUPTIONS WITH PLASMA SIMULATIONS

I have just finished my PhD with the University of York as part of the Fusion CDT. During my PhD I was based at Culham Centre for Fusion Energy (CCFE), one of the world’s leading fusion research laboratories, where the new MAST-U Super-X tokamak is based. My PhD focused on numerical simulations of instabilities, called edge localised modes, for MAST-U Super-X tokamak plasmas. I remember first reading about fusion and ITER in a science/physics magazine. My interest in fusion grew in my undergraduate degree, where I became passionate about working towards making fusion an energy source for the future.

One of the biggest challenges facing fusion researchers is handling large plasma instabilities, which can cause excessive erosion of tokamak materials. This must be solved before we build commercial fusion power plants, as constantly shutting down to replace damaged components would be very inefficient.

One of the plasma instabilities in a tokamak is called an edge localised mode or ELM for short. A lot of research is currently being done on ELMs. They appear as large filamentary structures of plasma where the filaments violently erupt at the edge of the main plasma. This eruption often leads to hot plasma touching, and thus damaging, the material surfaces inside the tokamak chamber. We know that filamentary structures appear during ELM instabilities because we are able to observe them in fusion experiments using diagnostics. One such diagnostic is the fast camera diagnostic. The fast camera creates images of visible spectrum light emitted during a plasma discharge. It can capture images of the ELM filaments, and the data gathered can be used to analyse the filamentary structures and dynamics.
The challenge is to understand these ELM instabilities and develop a solution to mitigate or completely suppress them. Fusion physicists are attempting to understand these instabilities through experiments, theory and numerical simulations. My work concentrates on the latter, where I run numerical simulations that test existing plasma models. Numerical simulations show which models best describe ELMs, which increases our understanding of plasma physics. Numerical simulations can also be used to make predictions for future tokamaks, most notably ITER.

In particular, I’m researching and trying to understand if altering the geometry of a tokamak exhaust system can significantly reduce the hot plasma and resulting heat loads reaching the surface materials. The new exhaust geometry upon which my research is based, is called the “Super-X”. It will be tested on the MAST-U tokamak, which is based at CCFE in the UK and is scheduled to start operation in the near future. If successful, this could make ELMs less of a concern, directly benefitting future fusion devices.

Another challenge occurs when attempting to simulate ELM instabilities. Some of the simulations I perform take up to three million core hours. To put this into perspective, an average laptop has two to four cores, so it would take roughly 85 years to run one of these simulations on your laptop. Luckily, we run the simulations on supercomputers, but even so it takes a few months to complete a large simulation. Once an ELM simulation is complete, I can choose from many analysis techniques to make sense of the data. One such technique uses a synthetic fast camera diagnostic. Just like a real camera diagnostic takes pictures of actual plasmas, the synthetic diagnostic code uses data from the simulations to create pictures.

I use the synthetic fast camera to create images of the filaments in a simulation. The eight synthetic fast camera snapshots I’ve included show the evolution of the plasma during a simulated ELM. Image a) shows a well-confined plasma before the instability occurs. Images b) to f) show the filaments starting to form and then violently erupting from the plasma edge, which degrades the plasma confinement. Afterwards, the filaments start to reduce in size — as seen in images g) to h), and the fast camera images also show that plasma has moved to the exhaust regions (the upper and lower bright regions in images d) to h)) during the ELM.

The advancements in supercomputing power have made these simulations possible, and the models used in the simulations are also becoming more advanced. Fortunately, this ELM simulation showed a reduction in the heat loads to the exhaust material surfaces, which is promising for the Super-X exhaust geometry at MAST-U. I find it exciting to contribute to one of the big challenges in fusion and hopefully my work can provide useful guidance for future research.

Vote for Siobhan’s article here: [www.euro-fusion.org/vote](http://www.euro-fusion.org/vote)
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