

FUSION IN EUROPE

NEWS & VIEWS ON THE PROGRESS OF FUSION RESEARCH



This special edition of Fusion in Europe does not only promote fusion writers but also fusion illustrators.



Picture: EUROfusion

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“ I am a master student of Green Electronics currently working in the field of optics at TU Munich. Being a science student, I have always thought that technical knowledge should be made available in a simple and attractive form, easy to understand by all, irrespective of their respective fields of expertise. EUROfusion has helped me realise this wish of mine to a large extent. As I have always been involved in the artistic field since childhood, I thought of giving it a try and testing my drawing skills by pushing the limits in a pioneering attempt to work as an illustrator for the renowned EUROfusion magazine. ”

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ON REALISING AN UNUSUAL PROJECT

To be brutally honest: I would never have thought that this would happen, that we would successfully achieve this special edition of Fusion in Europe, an edition written only by the untrained hands of volunteer fusion writers. I simply had very little trust in the reliability of busy students and their eagerness to meet my deadlines. I didn't truly believe in the power of a future generation which wants to have a say against the ongoing gossip which claims that fusion is 30 years away, and always will be. I was proven wrong. Totally.

When we launched the 'Fusion Writers Wanted' call at the beginning of this year we received dozens of applications from people, mostly in their 20s and 30s, who wanted to share their enthusiasm for this big science. 14 authors and one illustrator who now cover a wide range of ages, grades and specialisations and who – and that is what I find the most exciting – come from many parts of the world. They all had one goal in common: sharing their passion for fusion and learning how to explain complex science in short sentences.

That was the only thing I could do for them: teach them the tricks of a trained journalist. I did not tell them to meet my deadlines, but they did it anyway. Most of all, I did not have to tell them to be reliable.

From the very first minute, the fusion writers have been extremely dedicated to this project, coming up with different topics from within the big fusion quest and developing the ideas for their articles mostly on their own. They felt like sharing the benefits of fusion with the world. And, most of all, they felt like sharing their ideas about fusion science with the world and showing what progress has already been made. It was thrilling to see how much faith they put in the ongoing progress of fusion

research. Their articles clearly express their own positive views about the realisation of fusion energy.

Accordingly, this very special issue contains a wide variety of topics starring the big players ITER, JET, the infamous Brexit, as well as particular aspects of fusion such as material science, the important Lawson Criterion or plasma turbulences along with the history of Mexican fusion research.

I think this is simply fantastic and I am a little bit sorry for being so negative at the beginning. So, I have learned my lesson well: never underestimate a project which differs from the norm. Have faith and good things will happen.



Anne Purschwitz
Editor of Fusion in Europe
Picture: EUROfusion

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We all know that ITER will be a tokamak. Read about the hard times scientists had to overcome in order to make the tokamak the winning concept in the 60s.

FROM HARDSHIPS to the STAR BOTTLES

The stellarator W7X – the modern endeavour to compare stellarators to the long-time favoured tokamaks. Picture: IPP/ Tino Schulz

SECRECY UNTIL GENEVA

In the 1920s scientists realised that the nucleus stores an immense amount of energy. One way to harvest its energy is thermonuclear fusion. Just after WWII, the United Kingdom created the first devices designed to achieve controlled fusion in a few research centres. After the Argentinean president Juan Peron bravely claimed in 1951 that his scientists had succeeded in producing fusion energy, the USSR and the USA became more interested in taming the fusion fire. France, Sweden and Japan also joined the race later in the 50s.

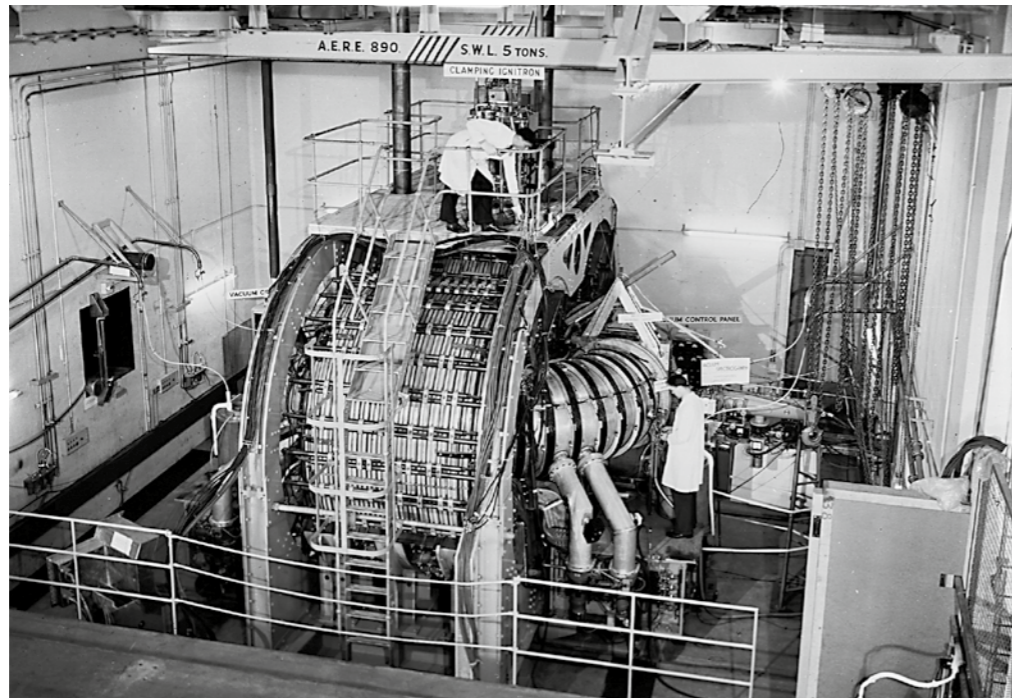
Besides building fusion devices, studies of fusion plasma physics were also boosted in the 50s, for example, investigations into plasma stability, Bohm diffusion and the Lawson criterion.

Read about the Lawson criterion in the text “Lawson’s Criterion: making fusion simple” in this issue, pages 20 – 21

Some phenomena were even “discovered” multiple times, since fusion research was classified back then – thanks to the Cold War and the potential military uses of fusion.

Bohm diffusion

The Bohm diffusion theory describes the particle transport across the magnetic field lines that are confining the fusion plasma. This was necessary to estimate huge losses in early fusion devices. However, experiments showed that the losses are over 100 times larger than the Bohm diffusion had predicted which made the Bohm diffusion the most optimistic transport theory for magnetically confined plasma.



The ZETA device at Harwell. The size of it was unmatched for almost two decades. Picture: © protected by United Kingdom Atomic Energy Authority

„COLD“ BUT NOT TOO COLD

However, things were not entirely “cold” all the time as two Soviet scientists were able to visit Western laboratories, where they spoke of their research in a notably open manner. The UK was the first to declassify their documents as early as January 1957. Other Western countries followed them, while the USSR waited for the next conference to open up about their fusion research.

During the Geneva Conference in 1958, scientists from both sides of the Iron Curtain openly discussed their research for the first time. Most of the presented results were on so-called “pinches and magnetic mirrors”. In addition, the USA introduced the first stellarator concept.

THE PINCH CONCEPT

The Pinch concept uses a magnetic field to squeeze plasma. Pinches could be open with a cylindrical shape or closed with a ring-like shape, also called toroidal. Depending on the direction of the current through the plasma, the pinch could be a Z-pinch (current along cylinder or torus) or a Theta-pinch (poloidal, around the ring). The open Z-pinch was investigated in Moscow and Berkeley, while other centres in the USA investigated open Theta-pinches. The most prominent example of Theta-pinches, Scylla, located in Los Alamos, demonstrated the first thermonuclear neutrons. At the time, the UK was leading research into the toroidal pinch system with their massive ZETA device. In addition to the UK, the USSR, the USA, France and Sweden also presented results from their toroidal devices.

MIRROR, MIRROR

The other approach is that of a magnetic mirror which stores plasma as particle trap – whereby a stronger magnetic field at the edge repels the particles towards the centre, where the magnetic field is weaker. Soviet as well as American scientists attempted to create continuous plasma with the help of low magnetic field mirrors. A beam of energetic ions was often used to reach the thermonuclear conditions, but the estimated radial losses were too large for practical purpose. Some centres in the USA developed pulsed magnetic mirrors with stronger magnetic fields, which slowly evolved into the Theta-pinch.

The third approach, the stellarator was an attempt to produce plasma without current flowing through it, thus providing full control over plasma by the magnetic coils. This is executed either by bending the torus and/or bending the coils.

Almost all reports contained neutrons that would sooner or later be proven to be of non-thermonuclear origin. Researchers later identified that these neutrons came from the beam-plasma interaction or fast-particle vs. wall interaction.

The Conference summary in Geneva finally concluded that fusion research has to ‘fill the missing gaps’ and it was obvious that obtaining fusion power will be far more difficult than had been expected ten years previously. Soon after the Conference, West Germany, The Netherlands and Switzerland joined the fusion community.

LOSING THE OPTIMISM

It is true that Scylla lifted the open Theta-pinch research, but due to the edge losses and impractical dimensions of the experimental power plant measured in hundreds of meters, the concept was abandoned. In Moscow, scientists worked on Field-Reversed Configuration (FRC) for better plasma stabilisation. The idea was to create a self-organised opposite toroidal field of the external toroidal field in the device, like a ring in the cylinder.

FROM ZETA TO STELLARATOR

The British pinch ZETA withstood the disappearance of toroidal pinches and detected the spontaneous reversed toroidal field at the plasma edge. Later this discovery would lead to the Reversed-Field Pinch (RFP) which is currently being investigated at EUROfusion’s Italian Research Unit in Padua.

“Baseball-like” shaped coils reduced the losses in the fusion devices using the mirror approach, but these improvements were unimportant for practical purposes. “Cusp” mirrors were tested to stabilise the plasma. This led to toroidal devices with the conductor implemented inside the vacuum chamber. These units are named Levitron because the conductor would levitate inside the chamber. The Levitron was never considered to be a potential power plant, but it helped with our understanding of the plasma stability and transport.

In the 60s, stellarators appeared to be the best candidate for fusion power plants. This was primarily due to them having an inherent continuous closed plasma system. After the Conference, many labs built their stellarators in line with the American approach. Unfortunately, designing the stellarator was cumbersome and included complicated calculations in an era without super-computers. As a result, the main design principle was “trial-and-error”.

During the 1960s there was no additional big advances, either the particle losses were too large, the heating was insufficient or the plasma would be unstable and too short.

THE SIBERIAN SUN

In 1968, there was 3rd Fusion Energy Conference organised in Novosibirsk. As the future of fusion seemed a bit discouraging at the time, one could say that this was the best moment for the USSR to present their “ace in the sleeve”: the tokamak. The strong toroidal field was what made the tokamak different from the other devices.

Lev Artsimovich was honoured to present the tokamak T-3 results. T-3 immediately achieved the temperatures

and an energy confinement much larger than any other device. The community was sceptic, especially in the USA and the United Kingdom. Moreover, the methods used to estimate the electron temperature were very indirect and this only increased the criticism. Yet, Artsimovich’s numbers were confirmed by direct measurements by UK scientists a year later.

The astonishing results of the tokamak made this concept superior to all other fusion concepts. This drove all research centres worldwide to build their own tokamak. Note that, Australia was the only country, besides the USSR, to have a tokamak prior to the Novosibirsk Conference and around 15 tokamaks were constructed in total up to that time. During the 1970s, fusion research was conducted on almost 80 tokamaks and the 3 largest tokamaks ever built (JET, TFTR and JT-60) had already been designed. Even the USA let their favourite stellarator go for a few years.

THE STAR BOTTLE

At the end of the 1960s, fusion was still far from the power plant level. But it took scientists only two decades to get from simple pinches and mirrors to the tokamak concept, which already had improved the quality of fusion plasma immensely. Finally, after choosing the best “star bottle”, the tokamak, scientists worldwide could start to think about a “star-like” power plant on Earth. With the kick-off of Wendelstein 7-X in Greifswald last year, stellarators quickly returned to the fusion stage. The following article will compare the stellarator to the tokamak. ■

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“ I am a PhD student of Fusion Science and Engineering at the International Doctoral College. In my opinion there is nothing more practical than fusion – an abundant energy source for mankind. A year ago I found myself interested in popularising fusion science and I thank EUROfusion for giving me the opportunity to further disseminate my two passions: fusion and history. ”

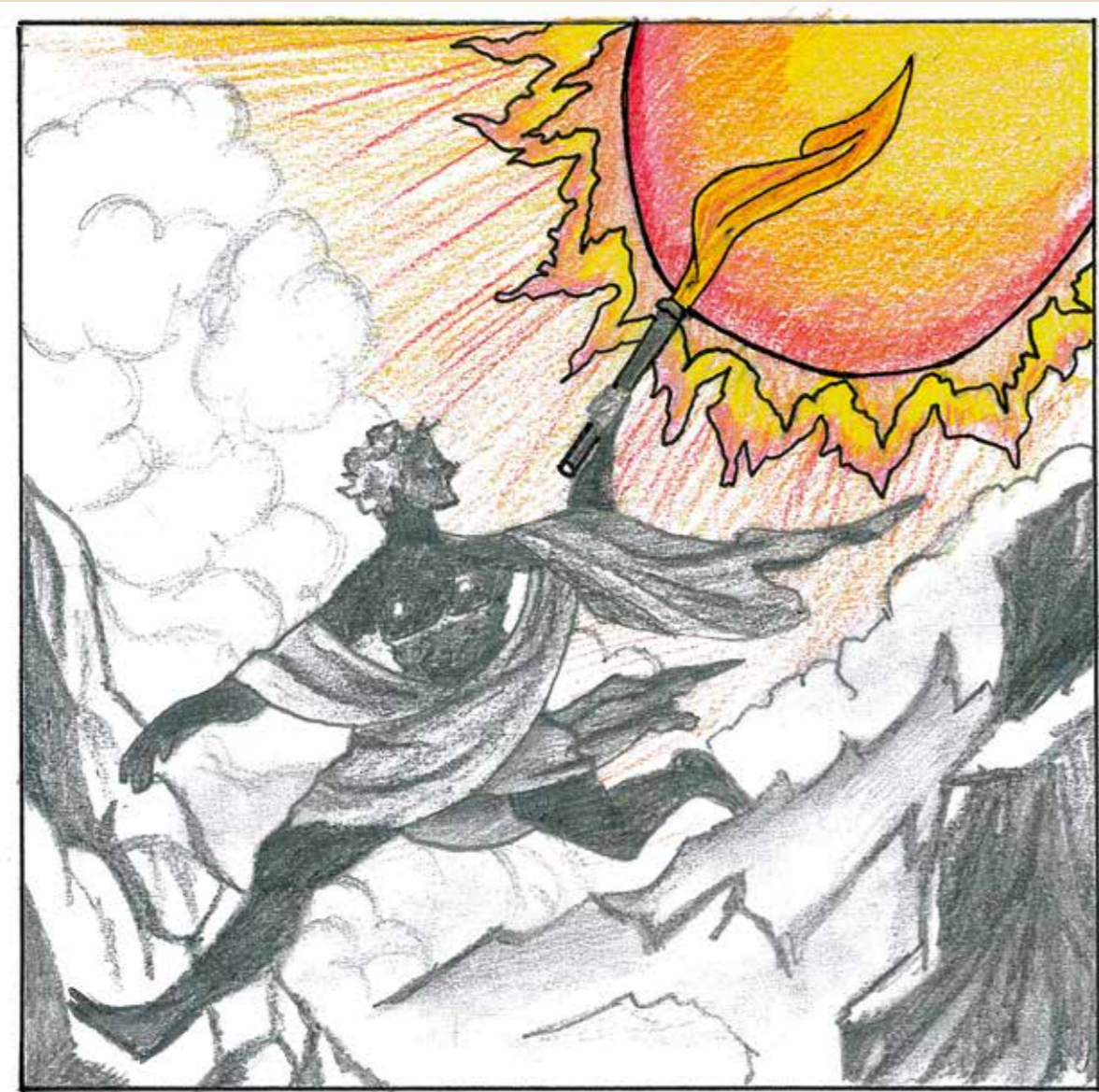


Illustration: Amita Joshi

Stealing THE FIRE OF THE GODS or realising FUSION ENERGY

The current environmental concerns lead us to look for cleaner, safer and more efficient ways in which to produce power. We are in constant growth and our technological lifestyles are increasingly demanding for more energy. In addition to sustainable power from renewable sources, scientists want to find a solution which employs nuclear fusion. This has a huge benefit, it is a source of energy that is virtually unlimited!

JUST LIKE PROMETHEUS

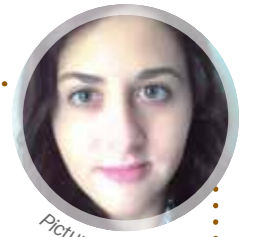
Achieving nuclear fusion can be compared to the Greek titan Prometheus feat: creating a little Sun on Earth! This is like stealing fire from the Gods. Fusion is going to become reality and European scientists are working hard towards it. The experts' goal is to exploit fusion to make power plants work. In order for this to be feasible, the fusion reaction must be able to produce more energy than it consumes. It has been a great challenge for years, nevertheless EUROfusion, the European Consortium for the Development of Fusion Energy, aims to realise fusion energy by 2050.

"MAGNETIC BOTTLES" ARE THE WAY

Building a fusion reactor is a bit more than just tricky. To achieve the densities and temperatures required for a successful thermonuclear reactor, a plasma must be contained by magnetic forces for a sufficiently long time to produce net thermonuclear power. Such a container is also called a 'magnetic bottle'. One of the most important problems discovered in the attempts to achieve this confinement is stability; since a plasma confined by a magnetic field is not in thermodynamic equilibrium. It can collapse due to a large variety of instabilities.

JET EXPERIMENTS

Despite the stability problems, significant progress has been made in building larger and "smarter" machines. One of the first and most important testing grounds is JET: the world's largest operational magnetic confinement plasma physics experiment, located at EUROfusion's Research Unit Culham Centre for Fusion Energy (CCFE) in the UK.



Picture: private

Sara Riccio

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“ I am studying to become an engineer because I am very interested in science and I believe in the intelligent use of technologies. Fusion fascinates me since it promises to satisfy our hunger for energy while keeping our planet clean. Given that is also a great challenge, it manages to bring all scientists to unite. So I think it is worth writing about it. ”

The experiments began in 1983, when the very first JET plasma was burned. In 1991, a Preliminary Tritium Experiment achieved the world's first controlled release of fusion power. Six years later, in 1997, another world record was set: JET produced 16 megawatts of fusion power. After more than 25 years of successful operation, JET is still at the forefront of fusion research and is closely involved in plasma physics research, systems and materials testing for ITER.

TOWARDS THE FUTURE: ITER

The international project ITER represents the next stage in the development of fusion energy. The tokamak ITER will be the biggest magnetic confinement experiment in the world capable of generating fusion energy surplus. That energetic surplus essentially comes from the difference between the sum of the masses of the two hydrogen isotopes tritium and deuterium and that of the reaction product: helium. Hydrogen is one of the most common elements in the universe. Deuterium can easily be found in sea water. Tritium is produced in a fusion reaction by splitting Lithium ions by a neutron (from the fusion reaction) into tritium and helium. Helium is "lighter" than the sum of the masses of the elements that generate it, so that "lost" mass is what is transformed into heat.

Until now, the most difficult part has been initiating the entire process. It needs very high temperatures and, above all, an effective way to confine the very hot reaction. At those conditions matter is in a physical state of plasma, a mixture of free electrons and ions characterised, amongst others, by a temperature reaching millions of degrees.

DOUGHNUTS FOR FUSION

For these reasons, the singular “doughnut-shaped” tokamak is ideal. It is a machine with a specific ring-shaped structure which generates a strong magnetic field (5 to 10 Tesla). The tokamak is able to isolate a thermonuclear plasma from the walls of its container; the walls also directly absorb the heat. In a tokamak charged particles move with circular trajectories when immersed in a magnetic field. That is why such intense magnetic fields require superconducting magnets whereby the word “super” is well deserved, since they hold plasma at millions of degrees 1 meter away from the super-conductor cable which has a temperature of only 4 to 4.5K.

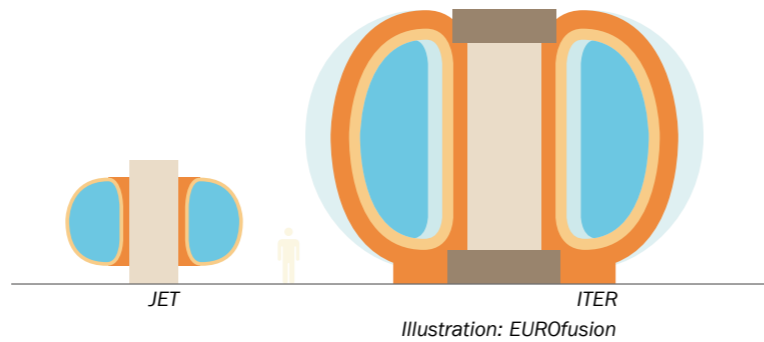


Illustration: EUROfusion

STAR RECORDS

In the meantime, in Greifswald in Germany the most progressive stellarator Wendelstein 7-X produced its first plasma last December. But, what in the world is a stellarator? Its ‘devilish design’ looks like something out of Star Trek or Star Wars when, in truth it is only a case of strong assonance. Yet, looking at it, a stellarator is very much akin to science fiction. The stellarator is the tokamak’s “cousin”. But unlike tokamaks, in which the magnetic field changes only in two dimensions, in stellarators it is three-dimensional: the twisting field is produced entirely by external non-axisymmetric coils. It is essentially, a fusion reactor with a twist, so hard to build that in fact it required the help of supercomputers to model the design in advance.



Illustration: EUROfusion

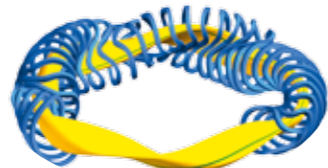


Illustration: IPP

ne to this problem: their fields come entirely from external coils, which do not need to be pulsed, and there is no plasma current to suffer disruptions.

A tokamak has the advantage of being technically much simpler and more straightforward, while stellarators, as mentioned before, are complex. Stellarators are steady state as there is no transformer action. They are almost currentless which implies that many of the instabilities occurring in tokamaks cannot occur in stellarators. What troubles fusion researchers are the fast ions in a stellarator’s plasma. The unconfined particles orbit and get lost along the twisted path.

As a result, most fusion research since the 1950s has focused on tokamaks. Less effort has been concentrated on stellarator devices, essentially due to the technical complexity in comparison with tokamaks. Now, stellarators have shown significant achievements and researchers want to prove that a stellarator is as good as a tokamak when it comes to realising fusion energy.

IN THE MEANTIME...

Whether a commercial fusion power plant is a stellarator or a tokamak is still up in the air. But, while we wait for this promethean quest to be accomplished, research provides us with many short-term benefits. Fusion exploration is a complex and multidisciplinary field, but it has pushed advances in medical technology, the environment, theoretical physics, astrophysics, material sciences and telecommunication. It is precisely its complexity that requires everyone to join in on collaborating their efforts. ■

GERMANY'S STELLARATOR

In February, the German team working on Wendelstein 7-X was able to heat hydrogen gas to 80 million degrees for a quarter of a second. This was the proof of concept: the team wanted to increase microwave plasma heating power to 20 megawatts, scaling things up to heat the hydrogen gas to the 100-million-degree benchmark. Hydrogen releases a whole lot more energy, it is also a lot harder to heat. This was a huge milestone in the decades-long pursuit of controlled nuclear fusion.

TOKAMAK VS STELLARATOR

Both stellarators and tokamaks work and both of their concepts have innate advantages and disadvantages with regard to the technical and physical aspects of a fusion device working towards burning plasmas. In fact, tokamaks have their drawbacks too. The current in the plasma may falter unexpectedly, resulting in “disruptions”: sudden losses of plasma confinement that can damage the reactor. Stellarators, however, are immu-

ITER UNITING NATIONS FOR FUSION



The ITER members. Illustration: EUROfusion

This collaboration is unique: On the 21st of November 2006, government representatives of China, the European Union (plus Switzerland), the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America officially signed the agreement to build an experiment which is designed to prove the scientific and technological feasibility of sustained fusion power generation. Although the idea stems from the Cold War, it officially gave birth to the construction of ITER, which means “the way” in Latin. According to a recent speech given by ITER’s Director-General Bernard Bigot in Prague, ITER expects to produce its first plasma in 2025.

SEVEN MEMBERS, ONE GOAL: THE ITER ORGANIZATION

The ITER Organization comprises a governing body, the ITER Council, and an executive body led by the Director-General. It involves participants from the abovementioned seven ITER member countries. The ITER Council, which normally meets twice a year, represents the principal organ of the organisation responsible for the promotion, overall direction and supervision of the activities of the executive body. For example, it appoints the Director-General and the senior staff.

The ITER Council approves the overall schedule and associated cost of the project. It monitors the activities of the ITER Organization and approves its annual budget. It also decides on the participation of additional states or international organisations. The ITER Organization in itself must ensure to promote the cooperation among its Members and the best exploitation of its facilities.

CONNECTING WITH THE INDUSTRY

Each member has set up a Domestic Agency to provide their contribution to ITER by working together with their domestic industry and research organisations to develop and manufacture high technology components. This is an important aspect of the organisation because the ITER

Find out more about the fusion spin-offs here:

www.euro-fusion.org/category/fusion-spin-off/

members pitch into the project by delivering components, equipment, materials, buildings or systems. In the ITER world these are the so-called “in-kind” procurements. Since the beginning of the process, the ITER Domestic Agencies have signed more than 1,800 contracts for the design or fabrication of components. While the scientific installation is set in only one place, the production of the ITER facilities involves almost the whole world.

SHARING THE COSTS AND BENEFITS

ITER’s administrative set-up should also enable the controlling overall project costs. Europe, which is treated as a single member of the ITER Organization although it represents 28 countries plus Switzerland, is responsible for the largest portion of construction costs (45.6 percent); the remainder is shared equally by China, India, Japan, Korea, Russia and the US (9.1 percent each). The members, by contributing a portion of the project’s amount, increase their scientific, technological and industrial knowledge in the fusion field. Indeed, the experimental results and intellectual property generated during the operation phase are shared between them.

EUROPE’S PARTICIPATION

Europe, as host of the ITER project and with plenty of involved nations, needs a particular Domestic Agency to connect ITER’s world to the European industry. Europe’s Domestic Agency even has its own name: Fusion For Energy (F4E).

This body – formally known as the European Joint Undertaking for ITER and the Development of Fusion Energy – was established in 2007 and is located in Barcelona, Spain.

F4E has 400 members of staff and is formed by Euratom (represented by the European Commission), the 28 Member States of the European Union and Switzerland. Each member state has a seat in the Governing Board, the main body which supervises, for example the nomination of the director, the approval of F4E’s organisational structure or the regulation of the financial funds, which are derived, for the most part, from the European Community budget.

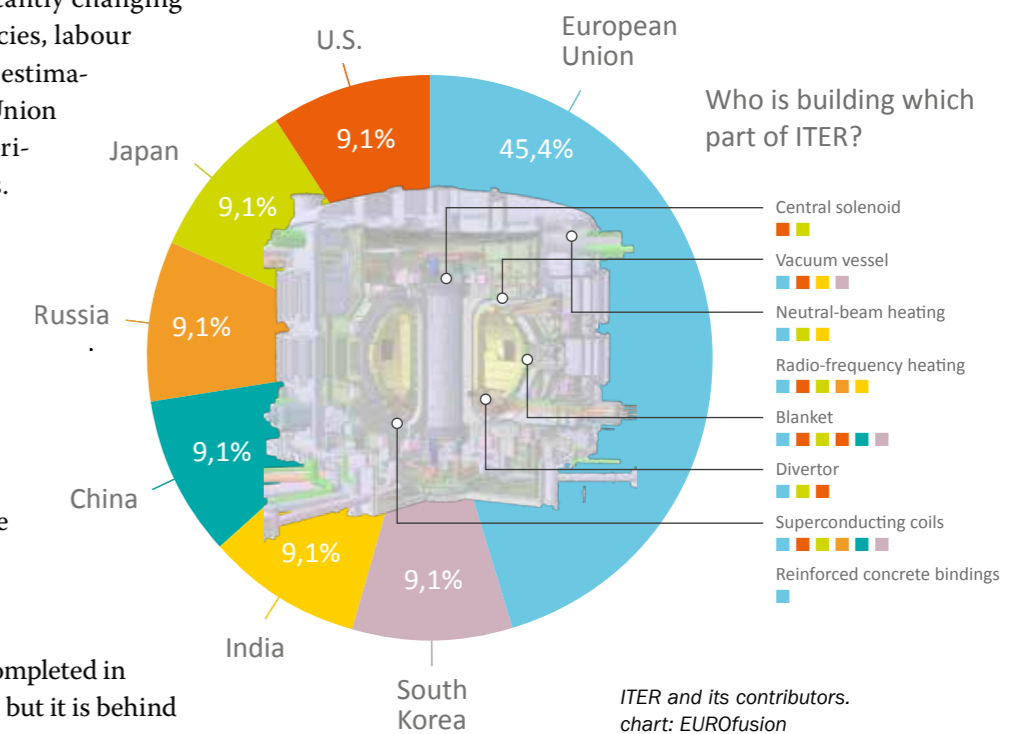
The Governing Board meets at least twice per year. F4E supervises the preparation of ITER’s construction site in Cadarache in France. The agency is also involved in the Broader Approach (BA) with Japan and in the DEMO Project, the first demonstrational fusion power plant.

ITER – TEN YEARS AFTER THE KICK-OFF

After four years of work to prepare the foundations the construction of the Tokamak Complex Buildings only began in 2014. At the meeting of the ITER Council in June 2016, almost ten years after signing the agreement, the ITER Organization presented a modified project schedule and renewed milestones. The costs of the ITER project have grown considerably. With ITER’s new plan estimating additional costs of about five billion euros, most of its members will need to acquire renewed approval from their budgetary authorities.



ITER’s costs depends on many constantly changing factors such as the members’ currencies, labour and material costs. So it is difficult to estimate the exact amount. The European Union has prized its global monetary contribution at almost seven billion euros. Before the recently announced delay in ITER’s schedule the European evaluation had calculated the sum of the outlay for the ITER construction for the seven Members to approximately 13 billion euros, if all manufacturing was carried out in Europe. This cost will be shared over the course of ten years by the 35 countries are contributing to ITER.



ITER on its troubled way

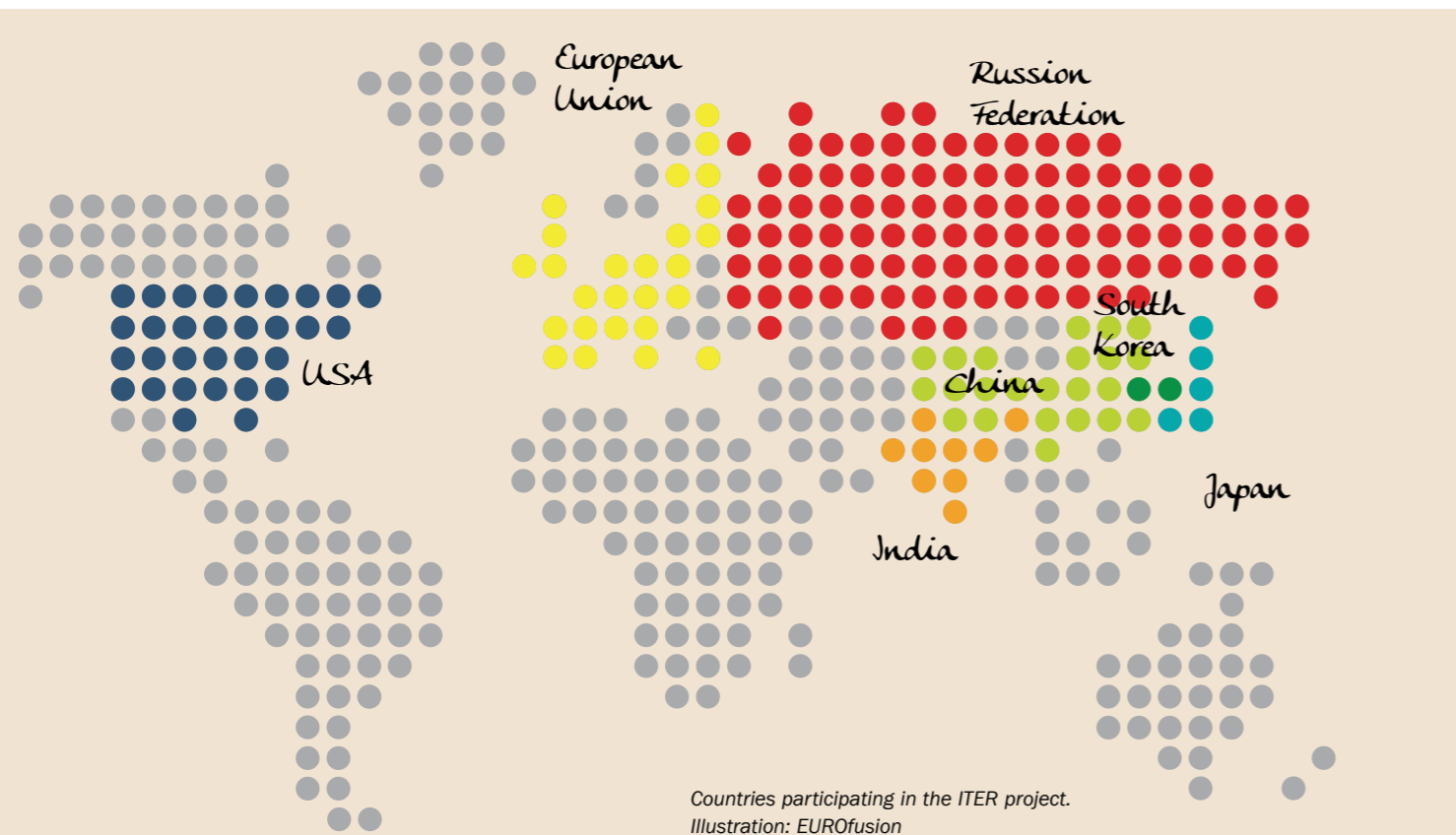
The project was originally due to be completed in ten years at a cost of five billion euros, but it is behind due to its complexity. Though the foundations have been laid, the construction of ITER has been delayed, in part by the rather complicated way in which contracts are dealt with. The Domestic Agencies, indeed, often have trouble completing and signing the design contracts with industrial partners because the technical and commercial negotiations are long and difficult.

Since the appointment of Bernard Bigot in March 2015, things are changing for the better. Eight months after his inauguration, Bernard Bigot’s team had presented a revised timetable for the project. The Director-General affirms with certainty that the 2025 deadline is technically achievable, and says that partner countries should do everything they can to meet that deadline.

The ITER spirit

The ITER Project, a globe-spanning participation of 35 nations, is the largest international collaboration in the scientific field ever set up, and the world’s greatest scientific project for energy research. Taken together, the ITER members represent three continents, over 40 languages, half of the world’s population and 85 percent of the global gross domestic product. With the exception of the United Nations there is no other organization that includes such a diversity of languages, origins and cultures. English, the official working language of the ITER Organization, is the native language of just 15 percent of the staff.

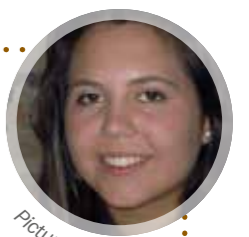
Multiculturalism is ITER’s additional asset. In this way, the people involved in the organisation can be enriched not only by newly acquired scientific knowledge but also by the different cultures encountered.



Countries participating in the ITER project. Illustration: EUROfusion

Elena Bulfone

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Currently based at: Padua, Italy



Picture: private

“ I am a university student and I am in my second year of a bachelor degree in Chemical and Materials Engineering. I wanted to partake in Fusion in Europe to experience an international collaboration for myself. I chose ITER as a topic to support the diffusion of this unique fusion project. Thanks to the opportunity at Fusion in Europe, I was able to combine my passions for science and writing. ”

DEMO

AND THE ROAD TO fusion power

Among several solutions which meet the requirements for a future energy source, there is one that may hold the promise of fuel abundance and being environmentally friendly: nuclear fusion power! If only it were not so technically challenging. Nevertheless, scientists are optimistic that fusion will indeed be our ultimate source of energy, possibly even by the turn of this century. To prove this, European researchers take on the challenge of building the first fusion power plant: **DEMO**

WHY "DEMO" ?

Starting in the 1950s, and up to the moment of writing this article, enormous progress has been achieved in plasma physics and fusion engineering. With this accumulation of knowledge on the one hand and the ever growing demand for energy on the other, it is high time that the progress made in fusion research is gathered into a single, integrated power plant design: this is exactly the goal of DEMO, the ...

„DEMONSTRATION POWER PLANT“

DEMO is presently in a pre-conceptual design phase. According to European and international fusion experts, DEMO is the milestone that separates fusion from being merely a topic of concern primarily of interest to research laboratories, to the wider, more public scope of interest. DEMO will be the preparatory step for generating fusion electricity for the benefit of society. Indeed, many of the

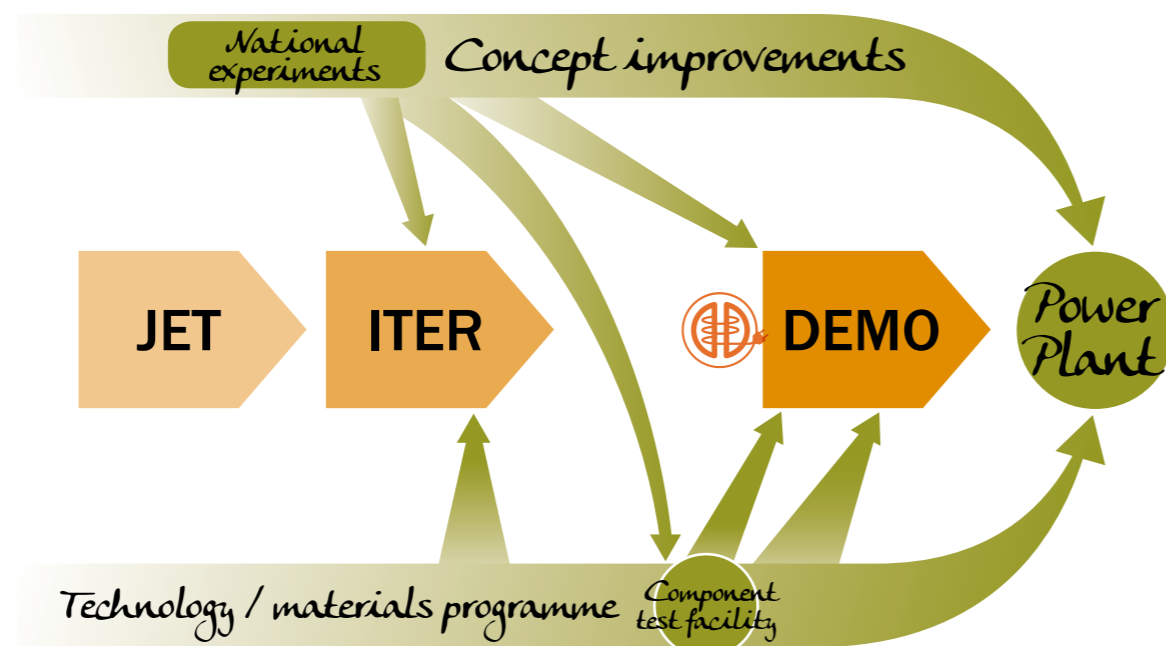


Illustration: EUROfusion / CCFE

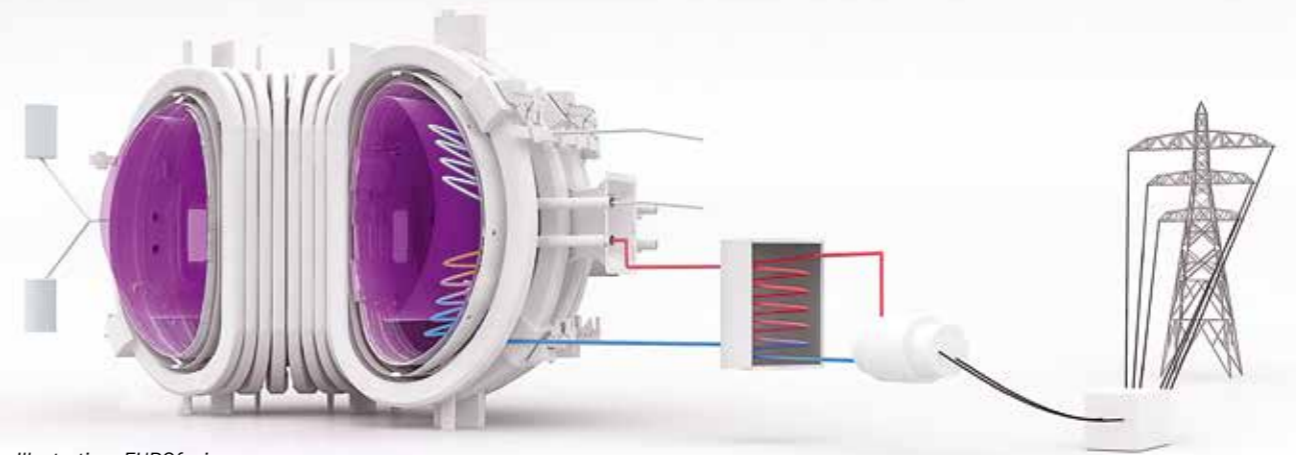


Illustration: EUROfusion

countries involved in fusion research already have their own programme for DEMO. Very recently, at the 2016 SOFT symposium held in Prague: Japan, China, and the EU, together representing a sizable portion of the global fusion community, reported on their own active DEMO programmes, reflected in several talks and posters presented at the conference. Those nations are focusing their resources and man power into aggressive research for building the first test fusion plant. They aim to demonstrate the potential of fusion as a sustainable power source. Indeed, these activities are independent from the countries contributions to ITER, thus emphasising DEMO's cornerstone role in the global fusion research map.

CHALLENGES FACING DEMO

DEMO is the single device that will mark the transition of fusion from a predominantly research phase to a commercial, power production phase. Although DEMO is not meant to be a power plant, it should demonstrate that fusion electricity can be exploited commercially in a future power plant. DEMO's success, however, depends on overcoming numerous technical challenges: most importantly, finding adequate heat exhaust solutions, developing of materials capable of meeting functional expectations in the harsh fusion environment, and the ability to run the machine for a sufficiently long time in order to achieve feasible power production.

DEMO - A CHALLENGING PUZZLE

Thomas Franke from the EUROfusion Programme Management Unit in Garching puts these challenges into perspective: "DEMO is complex, in the sense that we want to integrate, into one device, several technologies which often have conflicting requirements. It is like a puzzle. The challenge is thus to bring these many technological pieces together in a functional way."



Picture: private

Amro Bader

Age: 27
Origin: Jordan
Currently based at: Garching/
Munich, Germany

www.linkedin.com/in/amro-bader

" I am a researcher at IPP working on the design of heating and current drive systems (ICRF) for fusion plants (i.e. DEMO). Fusion is quite a challenging, yet exciting, technological endeavour for a young engineer to pursue, and I feel privileged to be able to take part. I come from Jordan, where I did my bachelor's studies, then moved to France and Canada for grad school. Following graduation, I started a career in academia at the UAE, before moving to Germany to help in the worldwide efforts towards the realisation of fusion as a power source.

WHY DEMO MATTERS

The need for a sustainable energy source that meets the growth challenges of the 21st century is undebatable. Whether this will be fusion depends on the success of the involved scientists and engineers when it comes to conquering the numerous technical challenges faced. If DEMO proves successful, then we can finally get some rest, in the sense that we may have eventually obtained our eternal quest for a clean and abundant energy power plant. That's one important reason why the public should support fusion research.

Nuclear radiation IN FUSION: LOW RISKS AND PLENTY OF BENEFITS

As Professor Ian Chapman, the new CEO of the UK Atomic Energy Authority (UKAEA), remarks on BBC5 Radio Live, nowadays explaining the concept of nuclear fusion to the public is a hard, but essential, task. Looking towards the future of fusion power appears challenging to most people used to relating nuclear technology to destruction and fear. Worries about the aftermath of a nuclear attack, accidents in nuclear power plants and a lack of education with regard to radiation have fed the distrust in nuclear applications. Although fusion power does come with some radiation risks, its perception remains affected by the general stigma attached to radiation.

10.000	Acute radiation poisoning – death within weeks
6.000	Typical dose received by Chernobyl nuclear plant workers who died within one month of accident
3.000	Survival rate approximately 50 percent
2.200	Reading found near tanks used to store radioactive water at Fukushima plant, Sep 3, 2013
1.000	Causes radiation sickness and nausea, but not death. Likely to cause fatal cancer many years later in about 5 of every 100 persons exposed
700	Vomiting, hair loss within 2-3 weeks
500	Allowable short-term dose for emergency workers taking life-saving actions
400 per hour	Peak radiation level recorded inside Fukushima plant four days after accident
350 per lifetime	Exposure level used as criterion for relocating residents after Chernobyl accident
250	Allowable short-term dose for workers controlling 2011 Fukushima accident
100	Lowest level linked to increased cancer risk
20 per year	Average limit for nuclear industry workers
10	Full-body CT scan
2.4 per year	Person's typical exposure to background radiation
0.01	Dental x-ray

chart: EUROfusion/IAEA (data)

Radiation doses in Millisieverts

Sievert is an indirect unit that represents the risk of the biological harm on the human body due to radiation exposure: the probability of cancer induction and genetic damage. In ITER the objective is to ensure an annual individual dose limit of 2.5 mSv (about that similar to background radiation) for the reactor workers and an annual maximum public dose of 0.1 mSv

FUSION COMES WITH NEGLIGIBLE RADIATION

JET, the Joint European Torus, one of the nuclear fusion devices that has already achieved fusion, producing 16MW in 1997, relies on the principle of bringing together (fusing) deuterium and tritium nuclei to produce helium and highly energetic neutrons (14.1 MeV). Magnetic confinement is used to overcome the mutual electric repulsion between tritium and deuterium, both of which are positive ions. The handling of massive amounts of tritium and the production of highly energetic neutrons are the main radiation protection concerns faced by fusion experiments using tritium. Although tritium has a very low radio-toxicity – it emits radiation which is not able to penetrate the skin – it easily forms organic compounds and diffuses through materials. So, due to the large quantity of tritium in fusion reactors (for example in ITER, about one kilogram per cycle plus a few kilograms stored on site), power plant staff members use protective clothing to avoid inhalation and direct contact with the material.

Moreover, pressure systems have been designed to limit tritium spread outside the power plant. High energy neutrons with a high fluency rate induce radioactivity in reactor materials. The radioactivity remains even after the experiment has been closed down. Specifically shielding, optimisation programmes of tritium handling and storage, protective clothing for the staff and a remote maintenance plan will result in negligible radiation risks for both the public and the power plant staff.

POWER FROM FISSION

Nuclear fission, on the other hand, is the physical phenomenon employed in nuclear reactors and also, when intentionally “uncontrolled”, in nuclear weapons. A large nucleus, for example of uranium-235, when bombarded with neutrons will fission, or split, into two smaller nuclei, called fission products, also emitting a few neutrons and gamma photons. These fast neutrons can themselves induce fission in other uranium nuclei, creating a chain reaction process. Avoiding a runaway chain reaction and managing radioactive fission products are the main issues of fission power. Uncontrolled chain reactions in reactors may, in fact, cause meltdowns and damages (however not comparable with the effects of nuclear weapons), while radioactive fission products are high-level radioactive waste that contains 95 percent of the radioactivity arising from nuclear power (according to the World Nuclear Association) and requires safe storage for more than a thousand years.



Picture: private

Bianca Giacomelli

Age: 23
Origin: Italy
Currently based at: Padova University, Italy

“ I am a physics student and I've always been impressed by the power of scientific communication and the challenges it poses to every scientist. Recently, I've become interested in radiation protection issues, for this reason, I chose to use my article in this special edition of Fusion in Europe to highlight some of the main differences between fission and fusion power plants. ”

A REALISTIC PERSPECTIVE ON RADIATION RISKS

Even though, in most countries, research into the operational safety of fission plants has progressed in ensuring a minimal risk of human and organisational error, the memories of Chernobyl have certainly contributed in increasing the distance between the population and radiation education which has resulted in a fear of radiation, often regardless of the actual circumstances. A realistic perspective on radiation related risks may therefore be crucial in improving fear management.

TOWARDS SAFER AND CLEANER ENERGY

Coming back to fusion, in case of the worst possible accident in a future nuclear fusion reactor, there would be no need to evacuate nearby residents. The implementations of radiation protection in fusion reactors, as mentioned earlier, follow the ALARA (As Low As Reasonably Achievable) approach: an ongoing and iterative process designed to keep the likelihood and the magnitude of radiation exposure, as well as the number of people exposed, as low as is reasonably possible. Furthermore, the absence of both long-lived, highly radio-toxic radioactive waste and dangers due to runaway chain reactions tips the nuclear fusion power scales in favour of the higher benefits and away from radiation risks to staff and population. ■

IS NUCLEAR FUSION



Fusion energy, the energy of the stars, which is generated without producing greenhouse gasses, seems to be the perfect solution to solve the demanding energy needs of mankind – except for one aspect: fusion is created with a nuclear reaction. But, is it the radiation itself which will be dangerous?

The first experiment to prove an energy surplus from a fusion reaction will be ITER. ITER, which also means „the way“ in Latin, is currently under construction in France. 35 countries have joined forces to build the world’s largest tokamak with a major radius of 6.2 meters.

Read more about ITER in the article “ITER – Uniting nations” on pages 11 – 13 in this issue.

ITER – WORLD WIDELY ASSEMBLED

This project is also referred to as the biggest puzzle ever. In fact, the pieces of the reactor are coming from all around the world and must be perfectly assembled, millimetre by millimetre. The European Consortium for Fusion Research, EUROfusion, has dedicated almost all of its research toward supporting ITER. The worldwide collaboration for ITER might be problematic in terms of organisation, but it is also a great opportunity. By joining all of these forces, we can create the perfect design for a future fusion power plant. Specialised teams will also take care of safety features to prevent radiation risks to ITER’s staff.

TWELVE YEARS OF DECAY

The temperature in a fusion plasma is approximately ten times higher than the heart of the Sun. This heat allows the fusing of two nuclei, deuterium and tritium.

Tritium, also known as hydrogen-3, is a radioactive isotope of hydrogen. While deuterium is stable, tritium is not and requires high levels of caution. Fusion experts have planned to build a storage area for tritium, right next to the fusion experiment.

But – can fusion be a hazard to people’s health? In particular, the beta particles of hydrogen-3, are unable to penetrate the skin. They can be dangerous when inhaled or ingested via food or water. Additionally, tritium only has a half-live time of about twelve-years.

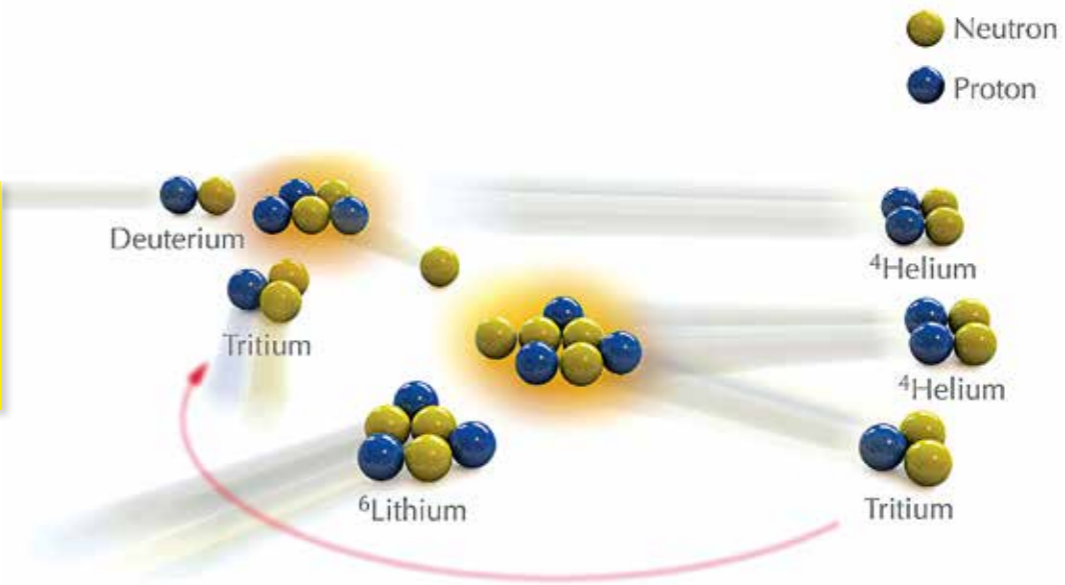
THE TRITIUM FUEL CYCLE

The biggest radiation issue we have come across is related to one of the reaction products: fast neutrons. The neutron, which carries 80 percent of the energy produced in the fusion reaction, is not confined within the plasma. It escapes and penetrates into the components surrounding the plasma chamber, mainly the blanket.

Learn more about neutrons in the interview with Paola Batistoni:



www.euro-fusion.org/?p=76936



The tritium fuel cycle in fusion experiments. Illustration: EUROfusion

Here the neutrons release their energy which is then used to produce electricity. But a side effect is that the materials near the plasma can become radioactive and must be treated accordingly when the fusion device is being decommissioned.

The blanket inside a fusion reactor should not only be there to absorb the energy in order to produce electricity. It should also ensure that the energy of the neutron is used to “breed” tritium since it occurs somewhat rarely on Earth. Tritium, generated by the neutrons in the blanket, can be removed from the blanket and sent back into the plasma as fuel. Among others, the scientists of EUROfusion are currently investigating such solutions.

IT WILL PAY OFF

Realising a nuclear fusion reactor is a great step for humanity. But, the hunt for fusion energy is both a worldwide collaboration as well as a competition. Both approaches will nevertheless work towards implementing fusion. Several labs around the world, and with a variety of features are studying the different ways to create stable fusion plasmas. Competing ideas with a variety of solutions and “lessons learned” will help fusion to be successful. The collaborative approach, on the other hand, brings together people from various backgrounds to work towards a joint solution.

Great achievements have been made for the sake of fusion progress. We now already know how to reproduce, on Earth, the energy that makes the stars shine. There are still some steps left to be taken before fusion energy becomes feasible and the efforts taken to realise it will pay off. ■



Picture: private

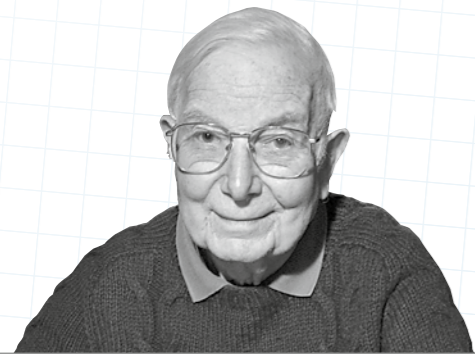
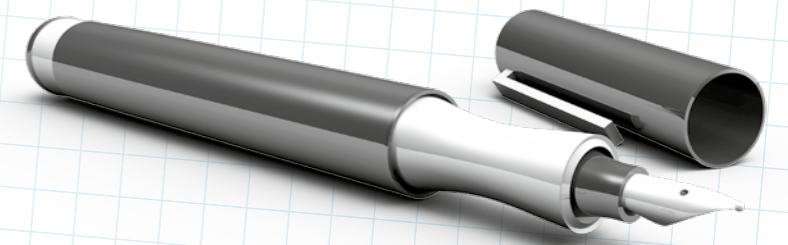
Giovanna Paladin

Age: 20
Origin: Italy
Currently based at:
Padua, Italy

“ After achieving my University degree in Chemical and Materials Engineering, I would like to work on biochemical materials research. I am really concerned by how far human knowledge can go, how we are able to grow technologically and ethically. A news diffuser such as EUROfusion which concentrates on topics such as future fusion reactors would play a large role in this. ”

Lawson's Criterion: MAKING FUSION SIMPLE

$$S_B = k_B \frac{p^2}{T^{3/2}} \text{ MW/m}^3$$



John D. Lawson, Picture: RAL

In 1955, John D. Lawson was the first person to systematically derive criteria for a useful thermonuclear reactor. His idea, the famous Lawson Criterion, was so effective that it is still used to determine the progress towards fusion.

MERGING NUCLEI

The goal of fusion research is clear: merging nuclei in order to release a desired amount of energy. However, the realisation of a reactor for electricity production based on the Lawson criteria, must satisfy severe physical and technological constraints. As an engineer, Lawson was able to reduce the complexity of this problem, defining the concrete milestones needed to realise a power plant that uses hydrogen plasma as fuel.

REACHING IGNITION

Lawson started from fundamental physical principles. In order to maintain a constant temperature of the plasma, thus avoiding the shutdown of the fusion reaction, the fusion-generated power should at least compensate the energy losses to the environment. When no energy must be introduced from the outside by way of reactor heating systems, a condition called "ignition" is reached: the reaction is self-sustained just as a wood fire, which does not require a constant supply of external sparks, but just keeps burning and remains hot as long as there are reactants.

A FAMOUS TRIPLE

From the plasma energy balance, the famous triple product of density (n), temperature (T) and confinement time (τ_E) can be derived mathematically. This figure of merit summarises the multiphysics problem of nuclear fusion in a simple inequality, defining the condition for ignition as $nT\tau_E > f(T)$ where the term on the right hand side is a function of the temperature.

THE MORE, THE MERRIER

The particles' density must be high enough to facilitate the fusion reaction. In the plasma, an ionised hot gas, hydrogen nuclei, move along their trajectories until they collide with each other. Increasing the number of particles in a given volume makes collisions more probable and fusion reactions more frequent, getting closer to ignition.

NOT TOO HOT, PLEASE!

Temperature, which is just another way to describe the velocity of the particles, plays a dual role. Collisions between charged nuclei should only happen at sufficiently high speed. This enables the long-range electrostatic

$$nT\tau_E > f(T)$$

repulsion to be overcome and brings them close enough to let the short-range strong nuclear force, responsible for fusion, prevail. However, as the temperature increases, the speed of particles is so high that the duration of interaction between colliding nuclei is too brief for fusion to happen. These facts point to an optimum temperature for ignition.

THINK BIG

The confinement time is a measure of the time in which hot plasma approaches the environment temperature. Imagine a hot metal sphere in a pool of cool water: the larger its radius, the longer the time required to reach the temperature of the water. In the same way, in magnetic fusion, the size of the plasma chamber determines the confinement quality to keep particles hot and this has motivated the design of larger and larger machines.

CREATING THE SUN IN A BOTTLE

The next step of the quest to create "a Sun in a bottle" is the implementation of ITER with a confinement time of around one second, a tenfold increase over existing fusion experiments. The optimum temperature for the triple product is above 150 million degrees K, astonishingly ten times hotter than the Sun's core. Luckily, the density needed to satisfy the triple product is much lower than air density on Earth, making at least this one goal easier to achieve on the way to realising fusion energy. ■

Federico Pesamosca

Age: 25
Origin: Italy
Currently based at: Eindhoven, NL



Picture: private

" I am a Nuclear Engineer and I am doing a PhD in the magnetic control of tokamak plasmas at the Swiss Plasma Center in Lausanne (CH). Along with technical and theoretical challenges, I consider science journalism fundamental for fusion due to its ability to share ideas and inspire more people to join this research: I am enthusiastic about making my contribution to this issue. "

$$\frac{k_B T^2}{(0v) - k_B T^{1/2} \text{ atm}}$$

$$(nT\tau_E)_{\min} = 8.3 \text{ atm s}$$



Close-up of a ceramic sample currently being studied at CIEMAT. Picture: CIEMAT

Ceramics

Thousands of years ago, the first civilisations started using clay pottery and tiles in their everyday life, turning ceramics into a key component of society. They could hardly imagine that future generations, far away in time, would still be using similar materials but incorporating them into one of the most ambitious projects of modern times: harnessing the power of the Sun on Earth in the form of a fusion power plant.

MATERIALS EVOLVING OVER TIME

Ceramics is a term that encompasses a broad range of materials. Those materials are usually associated with “mixed” bonding – a combination of ionic, covalent and even metallic processes. This variety of bonding makes the list of ceramics so long that David Richerson, author of the book “The Magic of Ceramics”, says: “most solid materials that aren’t metal, plastic, or derived from plants are ceramics.”

Throughout the centuries, the use of ceramics evolved according to the needs of the era and the discovery of new technologies. The use of different ceramic materials, as well as multiple manufacturing processes, have made ceramics a constant presence in our lives. It is natural to

realise that, for the technological challenges of the future, and in a world which controlled nuclear fusion plays a major role, ceramics will continue to be of particular relevance.

DEMONSTRATING THEIR FUSION VALUE

DEMO will be the future demonstration power plant designed to pave the way to the industrial and commercial exploitation of nuclear fusion.

See also the article “Demo and the road to fusion power” on page 14 – 15 in this issue.

Ceramics from ANCIENT POTTERY to FUTURE FUSION PLANTS

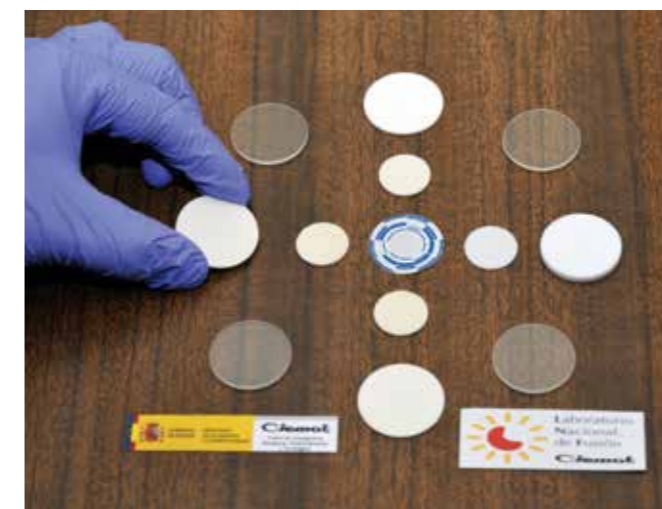
The choice of materials plays a key role in its development. Several ceramics have been selected as candidate materials because their electrical, dielectric, magnetic, optical, mechanical and thermal properties make them suitable for various applications.

Due to its excellent dielectric properties along a broad range of frequencies, aluminium-oxide (Al₂O₃) has been proposed as an insulator for diagnostics, for the Neutral Beam Injector high voltage source and possibly for the Ion Cyclotron Resonance Heating and Lower Hybrid Heating systems. Also, due to its optical and mechanical properties, it has been proposed as a candidate material for optical windows, along with silica composites, spinel and diamond. Yes, a Chemical Vapour Deposition Diamond is also considered to be a ceramic!

In DEMO, these ceramic materials will be operated under harsh conditions. They will, in particular, be exposed to considerable levels of neutron irradiation. Therefore, their optimum properties must be tested under relevant neutron irradiation conditions.

EUROPEAN WORK IN PROGRESS

Scientists at the EUROfusion’s Spanish Research Unit CIEMAT are currently testing and validating the best candidates. This work is part of the Functional Materials group tasks carried out under the umbrella of the Materials Work Package in EUROfusion. Ceramic manufacturing companies are involved in the project, since the manufacturing process plays a crucial role in determining the final properties of the materials.



Set of different types of ceramic materials currently being studied at CIEMAT. Picture: CIEMAT

Darío Andrés Cruz Malagón

Age: 33
Origin: Colombia
Currently based at: Madrid, Spain



“ My background is in both Physics and Energy Engineering. I think that the Fusion community is a very skilled global team that is trying to achieve a scientific and technological breakthrough for the sake of our future generations and I am proud to be able to contribute to that effort. My article is about EUROfusion’s current Research and Development on ceramic materials for DEMO, in which I participate through my PhD research. ”

So far, the results show that the un-irradiated samples exhibit the desired qualities for their intended applications. However, the resulting values vary between samples of the same material. This means that there is a reproducibility issue on the manufacturing side that has to be addressed before the irradiation phase takes place.

PLANS FOR THE FUTURE

Once the samples can be reproduced with the same quality, irradiation experiments of those ceramics will start. The plan is to use beta and gamma radiation from accelerators and radioactive sources, fission neutrons produced by nuclear reactors and finally fusion neutrons from specialised neutron sources as the Demo Oriented Neutron Source (DONES).

The ultimate goal of the project is to validate a standard manufacturing route that ensures a supply of ceramic material with homogeneous and standardised properties for the forthcoming fusion machines. And in doing so, ceramics will contribute to the future development of society just like they have been doing for so many thousands of years.

Predator & prey:

POPULATION DYNAMICS IN PLASMAS

Foxes, flowing tap water and nuclear fusion – these elements do not appear to have anything in common, right? You might be surprised, but there is a connection emerging. The familiar models of population dynamics might help researchers to tackle one of the most complex puzzles in fusion science.

As a fusion experiment, a tokamak is similar to a vacuum flask for coffee. It is not enough to heat the fuel so that it turns into a plasma. The performance of the device depends on its capability to keep the heat in. The fewer the particles, the less the heat leaks out of the machine, and the more energy can be produced. The usual rule of thumb is simple: bigger tokamaks with stronger magnetic fields ought to confine the plasma better thus resulting in improved performance. Researchers are working hard to understand the underlying processes in more detail. With the aid of advanced measurements, computer simulations, and inspiration from unexpected places, the European fusion scientists are definitely progressing.

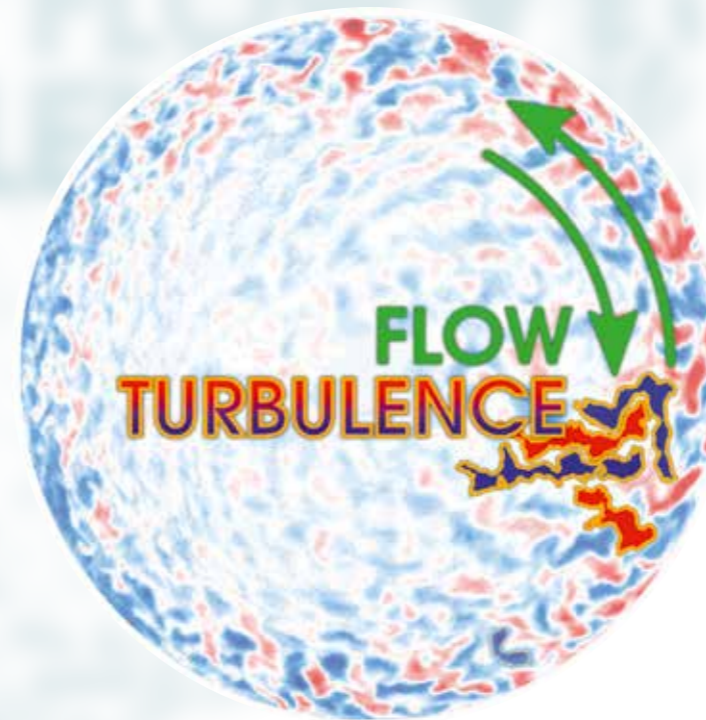
EDDIES EVERYWHERE

In the early days of fusion research, there was some over-confidence regarding the performance of the test devices. Simple calculations based on collisions in the plasma predicted that compact reactors would produce enough fusion power for commercial use. No ITER-size mammoths would be required. In reality, the performance has always tended to fall short of the expected. Even though the trajectory of a single particle in a magnetic field could be understood, the collective nature of plasma was not appreciated sufficiently.

The difference between simple estimates and experimental observations has been pinned on turbulence. The same phenomenon can be seen in smoke or flowing water, where eddies emerge like small hurricanes and break the nice and clean flow pattern. In fusion plasmas, the collective behaviour of charged particles creates analogous vortices that push the heat and the plasma towards the walls of the device. The size of the eddies is crucial: the larger the vortices, the bigger the losses tend to be.

Swirling eddies

Whenever water is flowing fast enough, there are small and large swirls that move the fluid transverse to the flow. The hot and fast flowing fusion plasmas have similar swirls, usually called eddies, that transport the otherwise well-confined plasma particles in unwanted directions. The bigger these eddies grow, the further and faster the particles are transported along them.



A snapshot of simulated plasma turbulence. The red and blue structures are the turbulent fluctuations, while the green arrows indicate the flows preying on the turbulence. Illustration: Paavo Niskala



Picture: private

Paavo Niskala

Age: 28
Origin: Finland
Currently based at:
Aalto University, Espoo, Finland

- @Paavi
- @popelotto
- www.peniskala.net

“ I am working on my doctoral thesis on turbulence in fusion plasmas. It is an intimidating, but also inspiring puzzle, that requires active collaboration across the globe. EUROfusion enables these joint efforts, which is priceless when it comes to making fusion power a reality. As the organisation also helps us students, I could not pass an opportunity to give something back to the community by discussing my topic. ”

IN THE FLOW

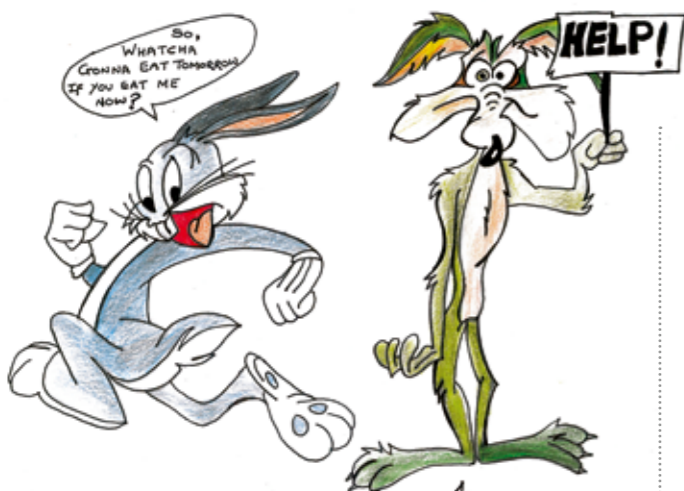
Plasma turbulence is clearly suppressed in some situations. For example, the performance of a tokamak improves drastically and suddenly in the transition to the high confinement mode. This famous H-mode was first discovered by a team lead by Fritz Wagner in 1982. Now researchers achieve it regularly in their experiments. As the turbulence is suppressed on the edge of the plasma, a transport barrier is created. It acts like a dam and removes the leaks from the plasma. Temperature and the density start to rise dramatically in the core, which increases fusion power as well. While the exact mechanisms still elude researchers, they know that flows within the plasma play a key role in creating a transport barrier. The flows in the plasma limit the growth of turbulence. To be more precise, the plasma stream needs to change greatly in the direction perpendicular to the flow. When the variation in the flow is rapid, the turbulent eddies become distorted. If the shear is strong enough, the vortices are practically torn apart and turbulent losses are suppressed which leads to improved performance. This is immensely important for a fusion reactor, since it means increased power output.

Confinement with a capital H

Fusion power output depends on the temperature and the density of the plasma. This is where the high confinement mode or H-mode enters the picture. As the heat and particle losses decrease in H-mode, temperature and density increase and the fusion power increases rapidly. Accessing high confinement mode is thus crucial for the success of ITER and fusion power in general.

NOT ONE DIRECTION

The transition to high confinement has been a challenging puzzle to crack because the interaction of flows and turbulence is not only one-way. As a turbulence pushes the heat and the particles around, it also participates to create the flows. The two-way nature of the interaction makes plasma a self-organising system. It is a formidable beast for theoretical and computational researchers to tame. On the other hand, as our understanding deepens, experiments may take advantage of this feature by driving flows externally and creating optimal configurations for sheared flows to develop.



Cartoon: Amita Joshi

The predator-prey models have been successfully applied to neutral fluids to describe the transition from laminar to turbulent flows. Now the physicists are harnessing them to tackle the self-organisation of plasmas by replacing the rabbits with turbulence and the foxes with flows. This should help us to find conditions that force the turbulence to become extinct, so to speak. The simplicity of the equations appeals to our intuition but it is also deceiving. Reducing the complex behaviour into just a few crucial processes and nailing down the details is challenging to say the least.

SIMPLY COMPLEX

The models require experimental validation like any theory. The predator-prey interaction has been seen in real plasmas, but the details are still fuzzy. Measuring the turbulent properties from blisteringly hot, rotating plasma needs innovative technological solutions and support from theory and modeling. Forging the path forward thus requires close collaboration between experimental, theoretical and computational researchers. They are doing just that at the European laboratories under EUROfusion.

Advanced computer models are developed next to the experimental fusion devices at EUROfusion's Research Units CEA (Commissariat à l'Énergie Atomique et aux énergies alternatives) in France and at IPP (Max Planck Institute of Plasma Physics) in Germany, for example. The most taxing simulations require thousands of processors and days of computing.

FROM RABBITS TO PLASMAS

One approach on modelling this highly nonlinear plasma behaviour draws its inspiration from familiar population dynamics. The predator-prey model has been used to study the dynamics of rabbit and fox populations, for example, using a simple set of equations. As the number of rabbits starts to increase, the fox population increases as well, but with a slight delay. Overgrowth of the predator population and overhunting of rabbits lead to depletion of both populations, and the cycle of growth and decline restarts. It is a classic example of nonlinear interactions in complex systems.

Find out more in the article 'EUROfusion goes full computational throttle' in Fusion in Europe 02/16, pages 10 – 11



www.euro-fusion.org/?p=96530

EUROfusion's new supercomputer, Marconi-Fusion will come in very handy for this work. It sounds like a far cry from the simple equations of predator-prey models. Familiar dynamics may yet emerge from the complex calculations, like they emerge from the collective behaviour of billions and billions of particles in the fusion experiments.

MEXICO: GETTING BACK ON THE FUSION TRACK



Fusion Research Group from the Autonomos University of Nuevo León at the 25th Fusion Energy Conference in Saint Petersburg. Picture: private

Mexico is not usually associated with fusion research. But in the 1970s, the country pursued the fusion quest but was forced to cease work abruptly. The remains of the "NOVILLO" tokamak are a starting point for new developments from the National Polytechnic Institute in Mexico City. The main targets for the new fusion projects are training people in fusion research and conduct experimental research. The efforts are supposed to enable Mexico to again become a country committed to fusion energy.

TWO TOKAMAKS, ONE WINNER

There is no doubt that during the 70s, Mexico aimed to play a vital part in developing fusion technology. There were two projects in consideration at that time: NOVILLO and TPM-1. The tokamak called TPM-1 (Tokamak Proyecto Mexicano), developed by Mario Vásquez, had a major radius of more than 50cm. It was the larger and more expensive of the two devices. TPM-1 was supposed to have a continuous winding for the toroidal magnets. The NOVILLO tokamak, by Jaime Ramos and Regulo López, was a smaller experiment but it had finally received approval for construction. NOVILLO was the first step towards creating fusion energy in Mexico. It contributed to testing, training and experimental research as of 1983.

THE ABANDONED TOKAMAK

Mario Vásquez started the construction of TPM-1 at the National Polytechnic Institute but it was never finished due to the lack of personnel and funding. The tokamak was abandoned later but some of the unused elements were saved by the Research Center for Applied Science and Advanced Technology for future fusion projects.

NEW FUSION ENERGY

The construction of NOVILLO and the planning of TPM-1 have been crucial for the development of fusion technology in Mexico. Since the shutdown of NOVILLO, about ten years ago, Mexico was left behind in the pursuit of fusion energy. But things are about to change. Two new Mexican fusion projects are under construction right now: the tokamak TPM-1U, with project leader Martin Nieto, and the tokamak T, with project leader Max Salvador. Design work for the tokamak T started in 2007 at the Autonomous University of Nuevo León, though the construction itself was only considered after the redesign of the electrical grid of the university. Project leader Salvador explains how the Mexican approach might benefit ITER. “The academics of the Autonomous University of Nuevo León add resources to the development of the magnetic confinement, proposing the design of the tokamak fusion platform in Mexico”.

The Tokamak TPM-1U team of the Research Center for Applied Science and Advanced Technology of the National Polytechnic Institute from right to left: Gonzalo Ramos, Miguel Lindero, Daniel Hernandez, Dulce Ventura, Francisco Ceballos and project leader Martin Nieto. Picture: Ricardo Villegas Ruedas



COMPLEMENT LARGER TOKAMAKS

Future tokamaks will be involved in national and international research. Martin Nieto affirms that Mexico cannot lag behind when it comes to research and development in this field: “We must ensure that we have specialists who are familiar with this technology and who contribute to solve open questions”.

The features of the Mexican devices are planned to serve the different approaches to fusion energy. The tokamak T is designed to deliver important results for material science. The research and data should serve as a complement to larger tokamaks, such as JET and ITER.

WHAT IS SUPERCONDUCTIVITY REALLY?

The future Tokamak T will have superconducting coils. Generally speaking, every conductor has a resistance which enables electrons to flow. Similar to a rock falling through air or water, resistance means the same for electrons. No matter whether it be water, air or any other medium. The conductivity varies from material to material and researchers also know that cooling the conductor lowers the resistance for the electrons.

Questions arise when we want to differentiate very good conductors from superconductors. Superconductors display almost zero resistance. This means that electrons can move freely but there is another important difference: the Meissner effect. This makes the real difference between conductors and superconductors. It means that the superconductor will not allow an external magnetic field inside.

THE IMPORTANCE OF BEING SUPERCONDUCTIVE

Why are superconducting coils so important for fusion research? – There are several ways to create a powerful plasma which should, in the end, deliver energy. One approach is to increase the density of the plasma. That doesn't happen in the magnetic confinement approaches used by tokamaks. The second way is to increase the time of confinement of the plasma so the tokamak can undergo more reactions and produce more energy. Both factors are considered by the so-called Lawson criterion. If it lasts long enough it will produce energy.

See also the article “Lawson’s Criterion: making fusion simple” in this issue, pages 20 – 21



César Alejandro Olivares Macías

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“ I am an undergraduate in physics and I am currently a teacher of science for juniors. I have been interested in fusion since the beginning of my career and I want to stay in the field. I wish for Mexico, as a country, to increasingly inform its own people about the importance of fusion. Just like EUROfusion does by way of articles or journals in Fusion in Europe or on its homepage. ”

HARD WORK AND DEDICATION

Right now it is just a matter of time for Mexico to establish a larger group of fusion scientists and engineers and the experts have already teamed up. The Mexican Fusion Research Group or GIF, based on the Spanish acronym Grupo de Investigación de Fusión, which is responsible for the upcoming Tokamak T with its superconducting coils, has twelve members.

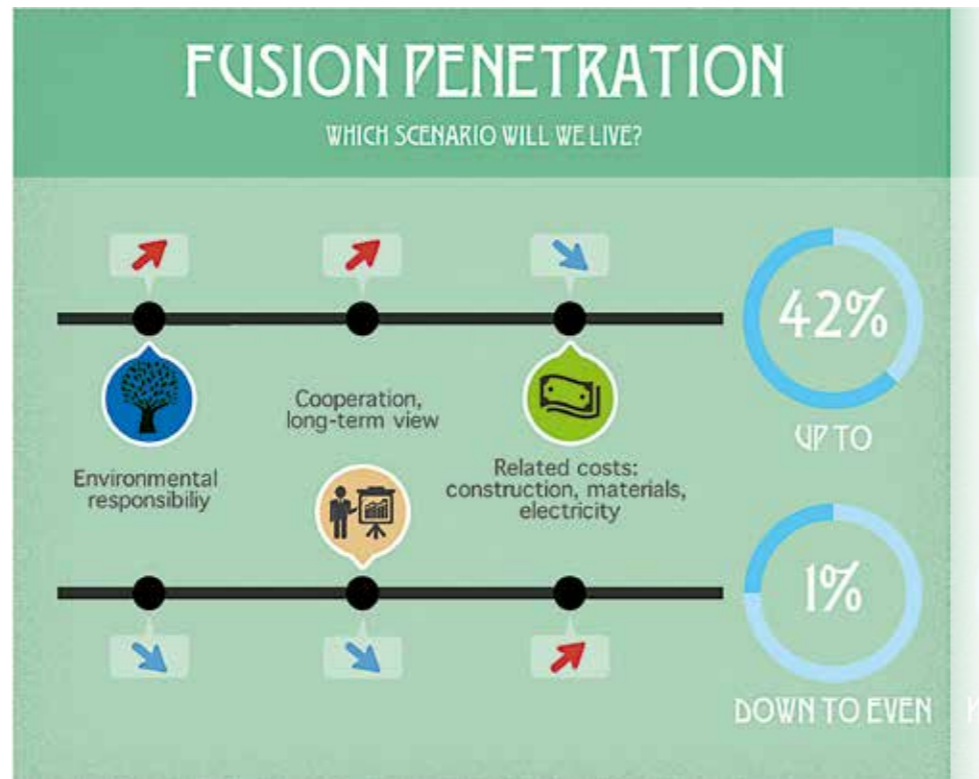
Team leader Max Salvador is aiming high by relying on his enthused staff and believing in hard and dedicated work. Although new to the field, they have already delivered contributions to the worldwide fusion research effort, for example, by delivering an injection system, a chamber design and several control systems. They are also working with the Pierre and Marie Curie University in France, the Technical University of Munich in Germany and the University of Pavia in Italy.

A DIFFERENT STORY TO TELL

Mexican fusion research is in a different position to the one it was in during the 70s. It will soon have two tokamaks online. In response to the demanding needs of energy and environmental solutions, fusion is a long term answer and Mexican teams have shown their commitment and passion for solving the challenge. NOVILLO, with its national and international contributions, was a good example and it will not be the last one.

OPENING FUTURES WITH FUSION ENERGY

EUROfusion aims to develop a reliable power source which can be used to produce energy from nuclear fusion. All efforts are concentrated on making the technology feasible for large-scale, economic electricity production. How can we really benefit from nuclear fusion and what are its advantages over other sources of energy?



The fusion market penetration depends on three major factors which determine the energetic scenario. The figure varies between 42 percent in the best case and 1 percent in the worst case scenario. Graphic: EUROfusion/Arlandini

Alessandro Arlandini

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Origin: Italy
Currently based at: Coventry, UK



“ I am a postgraduate mathematician and I am also very interested in science writing. Fusion energy is something of a day-dream to me and I find EUROfusion very stimulating because it works towards achieving fusion energy in a concrete way. As I have always been involved in the energetic issue, my article is about the role of fusion energy in the future energetic scenario, explaining its benefits and downsides. ”

FROM THE LAB TO THE PLANT

The potential of fusion power is worth researching a future market penetration. The nuclear fusion reaction itself is highly efficient, for instance, ITER’s power production will be ten times the power required to heat the plasma. As far as plants are concerned, we are interested in the overall plant efficiency (that is the output of electrical power divided by the fusion power), because the produced energy will also be used to operate the plant systems. DEMO will target about 25 percent efficiency, but future fusion plants would reach 30 to 40 percent. Further improvements are linked to the use of new materials or designs, both of which we expect to see in the upcoming years.

Secondly, fusion energy is suitable for supplying huge base loads. The first demonstrational fusion power plant, DEMO, targets 500 MW of net electrical output, whereas actual fusion power plants would target at least 1-1.5 GW of electrical output, a value similar to those reached by fossil fuel power plants. The basic fuel resources, deuterium (extracted from water) and lithium (used to breed tritium), are sufficient to ensure many centuries of global electricity supply. Even if the technology must overcome some testing, it appears that we will be able to scale it to meet our needs. Lastly, nuclear power plants do not emit greenhouse gases. Therefore, nuclear energy is going to be a key ingredient in decarbonising energy supplies.

INTO THE GRID

In order to expand, nuclear fusion must also be competitive on the energy market. The advantages must then be balanced with the cost of electricity (CoE). It is possible that power plants are unattractive prospects for investors. In general, the larger the machine the lower the CoE, as Dr Richard Kembleton, Fusion System Modeller at EUROfusion’s British Research Unit CCFE (Culham Centre for Fusion Energy), home of JET, explains:

“ A larger reactor can either target a higher fusion power due to better energy confinement, or the same fusion power which results in lower loads on the components as the power is spread across a larger area. The second option results in longer component lifetimes and therefore a lower maintenance overhead. All these effects contribute to lowering the cost of electricity, which is the critical factor in determining how competitive fusion can be. ”

On the downside, greater capital investments are needed to build larger reactors to the tune of ten billion euros and more. Private investors may be discouraged and governments may face opposition from the public due to the price tag, even though the actual CoE would be low, as is the case for fission plants. This issue can be tackled through cooperation and joint ventures, as EUROfusion, the most promising European-driven work on fusion energy, shows.

Furthermore, when it comes to supplying energy to the whole community, it is the total amount of energy that matters. Western European countries require on average something in the order of 13 GW, a power level that can be supplied by 8 to 13 fusion plants, but building them takes time and money. For this reason, we should regard fusion as one option among a mix of different sources of energy.

FUTURE SCENARIOS

Fusion energy is going to be an essential source of energy in the future. Its availability changes the possible energetic scenarios dramatically. In conjunction with nuclear fission, it can supply huge base loads with a low CoE, so that the remaining needs can be met with intermittent and peaking sources. Simulations show how the market penetration varies greatly depending on several factors such as the environmental responsibility or the material costs, as shown in the information chart. A realistic scenario suggests it will reach about 13 percent by 2100. In this fashion, EUROfusion is providing new opportunities to the community, working hard with national research units and industry to develop fusion technologies. ■

Fusion energy devices, now and then

EUROfusion is involved in several major projects working towards fusion energy. The central devices on the road towards fusion electricity are:

- JET (Joint European Torus) and ITER; nuclear fusion devices which scientists and engineers use as prototypes. JET is due to be shut down after 2018 and ITER will be inaugurated in 2025.
- DEMO (Demonstration Fusion Power Reactor) which will be the first fully-equipped fusion device supplying energy to the grid.

A taste of fusion

RESEARCH AT CULHAM

For anyone as passionate about nuclear fusion as I am, there is no better place to be than at Culham Centre for Fusion Energy (CCFE). Like trying to find a box in which to fit the Sun, Culham scientists, among others, are researching material properties designed to cope with the extreme environments needed to sustain fusion. I was fortunate enough to be able to contribute to this quest in a small way during my five-month placement at EUROfusion's English Research Unit.

GETTING REAL

Being an undergraduate in physics often feels like what you learn in lectures has very little to do with the real world. Since my very first day here, I got to practical grips with ANSYS, a computer-aided design software package which was also used to design ITER. ITER will be the first magnetic confinement fusion device to produce a net surplus of energy. I initially learnt some basic modelling concepts, but later I had to analyse my simulation results using the knowledge I had already acquired at school and at university. Although it is a placement focused on materials research, I realised how vital an understanding of physical concepts is in order to be able to suggest improvements to models for fusion devices.

UNDERSTANDING WHAT HAPPENS

Culham has just recently opened its Materials Research Facility (MRF) which contains specific "equipment for the processing and characterisation of radioactive materials", to quote the outgoing CEO, Professor Steven Cowley. During a fusion reaction, the involved components become irradiated. Thus, an understanding of what happens is crucial when the first ever fusion demonstration power plant, known as DEMO, comes online. This should hopefully take place within the course of this century, perhaps even within my lifetime.

DIFFERENCES BETWEEN STUDYING AND RESEARCHING

A traditional university physics course focusses on passing exams and going through lab scripts without putting any real thought into the experiments. At CCFE, on the contrary, everyone is working towards the most important scientific experiment of the century. During my stay, I have realised the multi-disciplinarity of the field. It requires people with a range of backgrounds and skills to work together to achieve this goal.

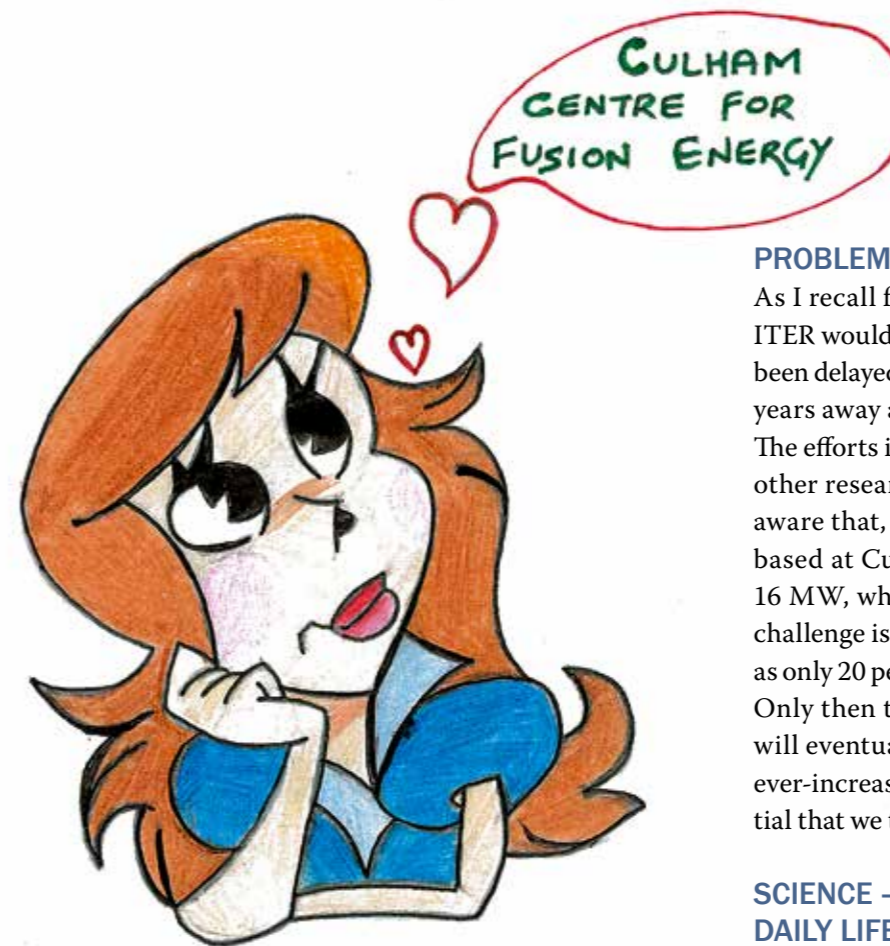
Elrica Feride Degirmen

Age: 20
Origin: Great Britain
Currently based at:
University of Leeds



Picture: private

“ I would like to thank Dr Llion Evans for supervising me during my placement, The Ogden Trust for financial support, Thomas Walker for proof-reading and editing work, Sarah Peace for photography and EUROfusion for allowing me to write about my experiences. ”



Cartoon: Amita Joshi

ESOF: A GREATER ACHIEVEMENT

I also attended the EuroScience Open Forum (ESOF) Conference in July in Manchester. This is held biennially and promotes scientific collaboration across many organisations. One of these is EIROforum, an excellent example of the idea that science goes beyond national borders. EIROforum consists of eight members, among them CERN, ESA and EUROfusion. These organisations have access to a wealth of collective resources and infrastructures, with operations across the world. In this way, the contribution of each individual member adds to the greater collective achievement and drives Europe's scientific progress forward to an unprecedented degree. The EIROforum stand at the ESOF showcased different fusion applications and presented how the outcomes are used within other fields, such as space science and biomedicine.

IT IS UP TO THE NEXT GENERATION NOW

My generation, the one currently in education, is responsible for making fusion work. It was a great privilege to listen to Bernard Bigot's speech when he visited Culham. The Director-General communicated his mission and the goals he wishes to achieve by 2025, which is when ITER is due to become operational. The talk has filled me with confidence that the project will go ahead and the sum of worldwide efforts will result in achieving fusion.

PROBLEMS OR CHALLENGES?

As I recall from my early teenage years, it was said that ITER would start experiments by 2019, but this has since been delayed. This feeds into the belief that fusion "is forty years away and always will be". That is just not the case. The efforts in Culham and in EUROfusion's twenty-eight other research units will play out. The public should be aware that, in 1997, JET, the European-owned tokamak based at Culham set the world fusion power record of 16 MW, which was 60 percent of the input power. The challenge is to achieve at least five times the input power as only 20 percent of the power will stay inside the plasma. Only then the plasma will be able to heat itself. Fusion will eventually be necessary to sustain the population's ever-increasing energy needs. For this reason, it is essential that we turn fusion into a working reality.

SCIENCE - TOO FAR AWAY FROM YOUR DAILY LIFE?

I welcomed being thrown into the deep end during my placement. I knew ultimately that the skills I was developing and the knowledge I was gaining would, bit-by-bit, make me more competent and confident when it comes to a career in fusion. What really matters is a great passion for the field. I think it is vital to see the challenges of fusion research in a positive light. These are the next set of tasks for humanity. We should not fear them, but rather, go forward with faith and regard them as the path towards the solution.

DESPITE THE SETBACKS, IT WILL BE WORTH IT

It can be intimidating reading through journals, scientific papers and the endless manuals on how to get to grips with software, not to mention attending plasma theory meetings with some of the world's leading theorists. However, it was a true learning experience. This was far better than being expected to memorise equations without obtaining a full understanding of the content.

In Culham, I have attended lectures by working scientists and PhD students regarding their very latest research. I was not afraid to question the things I did not know. Every day I was reminded that I was at a place where great things are going to happen, thanks to the many collaborations and networks formed to solve problems. I was sad to leave Culham in September and I hope that this will not be my last time at what is arguably the most inspiring scientific establishment in the UK. ■

Brexit Limbo: SCIENTISTS HAVE THEIR SAY

The UK's decision to leave the EU has been an emotional topic. Policy makers have finally begun to devise a plan in earnest, and the scientific community waits anxiously to understand the consequences for British and European science. Fusion research in particular has benefited from international collaboration, and the Joint European Torus (JET) based at the Culham Centre for Fusion Energy (CCFE) in the UK is at its forefront. However, funding challenges, restricted mobility and the complication of multi-national collaborations may hurt the future of British scientific research. Author Alyssa Mello spoke to international researchers.

UNATTRACTIVE PROSPECTS AT HOME

Eventually, many questions will be answered as agreements are signed. For those already established in their careers, it may be easy enough to wait and see how the dice falls. However, many students will not have this luxury. Natalie Wilson is nearing the completion of her Master's at Ludwig Maximilian University of Munich and remarks, "Initially, my plan was probably to go back to the UK and take back all the experiences that I have had here and incorporate those into a research group back home. But now, I think the UK looks unattractive. I think the main reason for that is just the uncertainty around what is going to happen."



Natalie Wilson



Sebastian Busch
Pictures: A. Mello

EU may nevertheless harm international cooperation. Scientists who are choosing between similar positions in EU vs. non-EU countries may be deterred by the added complexity of the latter. While acknowledging that, for many the immediate concern is funding, Dr Sebastian Busch of the Heinz-Maier-Leibnitz Center in Munich "fear[s] much more for exchange, mobility, and ultimately collaborations across the channel." As Dr Busch says, "For me, the crucial point is that being part of the European Union is about belonging together and having a common cause; the outcome of the referendum feels like a rejection of these ideas and of their proponents."

Watch Natalie's statement here

[www.euro-fusion.org/
?p=125221](http://www.euro-fusion.org/?p=125221)



MAKING IT HARDER TO CROSS THE CHANNEL

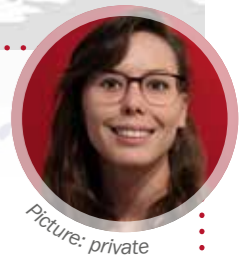
While the camaraderie of European and British science appears to have risen above the anti-foreigner rhetoric surrounding the UK's referendum, a withdrawal from the



Illustration: Creative Commons

Alyssa T Mello

Age: 26
Origin: USA
Currently based at: Munich, DE



Picture: private

“Coming from a background in film, I discovered that my favorite stories to share were about science. I'm currently pursuing a second bachelors in physics and hoping to make scientific communication a part of a larger research career. Fusion is certainly one of the most vital and interesting topics of the near future, and one that showcases the potential of international scientific collaboration.”

MORE THAN THE SUM OF ITS PARTS

A great deal of the debate around the referendum addressed the economics of remaining or leaving the EU. In science, however, monetary profit is often an inadequate measure of value. Prof Jonathan Finley of the Walter Schottky Institute remarks, "EU projects rarely bring in huge amounts of money but they do something much more than that – they catalyse international collaboration and, in my experience, are always more than the sum of their parts. As such, they incubate new projects by putting young scientists into touch with each other." Furthermore, cutting edge research often requires immense resources and, with regards to the financial considerations, Finley notes that



Jonathan Finley

"the various EU schemes for funding science are a wonderful way for European science to collectively compete with large scale coordinated projects in USA and Japan – especially flagship projects that would be unthinkable for domestic support."

CRACKS IN THE CRYSTAL BALL

It is impossible to say exactly how the 'Brexit' will impact British and European science, but the extended limbo has certainly proved stressful for many. Official statements were quick to assure that European funding and collaborations are secure for the time being. Nevertheless, as Prof Steve Cowley of UKAEA says of JET, the future is "much more uncertain". Indeed, it seems to be with mostly braced and heavy hearts that British and European scientists await the outcomes of official negotiations.

I want to make a
DIFFERENCE,
I want to change
THE WORLD

Professor Ian Chapman is a rising star in the fusion world. Chapman succeeded Professor Steve Cowley as Chief Executive Officer (CEO) of the UK Atomic Energy Authority at the beginning of October. At the age of 34, Chapman is one of the youngest CEOs of a major research centre. He brings his passion for fusion to the role while leading the UK's research programme for magnetic confinement fusion at the Culham Centre for Fusion Energy (CCFE), the home to JET. Meriame Berboucha had the opportunity to ask Professor Chapman a few questions. His answers also shed some light on the future of fusion in the UK after Brexit.



Ian Chapman with fusion writer Meriame Berboucha. Picture: private

Why haven't we perfected fusion yet?

"The big challenge we face in fusion is integrating all challenging constraints into one stable fusion reactor. The individual tasks sound bonkers: we say we are going to take a fuel which is the most intense neutron source on Earth. We are going to make it ten times hotter than the Sun's core – sounds ridiculous, but we do it every day. Then we put that fuel in a box and parts of that box have to withstand heat loads of similar conditions to a re-entering space shuttle – again sounds bonkers, but we can find ways to do that. Fusion offers so many potentials: it is limitless energy, produces no radioactive by-products or long-living radioactive waste, it requires little space, steady state – it's everything that you want in a power source. Solving the individual tasks are challenging for the community. ITER will be a proof of the

principle and an absolutely essential step. I think the UK programme, in particular, as well as the European programme are both efficiently set up to do so. But we must do it".

“ *Plasma physics is far more embryonic so you are learning new things every day.* ”

What is it about fusion that fascinates you the most?

"The beauty of fusion for me is that it has the two things that I wanted when I was looking into different career options. Fusion is very mission oriented, I'm quite an altruistic per-

son, I want to make a difference, want to change the world. Fusion really does that, it is such an important thing for mankind to find a solution. At the same time, the science that we do is just intrinsically fascinating. Plasma physics is not a very old field, it's not like classical dynamics which has been around for centuries. Plasma physics is far more embryonic so you are learning new things every day. And so, you're coupling those two things: a very important mission with an intrinsically fascinating science".

What does it feel like to be one of the youngest CEOs of a major research centre? Will you bring something different to the role?

"First of all, I firmly believe that Culham is the world's best fusion laboratory. We have a unique mix of engineering

skills, scientists and cutting edge technologists and I just feel really honoured to be able to lead that amazing group of people. Fusion for me is the challenge of my generation. I am committed to realising fusion energy. I hope that I bring that passion through in this job".

“ *Fusion is the challenge of my generation.* ”

How did you make it to the top of CCFE and what do you think about ITER?

"I did a masters in Mathematics and Physics at the University of Durham, then I did a PhD in plasma physics

at Imperial College London, after that, I joined Culham on the graduate scheme and I've slowly moved up the hierarchy. When I was at university I was reading a lot about ITER and the preparations for it. Not long after I joined Culham in 2004, the ITER agreement was signed, so ITER, in some sense, defined my career. I was here more or less as ITER was signed and, at the end of my career, we will have achieved success with ITER".

JET is used by about 29 European laboratories and their partners – how important is international collaboration for a successful fusion quest?

"I am firmly of the opinion that science moves faster if you collaborate. That is the beauty of fusion, everything is open, we're completely open and collaborative. In my opinion, ITER is the most collaborative endeavour that mankind has ever done. We are progressing faster as a field by being together, there's no doubt about that".

How will you proceed in the international exchange in times of Brexit?

"Brexit is certainly a concern for us, we need to find a route through this somewhat more complicated landscape now. It is really important that the UK remains open and collaborative and doesn't turn its back on our partners, be that European partners or international partners. It is vital that we stay within that community and don't become insular. We continue to look outward and that is what we will do as a laboratory".

What are the main new technologies that are being developed to advance magnetic confinement fusion at CCFE?

"If we look around the Culham site, we have JET, the world's best tokamak at the moment. It is absolutely essential that we are running that in preparation for ITER, but we are beginning to think about what comes thereafter. We have a new research facility which is looking at material properties under significant irradiation. Since a fusion reactor is a very challenging environment, we have a specialised robotic applications centre. Answering the question of how to maintain that reactor and make sure it is available for as much of the time as possible is very important. How we are going to manufacture the materials that can withstand these high heat fluxes and intense neutron bombardments are the challenges the fusion community faces. At Culham, we have facilities which are designed to do exactly that".

“ *JET won't be here when ITER is burning plasmas.* ”

What happens to JET when ITER finally starts to burn its first plasma?

"JET won't be here when ITER is burning plasmas, as a community we should be putting everything towards ITER – we must make ITER work. Having said that, JET is the best place to make sure that ITER does work, we must prepare as thoroughly as possible using JET, but once we have ITER and ITER is operational, we should be focussed on ITER, and at that point we won't be operating JET anymore".

Watch the entire interview here:



www.euro-fusion.org/?p=125163



Picture: private

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- www.merameberboucha.weebly.com

“ *I am fourth year MSci Physics student with a passion for science and science communication. I've caught the physics bug and I'd like to share my enthusiasm for the subject with others in the hope that they will catch the physics bug too!* ”

EUROPEAN CONSORTIUM FOR THE DEVELOPMENT OF FUSION ENERGY
REALISING FUSION ELECTRICITY BY 2050

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EUROfusion



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