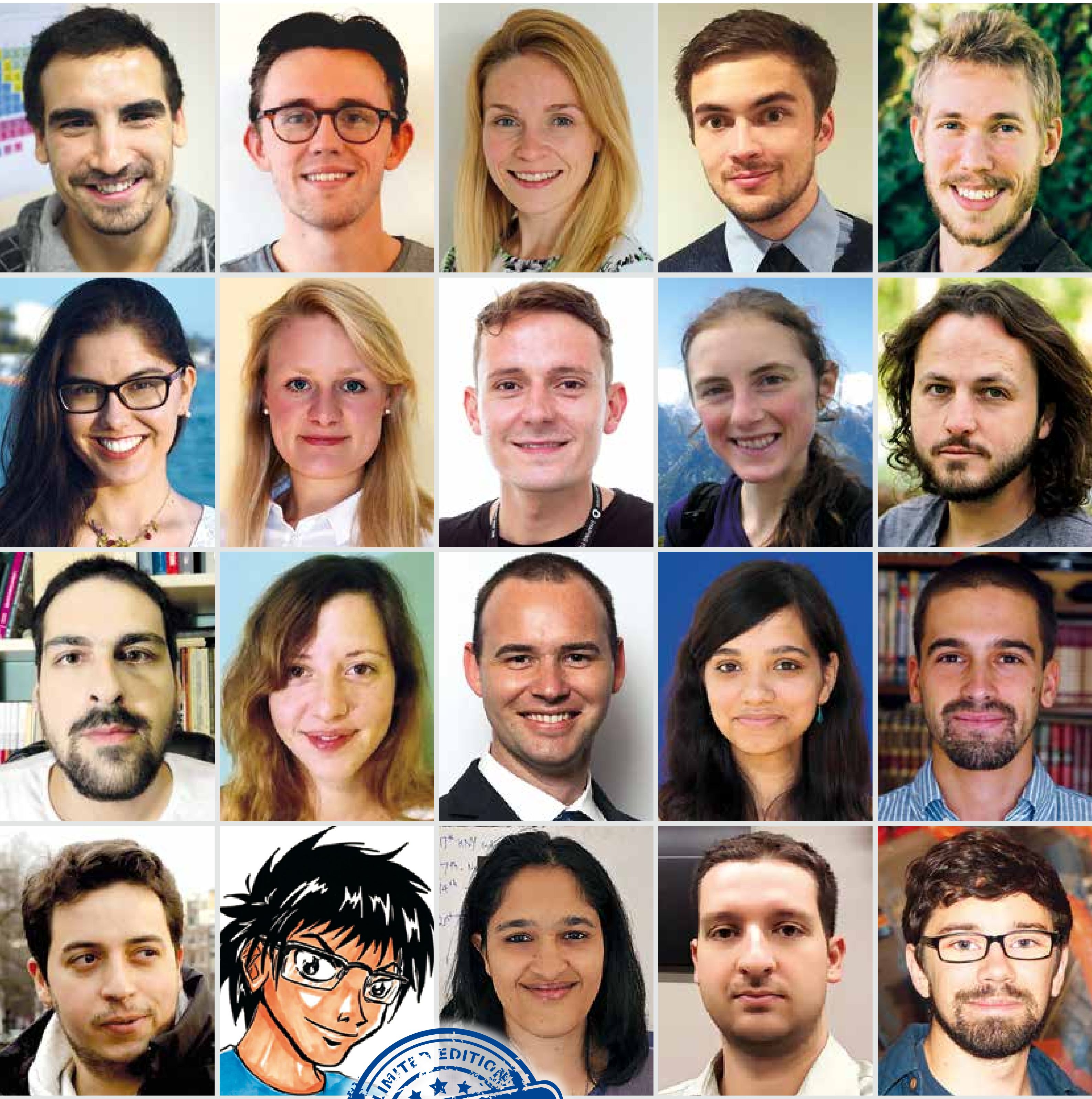
FUSION IN EUROPE

NEWS & VIEWS ON THE PROGRESS OF FUSION RESEARCH

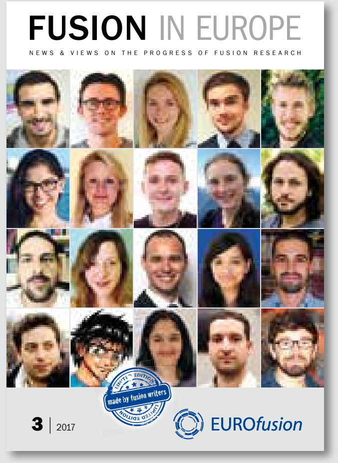


LIMITED EDITION
made by fusion writers
LIMITED EDITION

3 | 2017

EUROfusion

Here we are with a second edition of the Fusion Writers Project. This time we took a look into EUROfusion's Research Units and discuss rather unusual topics such as proliferation.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Whodunit?? Tracing back a saboteur who had killed a beautiful fusion plasma.

Picture: B. Simony

How will the energy mix of the future look like? Author Davide Silvagni discusses the next century.

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Picture: EUROfusion

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JUMP ON BOARD!

Wow, what a journey! Fusion in Europe continues the successful Fusion Writers project in 2017! You now hold in your hands an edition that includes articles from young fusion enthusiasts, born in Australia, Brazil, the U.S., India and, of course, many European countries.

We know, this magazine is called "Fusion in Europe" but EUROfusion's research also has links with what is happening across the pond ... and even further beyond.

The current edition features 16 essays written by authors who are mostly about to finish their PhDs. Hence, you'll find more scientific content compared to the 2016 edition. We wanted to take a look inside EUROfusion's Research Units, wherever we were given the opportunity to do so, and we wanted to hear the news straight from the horse's mouth. They chose their topics entirely on their own and they were free to speak their mind. We have encouraged our authors to report from their labs in entertaining and understandable ways. And many have succeeded, Žiga and Sarah for instance.

Their secret? Passion. What drives a person to chase neutrons, what's so interesting in checking out the ashtray of a fusion device and, most of all, why should it matter to the world? If the writer is able to share his or her motivation, then we are winning.

I have been on that journey for years and I sometimes don't know where the road is taking me. Unexpected things happen and lead to something new, such as this fresh feature: the fusion basics boxes.

The author of those packages is Oisín McCormack. He has an extraordinary ability which enables him to explain crazy complicated fusion matters in just three minutes. We used that skill and identified fusion topics which come up on a constant basis and which need further explanation. As a result, we ‚forced' Oisín to explain them with the help of 80 words only, pack them in a box and, hence, take the burden off the author's shoulders. And Oisín did very well.

In fact, the boxes made the authors collaborate. For instance, writers whose essays dealt with, let's say "tritium"; such as Paul, David and Rodrigo, who, by the way, live on different continents, needed to talk things over. They held intensive discussions to achieve a crisp but correct explanation, and finally agreed on a tiny square which is now shared by all of their essays.

I would dearly like to thank all of the involved writers and, especially, the cartoonists Amita and Benoît, for their incredible commitment and their reliable punctuality.

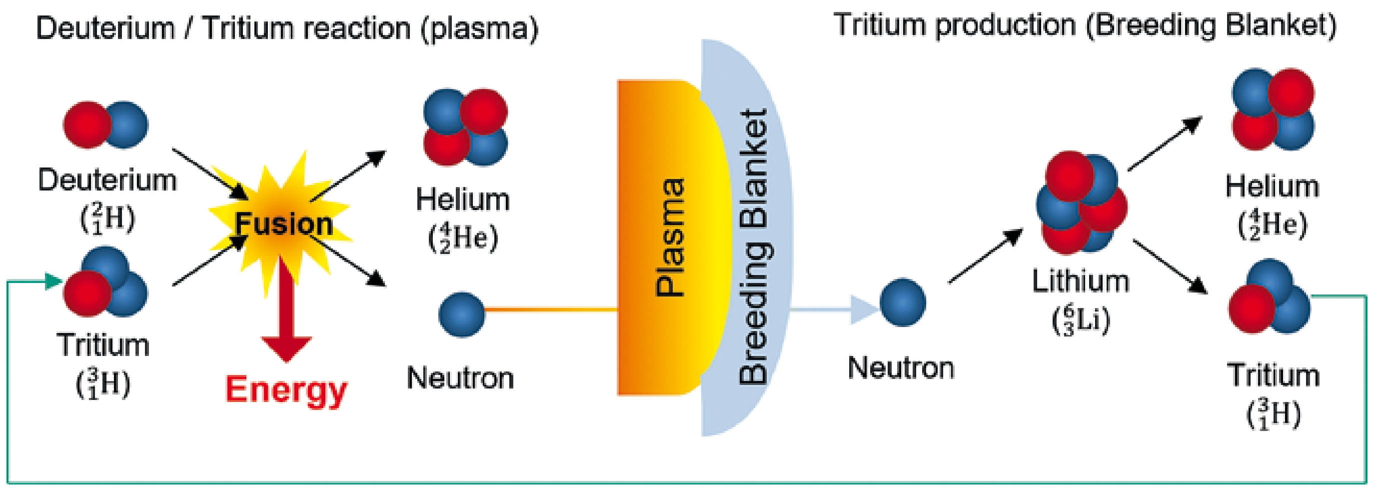
It was a thrilling ride and I am happy that we decided to embark on that journey once again. It was a great lesson to learn that even while travelling down the same path twice, you will find something new along the way.

Anne Purschwitz
Editor of Fusion in Europe
Picture: EUROfusion

TRITIUM:

A CHALLENGING FUEL FOR FUSION

Deuterium and tritium, two isotopes of hydrogen have, for decades, been considered the fuels for the first generation of fusion reactors. Deuterium is practically inexhaustible due to its presence in our oceans. When it comes to the heavier tritium, the story differs considerably. Tritium is radioactive, decaying with a half-life of 12.3 years, which explains its almost natural lack of existence. In fact, the natural tritium abundance is only around 3.5 kg



Picture 1: Schematic diagram of the tritium breeding inside a fusion reactor. Deuterium-tritium atoms fuse in a hot plasma to produce one atom of helium-4 atom, one neutron and, along with it, energy. The fusion neutrons will escape the plasma and react with lithium atoms present in the so-called breeding blanket to produce atomic tritium. Picture: KIT-ITeP-TLK

Picture: private

Rodrigo Antunes

Age: 25

Origin: Portuguese

Currently based at:

Karlsruhe Institute of Technology – Institute of Technical Physics – Tritium Laboratory Karlsruhe (KIT-ITeP-TLK)

> *“I am currently doing my doctoral research at the tritium laboratory in Karlsruhe. For many years, I have been interested in the challenges our society will need to face to solve our ever increasing energy demands. Nuclear fusion is a promising energy source to which I have been contributing over recent years. Therefore, together with young fusion scientists and engineers, I am glad to take part in this special issue of Fusion in Europe.”*

THE NEED FOR TRITIUM BREEDING

This means we have a problem. How are we able to harness energy created by fusion reactions if one of the fuels (that is to say, 50% of the required reactants) is basically inexistent? The simple answer is: we need to produce our own tritium inside the reactor in the so-called Breeding Blanket (BB). The BB is comprised of lithium-based materials and covers the inner wall of the reactor vessel to guarantee tritium production. The reactions between the fusion neutrons produced inside the vessel and the lithium atoms present in the BB generate atomic tritium (Picture 1). Then, another important question arises: how do we process the new-born tritium?

As you can imagine, there are a collection of other systems responsible for extracting, processing, measuring and injecting the fresh tritium inside the machine. The designs of these systems are largely determined by the special properties of tritium.

HOW DO WE HANDLE TRITIUM?

Tritium behaves in a similar way to hydrogen: it easily permeates metals (especially if hot!) and reacts explosively with oxygen. However, tritium decays, as opposed to hydrogen. In addition, tritium will readily swap with hydrogen if both meet on the way (the so-called isotopic exchange). This is of particular concern since tritium poses a serious threat to

TRITIUM

Tritium (also called hydrogen-3) is a radioactive isotope of hydrogen, and has one proton and two neutrons. It can be produced using lithium to absorb the energetic neutrons created in both fission and fusion reactors. Tritium has a rate of decay of about 5% per year. It radiates rather weakly externally, however it is hazardous if ingested, inhaled, or absorbed through the skin. It can react in order to create dangerous radioactive “tritiated” water, which must be controlled to prevent it from contaminating local groundwater.

Picture 2: Rodrigo Antunes (right) and his colleague working in the "CAPER C" glovebox. This glovebox hosts the experimental setup to separate tritium species from helium with zeolite membranes, which is the core of my PhD. Picture: KIT-ITeP-TLK

human beings if it replaces hydrogen in our biological systems. Therefore, it is very important to confine tritium within carefully chosen materials and conditions. Polymers, for example, which are present in commercial pumps or used as sealant materials, are not an option. The hydrogen-tritium replacement would considerably alter the properties of the material. Therefore, a rule of thumb among tritium fellows is: no use of polymers, just inorganic/metal substances. However, as mentioned above, an additional challenge arises when metallic ducts contain tritium, as it can readily permeate them. A good trick is to constantly maintain low tritium partial pressures at low temperatures (for instance, around 20°C) in order to control permeation. If this is not possible, it is necessary to implement tritium permeation barriers. If this is still not sufficient, a glovebox surrounding the tubes containing tritium must be considered.

WORKING AT A TRITIUM LABORATORY

Major tritium laboratories, such as the one at the Karlsruhe Institute of Technology, operate under an air pressure cascade. In this situation, the pressure inside the lab is slightly lower than the pressure outside in order to prevent tritium being released into the environment. Gloveboxes, which host the tritium processing lines, offer another level of static confinement with an interior pressure slightly lower than that of the lab.

The inert atmosphere of these boxes is constantly refreshed providing an additional dynamic confinement. In Picture 2, you can see a picture of my colleague and me working with a glovebox. The box contains the components which I require in order to obtain my PhD on tritium separation technologies in view of DEMO.

> *"All in all, these collaborative efforts are necessary to ensure that tritium, along with deuterium, will be the fuel of commercial fusion power plants."*
>
> Rodrigo Antunes

Tritium will have its own plant

In a fusion reactor, most of the systems processing the fusion fuels will be hosted in the so-called Tritium Plant (TP). Here, the different isotopes can be isolated by detritiation of gas streams, so that deuterium and tritium can again be fuelled into the reactor. ITER, now under construction in France, will have a 35 m tall x 80 m long x 25 m wide TP building. These dimensions are necessary to house the systems responsible for tritium recovery, isotope separation, deuterium-tritium fuel storage and delivery.
However, it should be noted that ITER will only test small mock-ups of tritium breeding elements, with an estimated daily production less than 0.4 g. In contrast, the European DEMO, designed to demonstrate tritium self-sufficiency at a reactor scale, may reach a production as high as 250 g/day. Thus, in view of DEMO development, many European labs are studying and designing different tritium breeding, processing and extraction systems. All in all, these collaborative efforts are necessary to ensure that tritium, along with deuterium, will be the fuel of commercial fusion power plants.

A BLANKET
TO FUEL FUSION

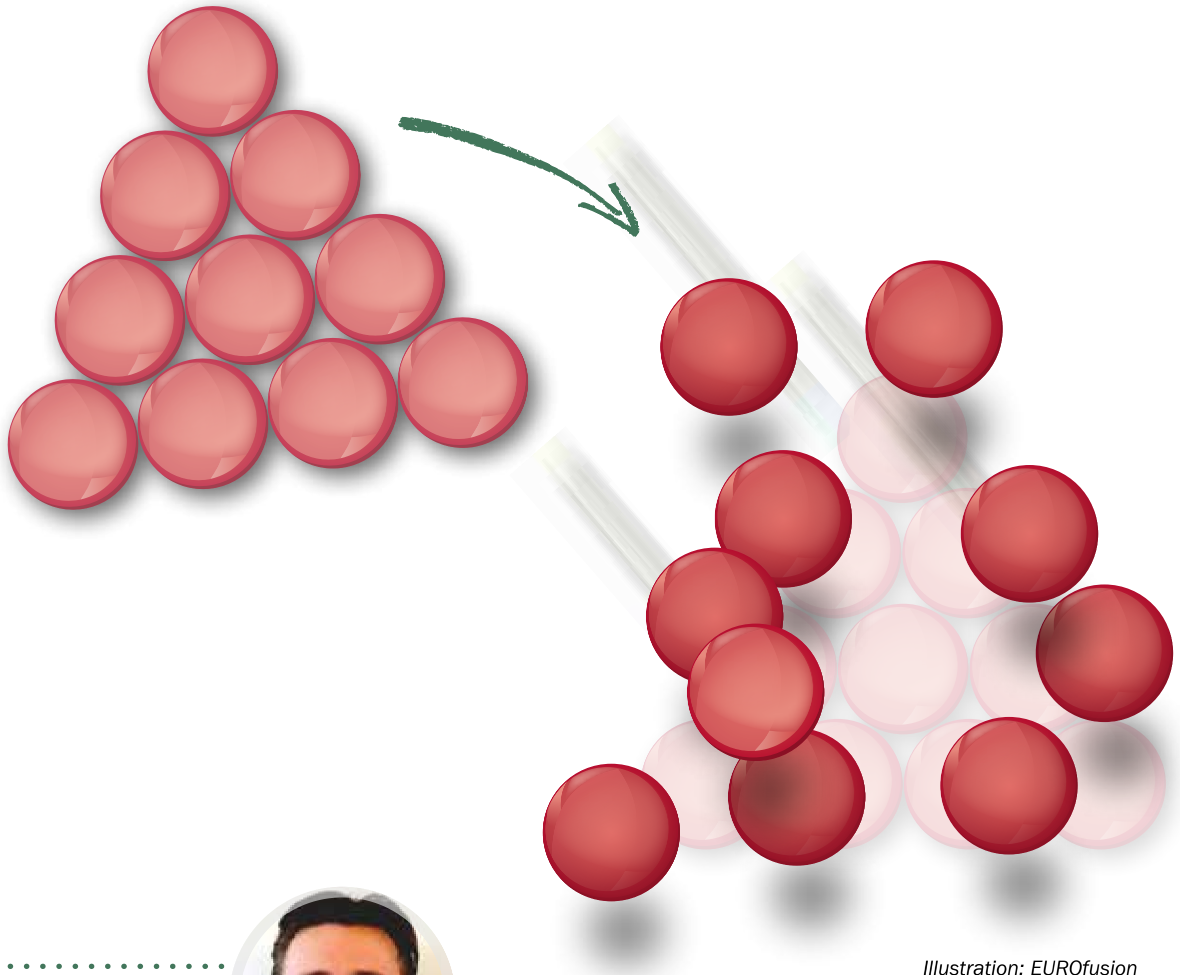


Illustration: EUROfusion

Harnessing the energy generated by a fusion reactor while simultaneously generating more tritium fuel to sustain the reaction is no easy task. However, that is what is required from a blanket, the enormous structure that lines the outside of the first wall.

ENERGY CAPTURE

The energy given off in a fusion reaction comes in the form of highly energetic alpha particles and neutrons. The neutrons escape from this confinement and are eventually captured by the blanket. The kinetic energy of these particles gets imparted to the structure that captured them, generating large amounts of heat. Heat from the blanket is then transported with a coolant which goes on to drive turbines to produce electricity. This part of the reactor works in the same way you might see in a fission or coal power plant. It sounds simple enough, but there are a number of caveats that make this task difficult. For example, even the coolant can cause corrosion of the metal due to the high temperatures involved.

RADIATION DAMAGE

When neutrons collide with a solid material, they scramble the well-ordered atoms inside of it (imagine the start of a game of pool). Atoms that have been displaced from their original positions can have a profound effect on the properties of materials, causing them to crack or fail unexpectedly. On top of this, when a neutron is absorbed, a completely different atom can be created in a process known as transmutation. These new atoms further change a material's properties and can often be radioactive. As a result, special new materials must be designed that can withstand the effects of neutron damage without becoming too radioactive.

TRITIUM BREEDING

Not only must the blanket withstand neutron bombardment, it must also be responsible for generating more tritium, required to sustain a continuous fusion reaction.

There are many different potential designs for the blanket breeding system and they all have advantages and disadvantages. One design utilises a molten mixture of lead and lithium to multiply neutrons and breed tritium respectively. However, liquid metal flowing around the structure can cause problems as it interacts with the massive magnetic field of the tokamak.

PUTTING IT ALL TOGETHER

As the blanket is an enormously complex structure, it needs to be tested before operation. ITER will be built with six ports where test blanket modules can be inserted and removed. The data gathered from these test components will be vital for continuing to develop and improve what is arguably the most challenging component of the fusion reactor to design. ■

Read more in the article "Tritium: A challenging fuel for fusion" by Rodrigo Antunes on the pages 4 – 7 in this issue.

TRITIUM
AS FUSION FUEL

There are many particles that can create fusion energy, but fusing two isotopes of hydrogen – deuterium and tritium – is the easiest to achieve. This reaction produces a high-energy neutron which will escape the plasma and hit the reactor walls. Tritium is very rare, but self-sufficiency can be achieved by a "breeding blanket" lining the walls, where the escaped neutrons are augmented by a neutron multiplier and react with lithium to produce tritium. This tritium is then extracted and recycled for fuel.

Picture: private

Paul Barron

Age: 23
Origin: British
Currently based at: Manchester, UK
@paulbrrn

> *"In my opinion, if fusion energy is harnessed as a viable power source, it will be the greatest scientific achievement in the history of humanity. In addition to the scientific merit, it will also help reduce the world's reliance on carbon energy sources. It is for these reasons I have chosen to study a PhD in materials for fusion reactors."*

COULD THESE SHINY METALS UNLOCK THE POWER OF THE SUN?

While Beryllium and Lead may hold the honors of being tested in upcoming DEMO breeding blankets, Bismuth (picture) is the undoubtedly most colorful of neutron multipliers. Picture: Wikimedia, Hans Braxmeier

Neutron multiplying materials may help us create all the fuel we need to ensure a fusion powered future.

Picture: private

David Tompkins

Age: 25

Origin: American

Currently based at:

Providence, Rhode Island

“I am a marketer at Hasbro, Inc. with undergraduate degrees in Marketing and Mechanical Engineering from the University of Pennsylvania. I believe that if you want to make the world a better place, you should build something that is either for kids or for the future. The work being done by EUROfusion will make the world a better place, and I’m very thankful for the opportunity to write this piece.”

If a strange man were to approach you on the street and offer to sell a jar of mystic metals which would magically allow your car to create all the fuel you could possibly need – you would not be faulted for laughing. However, if a fusion scientist approaches you with a similar offer, you should hear them out. They just might be telling the truth.

TRITIUM – AN EXPENSIVE, PRODUCIBLE FUEL

Unlike a car, which constantly requires new fuel, a fusion reactor is capable of producing some of the key components of its own fuel. In fact, most reactor designs are intended to create at least as much fuel as they consume. This is a rather wise design choice, since tritium, one of the key ingredients in most nuclear fusion fuels, costs about €25k per gram (roughly $30k for my American fellows).

Making tritium can be tricky in practice, but it is straightforward to explain. The standard fusion reaction consumes one bit of tritium and releases one neutron. We can use the neutron to make one more piece of tritium. At the end of the day, we have the same amount of tritium, some extra energy, and a little less lithium, since this is used to make the new tritium. Unfortunately, we have not yet perfected this task. Sometimes, we lose a piece of tritium (it’s a slippery one), or our neutrons hit the wrong bit of wall and are wasted. Either way, we slowly deplete our tritium supply.

> ***Rodrigo Atunes and Paul Barron have written excellent articles on the pages 4 – 7 and 8 – 9 in this journal discussing the details of tritium production. Both are very much worth your time.***

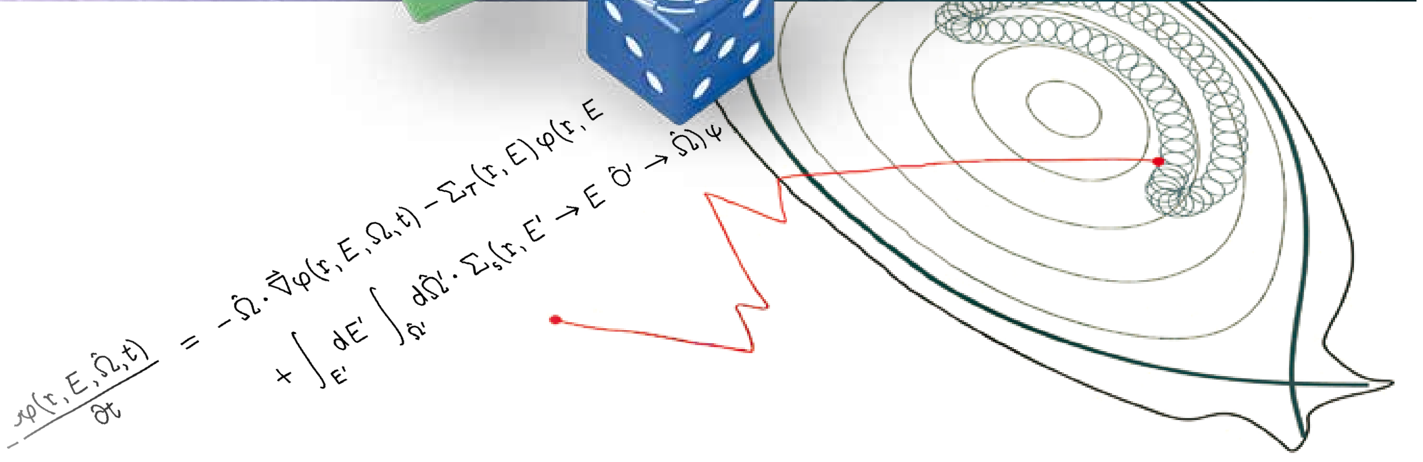
A JAR OF MAGICAL ELEMENTS COMES IN HANDY

Particularly if that jar is full of “neutron multipliers” – substances that, when hit with one neutron, release two neutrons. If we are able to use substances like these, such as the commonly available lead, the rather exotic beryllium or the colourful bismuth, we make it much easier to create all the tritium we need. With neutron multipliers, we trade in a very high-energy neutron for two slightly less energetic neutrons. If we manage to, in turn, combine both of these with lithium – we could actually end up with more tritium than when we started. In fact, present designs suggest that we could breed roughly 20 percent more tritium than we consume! For reference on the TBR stat which discusses analysis of a breeder blanket module that utilizes beryllium as the neutron multiplier.

THE ROAD AHEAD

There are many challenges to overcome when using neutron multipliers (some are quick to melt, some are toxic, etc.), but there is also a tremendous opportunity, namely cheap, clean, and nearly limitless energy. We face a very curious future – where these beautiful and sometimes hazardous metals might help us harness the same reactions that power the stars above. ■

FUSION NEUTRONICS – THE **BIGGEST GAMBLE** IN THE GALAXY?



Picture: Istock/seyfettinozel

Illustration: Žiga Štancar

Picture: private

Žiga Štancar
Age: 27
Origin: Slovenian
Currently based at:
Jožef Stefan Institute, Slovenia

> *“Since I was a child I was captivated by the world of science, motivated by things we cannot yet explain. Working in neutronics, I am still mesmerised by the fact that one can successfully recreate the phenomena observed in large fusion devices by simulating an immense number of individual sub-atomic particles. I consider it a great honour to contribute my part to the mosaic of fusion energy research by way of my endeavours in neutron and plasma physics.”*

Who would have thought that simulating games of chance could be considered a serious scientific pursuit, giving birth to a technique capable of solving complex problems in physics? The story of the Monte Carlo method begins in the underground labs of the Manhattan Project and continues with modern supercomputers running neutron transport calculations. For more than 60 years, the use of this method for advanced neutronics codes has been aiding mankind in our quest to harness fusion energy.

DETECTING ILLUSIVE, YET POWERFUL PARTICLES

In commercial fusion power plants, the energy deposited by neutrons into a blanket surrounding a plasma will provide power to the national grid. JET has shown that deuterium and tritium create a promising fuel for fusion, producing neutrons travelling at around 40,000 km/s. It is essential that we are able to predict neutron intensities reliably in order to optimise a future fusion power plant

Neutrons are an inevitable part of fusion. They are born within fusion reactions in plasmas composed either solely of deuterium ions, or of a mixture of deuterium and tritium. Being chargeless, neutrons escape from the plasma chamber, hitting the walls and penetrating deep into the tokamak's structure. Neutrons are able to change the nuclei of the atoms they interact with – the consequences are either vital to the envisioned fusion device's electricity production or destructive. It is therefore crucial to be able to predict how many neutrons are born in the plasma and in what manner they interact with their surroundings. To uncover the collective impact of neutrons, scientists perform complex neutron transport computations using sophisticated computer codes. These codes rely on the Monte Carlo method, and enable us to simulate the individual behaviour of billions of neutrons by drawing upon large quantities of random numbers. What the last century deemed science fiction has become science fact thanks to the rapid increase in the world's computational power.

FROM THROWING BAGUETTES TO A CASINO IN MONACO

The question of whether random events are able to lead to concrete conclusions was first answered in the eighteenth century by an influential French scientist, Count Buffon. He proved it was possible to determine the value of pi by tossing baguettes onto a lined tile floor. Thus, the probability that a baguette will land on a crack is proportional to the mathematical constant. Moreover, he showed that the pi estimate was more accurate with every additional baked delicacy thrown over his shoulder. It was not until the Manhattan Project, designed for the development of nuclear weapons, that the fundamentals of the Monte Carlo method were established by some of the brightest minds of that era. The method is named after a casino in Monaco, since it enables complex physics problems to be solved by repeated random sampling, a process akin to playing games of chance.

ANYONE INTERESTED IN A GAME OF DICE?

The Monte Carlo method was applied to neutron physics from the very start, more specifically to the study of neutron travel through radiation shielding material. Although the theory of neutron transport has been well established using the Boltzmann equation, it proves difficult to solve analytically without significant simplifications. This is especially true for complex systems such as a tokamak. In contrast, modern Monte Carlo simulations treat deterministic problems by first finding a probabilistic analogue. This means the lives of neutrons in a fusion device, known as histories, are individually simulated from birth to absorption or loss from the system. The specifics of a neutron's path – place of birth, direction of movement, distance travelled and type of interactions – are determined by random sampling of well-known physics phenomena. One can imagine the sampling process to be akin to throwing dice, the outcome of which defines the result of an event the neutron encounters. For example, if a neutron is bound to interact with an atom in the walls of the tokamak, we can use the knowledge of the probability of absorption, scattering or an inelastic scattering reaction and determine which one of the three will occur in the simulation – all based on the result of the roll of a dice.

A MULTITUDE OF NEUTRON HISTORIES

The number of neutrons generated in a tokamak plasma is enormous. To get to an accurate representation of reality, several billions of neutron histories need to be simulated using Monte Carlo neutronics codes. In order to combine this with complex tokamak geometry, we need to perform a huge number of "dice rolls", a task that is made possible by the increase in computational resources. The conclusions drawn from a multitude of single neutron simulations are analysed to obtain knowledge of quantities of interest. For example, the amount of tritium breeding, wall heating, material embrittlement or dose rates.

It is somewhat counterintuitive to imagine that throwing dice might give us insight into not only what is going on in a fusion reactor, but also how galaxies have evolved or whether it is going to rain tomorrow. However, Monte Carlo simulations repeatedly prove to be a powerful tool in providing answers to problems that are difficult to solve analytically. ■

WHAT MAKES NEUTRONS INTERESTING?

In a fusion device neutrons are both instrumental and problematic. High-energy neutrons released during fusion reactions may escape from the plasma and deposit energy in the blanket. Converting this energy into heat will be the most promising way to power the national grid. The measured number of neutrons produced in fusion reactions provides information about the power output, as well as the rate of fuel consumption. In addition, neutrons are used to breed the tritium necessary to fuel a self-sufficient reactor.

See also the article „A blanket to fuel fusion“ by Paul Barron on pages 8 – 9 n in this edition.

Picture: private

Chantal Nobs

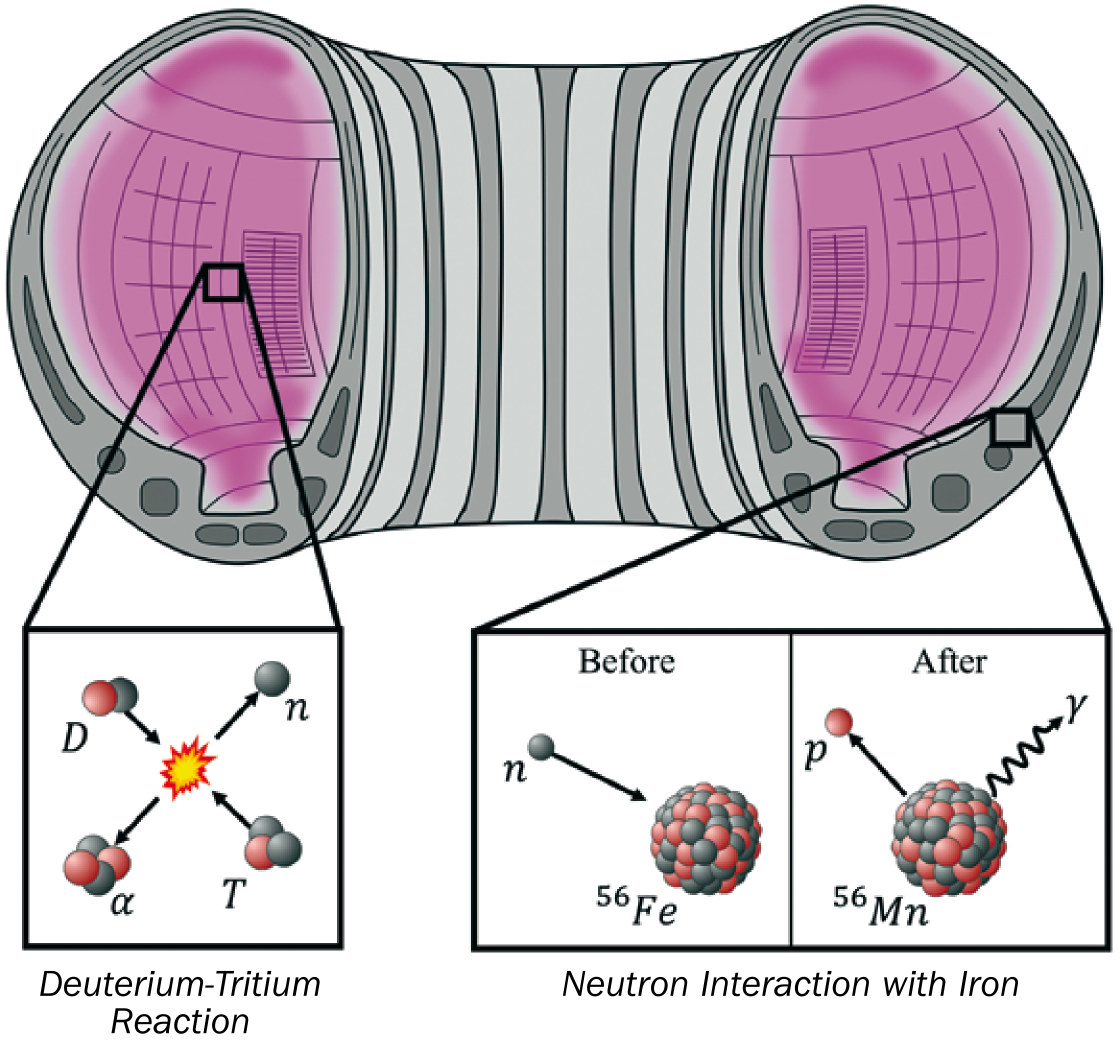
Age: 26

Origin: British

Currently based at: Abingdon, Oxfordshire

@Chantal_Nobs

> *“In March 2017, towards the end of my PhD at the University of Brighton, I started working at the Culham Centre for Fusion Energy. I wanted to help solve the challenge of fusion energy because it has the potential to provide huge benefits to society. To ensure continued progress in fusion I think it is important to share my research with the wider community.”*



Picture 1: An illustration of nuclear reactions inside a tokamak device. Bottom left: inside the plasma, deuterium and tritium fuse together in a high temperature plasma releasing a neutron and an alpha particle. Bottom right: Neutrons cause activation by way of interactions with atoms, such as iron. This results in transmutation to other elements, such as manganese and the release of characteristic gamma rays using radioactive decay processes.

NEUTRONS

Neutrons are subatomic particles with slightly more mass than a proton, but with zero electric charge. The chemical and nuclear properties of an atom depend on the number of protons (P) and neutrons (N) it has. In a fusion plasma, deuterium (1P, 1N) fuses with tritium (1P, 2N) to produce helium (2P, 2N), one neutron (1N), and 17.6 MeV of energy. The energy is divided between the helium (3.5 MeV) and the neutron (14.1 MeV), but since the neutron has no charge is able to escape the magnetic field that confines the plasma.

HOW NEUTRONS WILL HELP TO PREDICT FUSION PERFORMANCE

When neutrons collide with materials they may impart some of their energy, transforming and exciting the atoms within the material. This process is known as activation, and is illustrated in Picture 1. Activated materials then undergo radioactive decay. Activation is also a tool that may be used to indirectly measure the neutron production rate in fusion. The energy spectrum of neutrons is used to gather important plasma parameters such as the temperature. In the blanket of a fusion power plant, the spectrum information may be used to predict the rate of tritium production.

HOW CAN WE MEASURE WHAT WE CANNOT SEE?

The diameter of the neutron is on the femtometre scale (10^{-15} metres). For comparison, the diameter of a strand of human hair is on the micrometre scale (10^{-6} metres), thus a billion times larger than the diameter of a neutron. It is difficult even to comprehend something this small, but the nature of neutrons makes them even more challenging to measure. Conventional radiation detectors rely on the collection of charge to provide information about the radiation detected. Unlike protons and electrons, neutrons have no charge; and unlike alpha, beta and gamma radiation, neutrons do not induce a charge in materials. To measure neutrons we must instead use an indirect process and look at the way in which they interact with other materials, a field known as neutronics (introduced in the Fusion in Europe March 2016 edition). Neutron activated materials emit gamma rays with characteristic energy “fingerprints” thus providing the identification of the atom excited during activation. By detecting these gamma rays, along with simulations predicting how the atom may have been excited by neutron interactions, it is possible to deduce the neutron spectrum.

VERDI – THE COLLABORATIVE DETECTOR

The high temperatures, intense magnetic fields and high neutron fluences of a fusion environment present significant challenges when it comes to neutron detection. The UK, Greece and Italy have collaboratively developed the VERDI detector (Picture 2). It will transport material samples inside the fusion device blanket, where they will be bombarded by neutrons. The samples will then be removed and placed in front of a conventional radiation detector. Carbon has a high melting point (over 3000°C), so by encapsulating material samples in a carbon shield the VERDI detector can be placed much closer to the plasma core than existing neutron detectors. Detecting neutrons is just one of the many challenges that must be overcome in nuclear fusion. It takes multiple experts from several nations to come together to solve even comparably small tasks in the huge quest for fusion energy. ■

Picture 2: A prototype of the VERDI detector, prior to initial testing.

WHO WRITES THE INFO BOXES?

Picture: private

Oisín McCormack

Age: 30

Nationality: Irish

Currently based at: Padova, Italy

> *“I am a PhD student at Consorzio RFX and I work with developing new techniques for plasma temperature diagnostics. Fusion is the only field I have ever considered dedicating my life to. I enjoy spreading the good word of fusion, seeing the expression of wonder on other’s faces as they realize the grand importance of it. To me, communication is an essential part of being a good scientist.”*

MAKING THE **REACTOR WALL** **SMARTER**

There are a lot of "smart" devices that support you in your daily life. But "smart" surely also serves fusion. Smart alloys are a possible way of preventing the release of radioactive material in the event of an accident when operating future fusion reactors.

Picture: private

Janina Schmitz

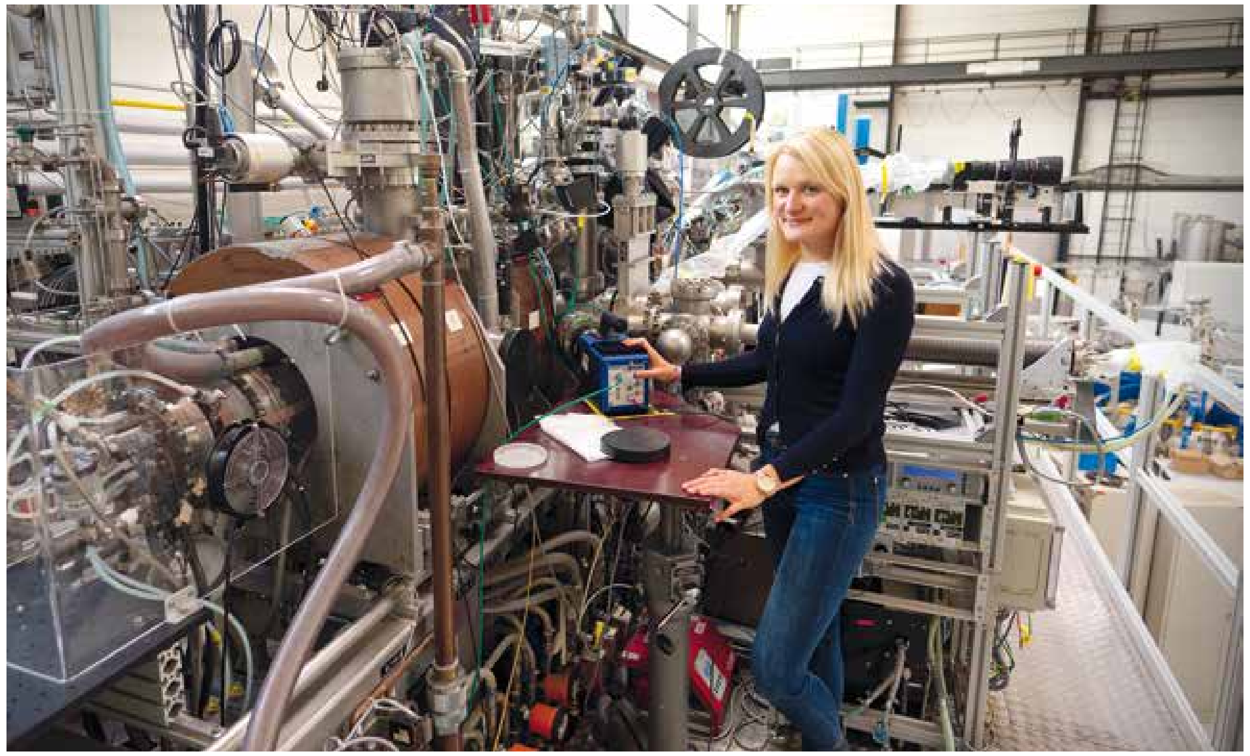
Age: 25

Origin: German

Currently based at:

Forschungszentrum Juelich (FZJ)/Ghent University

> *"The idea of creating a Sun-like power generation source on Earth can only be realised by the joint efforts of fusion researchers from all over the world. With my PhD work within the Fusion Doctoral College framework, I want to contribute to this aspiring project. At FZJ, and elsewhere in Europe, we are developing tungsten-based smart alloys for future fusion power plants like DEMO. My research is focussed on the plasma compatibility of smart alloys."*



Janina Schmitz at the linear plasma device at Forschungszentrum Juelich. The experiment tests material for future fusion reactors. Picture: Tobias Wegener (CC-BY-NC-SA 3.0)

W – THE MATERIAL'S SOLUTION?

Tungsten (W) is currently the prime candidate for the plasma-facing wall of a fusion experiment. It features a high melting point and low tritium retention. Another factor that meets the requirements of a future fusion reactor wall, are its low sputter yields. Sputter yield is the term for the number of sputtered or dispersed target atoms per incoming projectile. A unity sputter yield means that each incoming atom sputters one target atom. Despite these advantages, there are also some drawbacks in using W as plasma-facing material: W is inherently brittle and its ductile-to-brittle-transition temperature even increases along with high temperature as well as neutron irradiation. In order to improve the material's ductility and enhance its toughness, different approaches must be investigated.

THINGS SHOULD NOT GO LOCA

In order to build a safe fusion experiment, we must consider extraordinary events in addition to the operational scenario. These might put additional constraints on the development of plasma-facing components (PFCs). In case of a so-called LOCA (loss-of-coolant-accident), the cooling of the first wall fails and, as a consequence, the wall temperature may rise up to 1200 °C for several months. With additional air ingress, W oxidises easily and radioactive volatile tungsten oxide (WO_3) is formed. This requires elaborate measures to prevent this gas from being released into the environment. In order to finally achieve an intrinsically safe fusion operation, it would be best to entirely avoid the mobilisation of the wall material.

SMART ALLOYS – A POSSIBLE SOLUTION

Smart alloys might provide an answer to this demanding question. Alloys are materials consisting of two or more compounds, for example, metallic compounds. Often they are designed to improve the materials' properties. Steel for example is an alloy made up mostly of iron, but containing a few percent of chromium (Cr) and other elements that altogether improve the corrosion resistance of the material.

W-based self-passivating 'smart alloys' are intended to suppress the WO_3 formation and thus passivate the oxidation properties compared to pure W. The alloy's smartness consists of its ability to adapt to two kinds of operation scenarios. When the smart alloy comes into contact with oxygen, its elements form a dense protective oxide layer at the surface and thus prevent tungsten mobilisation.

In its normal operational mode as plasma-facing material, preferential sputtering of light alloy elements causes the depletion of these alloying elements at the surface. It forces the alloy to behave like pure W during reactor operation.

NEUTRON ACTIVATION

Neutron activation is where energetic neutrons induce radioactivity in a material. Free neutrons are captured by atomic nuclei, pushing them into an excited state. These atoms then release decay radiation in order to return to a stable state. The neutrons produced in fusion reactors are not confined to the plasma and can hit the wall material, which will predominantly be made of tungsten in future devices. Continuous activation will degrade the tungsten, which will then need to be replaced and disposed of as low-level radioactive waste.

Ultimately, our efforts must be combined and a composite designed which has suitable properties for both the operational and accidental reactor scenario, and which is geared to any eventuality.

The smart alloy is exposed to fusion conditions, Picture: Andrey Litnovsky

At the same time, the self-passivation properties of the smart alloy should remain unaffected by the plasma impact as the alloying elements in the bulk material remain.

For the currently most promising alloys, Cr is used as passivating element, while yttrium (Y) serves as an active element to improve self-passivation. Oxidation tests carried out at Forschungszentrum Jülich (FZJ) demonstrated a significant improvement in oxidation suppression for the WCrY system. And initial plasma tests at the linear plasma device PSI-2 showed no impact on the oxidation behaviour.

ADVANCED W MATERIALS FOR DEMO

Smart alloys are possibly a solution in the event of LOCA. However, for DEMO, the next step after ITER and the first fusion power plant, the need for long-lasting PFCs with additional stable mechanical properties during plasma operation is just as important. The development of advanced materials designed to meet the demanding requirements of a fusion operation is progressing. Material solutions tailored to ensure low erosion and long lifetime PFCs are moving forwards. Yet their behaviour in regimes beyond regular reactor operation must be examined more closely.

At FZJ, we are currently also working on improving the various drawbacks of pure W. We are also looking into the use of tungsten fibre-reinforced composites (Wf/W) as a solution to the inherent brittleness. At the same time, we are developing self-passivating smart alloys in order to improve the material during LOCA events.

Ultimately, our efforts must be combined and a composite designed which has suitable properties for both the operational and accidental reactor scenario, and which is geared to any eventuality. ■

THE STORY OF SABOTAGE: THE TUNGSTEN INVESTIGATION

HOW SPECIAL FORCES COMBINE TO CATCH PLASMA KILLERS

AUTHOR

Picture: private

Sarah Breton
Age: 26
Origin: French
Currently based at:
Aix-en-Provence, France

“In four months I will finish my PhD in nuclear fusion (hurrah!). I believe that fusion is capable of solving the energy crisis and I want everyone to know about it. A teacher once told me “If you can’t explain your job in a way that anyone can understand, then you don’t understand it yourself”. Writing about fusion in an accessible and illustrated way is challenging but so fun and fulfilling!”

CARTOONIST

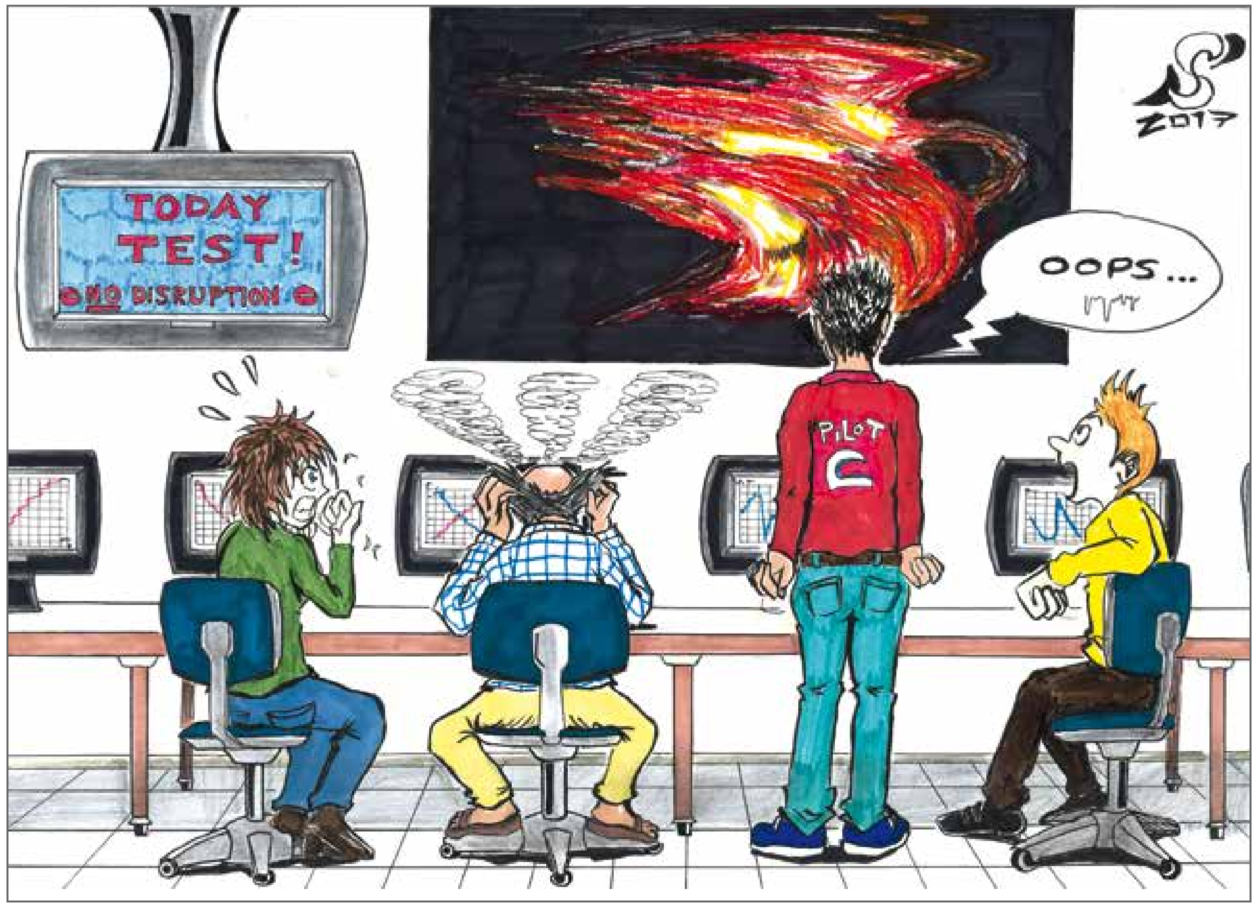
Picture: B. Simony

Benoît Simony
Age: 26
Origin: French
Currently based at: Aix en Provence, France

“I just finished my PhD in passive neutron coincidence counting on radioactive waste drums. Although it is not applied to fusion, I am also very interested in it, and more generally, in wider topics of physics. Furthermore, I like to use my passion for drawing in order to illustrate physical phenomena and the life of researchers.”

THE FACTS

It had all started well. We managed to heat up the reactant in order to make the expected fusion reaction happen: in this case, deuterium, an hydrogen isotope. We initiated a current into the tokamak, that strange doughnut-shaped reactor. Very strong magnetic fields are used to ensure that hot particles don’t touch the inner wall of the tokamak. Finally, we were very pleased when we witnessed that the deuterium started to warm up, became ionized and converted into a gas called plasma. Ion and electron temperatures were increased successfully in the centre of the plasma, up to 150 million Kelvin. Fusion is happening right now. So far so good.



The control room

THE DEAD OF THE PLASMA

There are about twenty people glued closely to the screens in the control room. One of us, the pilot, makes the decisions. He or she watches the live footage from inside the tokamak. All of the plasma parameters had been finely tuned before the experiment started. Now the plasma control system manages everything automatically. The pilot is simply in charge of the emergency button to immediately stop the operation in the event the machine may be damaged.

Meanwhile, another part of our team is responsible for monitoring the experimental signals from previous experiments. But suddenly, the core temperature starts to drop. This is exactly what we don't want: a decline in the plasma temperature! This surely would kill the highly desired fusion reaction.

Immediately, the system responds and increases the central heating function. But the temperature keeps dropping. Within a couple of seconds, the plasma dies, releasing enough energy to damage the walls. The camera shows a sudden light, like a flash, then it all goes dark. In the control room, nobody speaks. Wordless question marks hang in the air. Something went wrong. What happened?

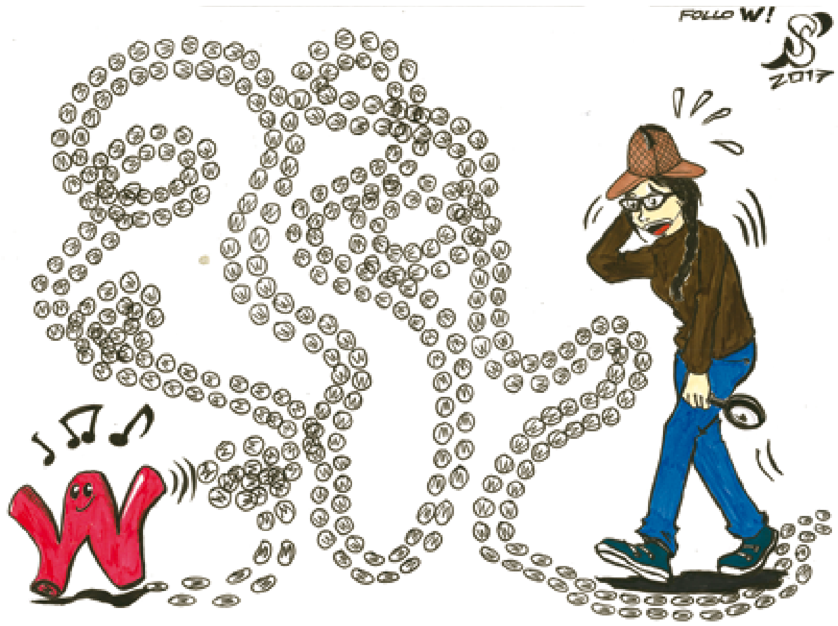
THE EVIDENCE

Fusion experts like us measure several plasma parameters: current, temperature, density, radiation. In this instance, the radiation emitted by the plasma had increased over time. This is the signature of one suspect: Tungsten, or W. We know where this tungsten comes from, a special area called the divertor. It is designed to receive a lot of energy.

More on divertors: see also the article „A snowflake for fusion?“ by Carrie Beadle on the pages 28 – 29.

More on Tungsten: see also the article „Making ths reactor wall smarter“ by Janina Schmitz on the pages 18 – 20

Tungsten is a popular fusion material because of its high temperature resistance and its low erosion rate. Unfortunately, some erosion is still caused by the energy that ends at the divertor. W enters the plasma, but is so heavy it does not get fully ionised. This means that not all the electrons are torn away from the nucleus, and that causes W to radiate. And W is the only species in the tokamak that has this property: it has to be the material used.



The W investigation, allegory,
Cartoons: B. Simony

THE SUSPECT AND THE TIMELINE

So now, we have found the saboteur. And we have to stop it. To prevent this situation from occuring again, we simply must understand how tungsten managed to radiate so much that it made the plasma collapse. We decide to reconstruct the timeline of W impurities, just like in a police investigation. First, we gather together the information we have about the temperature, density and rotation profiles, radiation levels, and especially the radiation distribution in the plasma.

Aha, here is our first important clue: the radiation first appeared at the edge of the plasma. But after a couple of seconds, all of the emitted radiation is derived from the centre of the plasma. This means that W travelled from the edge to the centre. And this is what has caused the core temperature to drop and the plasma to collapse. But how did W travel through the plasma? W was transported, W had accomplices.

PERSONS OF INTEREST AND MODUS OPERANDI

The measurements are necessary to reconstruct W's time evolution, but not sufficient to figure out the transportation of W. We need to use another tool: simulation. The W transport obeys known mechanisms and equations. Informatic codes have implemented these. The inputs are W's accomplices, the Persons of Interest: temperature, density and rotation profiles. The outputs are the coefficients that quantify how far and how fast W is transported. But W also impacts the evolution of temperature and density, and radiation as we have seen before. There are many feedback loops to be simulated if we wish to reconstruct the modus operandi. The combination of several codes is called integrated modelling. It is a very complex and sensitive tool. Simulating just a few seconds of plasma can take days, or weeks, depending on the level of complexity.

HOW A THREE SECONDS SABOTAGE REQUIRES MONTHS OF WORK

As a result, we have to gather our Special Forces, a team made up of experts with various scientific backgrounds in order to finally catch the saboteur and to figure out its modus operandi. This is what fusion and the realisation of fusion energy is about. We, as scientists, are dealing with phenomena that have not yet been investigated. We are pioneers ... and, more often, even detectives.

TUNGSTEN

Materials inside a fusion reactor must be able to operate for a long time under neutron bombardment and hot plasma attack. **Tungsten** is the most promising material for use as plasma facing components. Tungsten is a robust, rare, metal chosen for its very high melting point (3422 °C), low tritium retention, and low erosion rate. However, even relatively small amounts of eroded tungsten dust are able to poison the plasma, cool it down and cause a disruption, which may result in serious damage to the machine.

DOMESTICATE THE FIRE:

A CRUCIAL STEP TOWARDS FUSION ENERGY

Tungsten target exposed to hydrogen plasma in the linear machine Magnum-PSI. Picture: DIFFER

Picture: private

Renato Perillo

Age: 27

Origin: Italian

Currently based at: Differ Institute, Eindhoven (NL)

> *“I am a driven PhD student working within the Plasma Edge Physics and Diagnostics group at the Dutch Institute for Fundamental Energy Research. I combine numerical simulations with experiments, addressing the issue of power exhaust in a fusion reactor. I do believe fusion energy is the most promising energy source for the future. Working day by day in such a stimulating environment is the best thing that could have happened to me.”*

Fusion energy is created by merging two atoms in a very hot gas, called plasma, with temperatures around 150 million Kelvin. This extreme scenario takes place in a reactor with a doughnut-like geometry, called a tokamak. Plasma-surface interactions pose one of the biggest obstacles for fusion experiments. The future reactor wall materials have to withstand incredible heat and particle fluxes. Scientists are currently investigating plasma scenarios in which the wall loads are more benign. One way to cool the plasma down is by means of impurity seeding.

THE POWER EXHAUST PROBLEM

The particles and heat flux coming from the plasma core are channelled downstream along magnetic field lines to a region called the “divertor”. Divertor targets must withstand power fluxes in the order of several MW/m^2 in steady state conditions, and up to 1 GW/m^2 during intrinsic instabilities of the plasma. This is comparable to the friction that occurs during re-entry of a spacecraft into the Earth’s atmosphere. This holds true just for the steady-state regime, while plasma instabilities can lead to a hundred times the expected power loads of the plasma during ~0.5 millisecond.

INTERDISCIPLINARY RESEARCH AS A KEY TO SUCCESS

Since the early ‘80s, scientists have been trying to reduce the heat flux on the target by increasing the gas pressure in the divertor region. The plasma is cooled down throughout its path to several thousands of Kelvin due to radiation, momentum transfer and volume recombination processes. In this way, the heat loads become sustainable for the material. This phenomenon is called “plasma detachment”. In order to fundamentally understand detachment and PSI in a tokamak, various disciplines, such as material sciences, control and mechanical engineering, plasma physics and chemistry have to work together properly.

FROM MAGNUM-PSI TO ITER

The linear plasma machine Magnum-PSI, located at DIFFER (Eindhoven, NL), is capable of mimicking the plasma-surface interactions foreseen for ITER. The excellent diagnostics accessibility provides accurate insights into the mechanisms occurring in both the exposed material and in the plasma located in the vicinity of the target.

WANTED IMPURITIES IN THE DIVERTOR

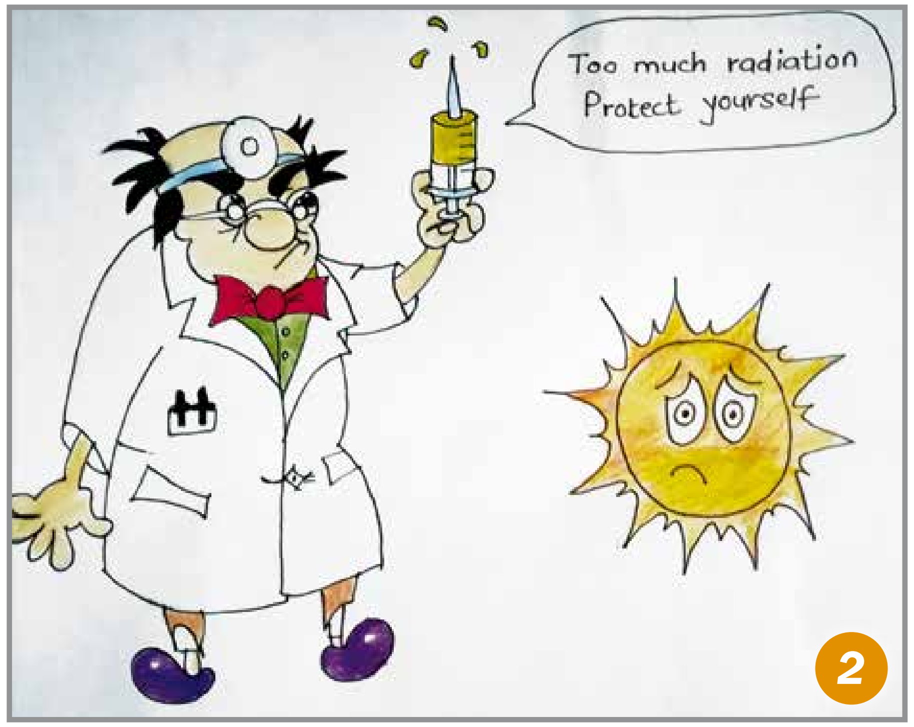
Experiments in tokamaks over the course of the last two decades have shown that the injection of gas (so-called impurities) into the divertor region leads to an enhanced detachment. At DIFFER we are currently pursuing such experiments. In particular, we are investigating the influence of nitrogen seeding on a hydrogen plasma, focusing on the plasma chemical processes occurring in such scenario. So far, experiments and numerical simulations deliver promising results while achieving a more comprehensive understanding of plasma detachment in a fusion reactor. In the end, this will be a key factor in making this technology feasible within the second half of this century. ■

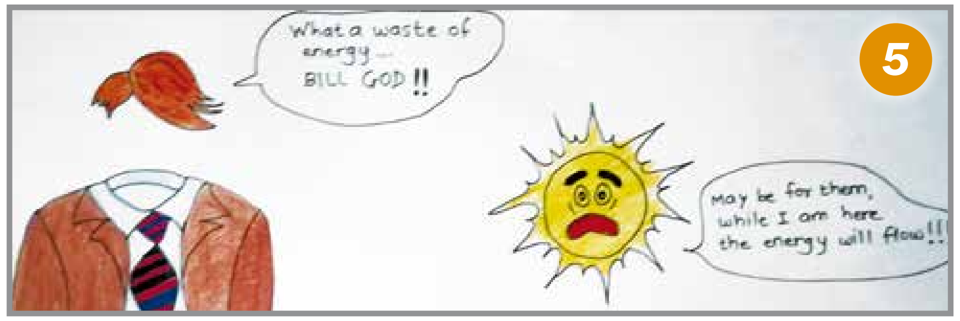
Renato Perillo (right) in the control room. Picture: private

PLASMA INSTABILITIES

A fusion plasma is an extremely hot electrified gas which naturally wants to expand. It is suspended in a strong magnetic field designed to keep it from touching the chamber walls. As the temperature and pressure builds, the plasma forms areas of increasing turbulence, called instabilities, that must be controlled. There are many different types and sources of instabilities that may cause plasma disruption. The worst instabilities are able to eject streams of hot plasma out of the magnetic confinement, severely eroding the wall materials.

TOTAL ECLIPSE





Idea: *Luiz Trevisan*
Cartoon: *Amita Joshi*

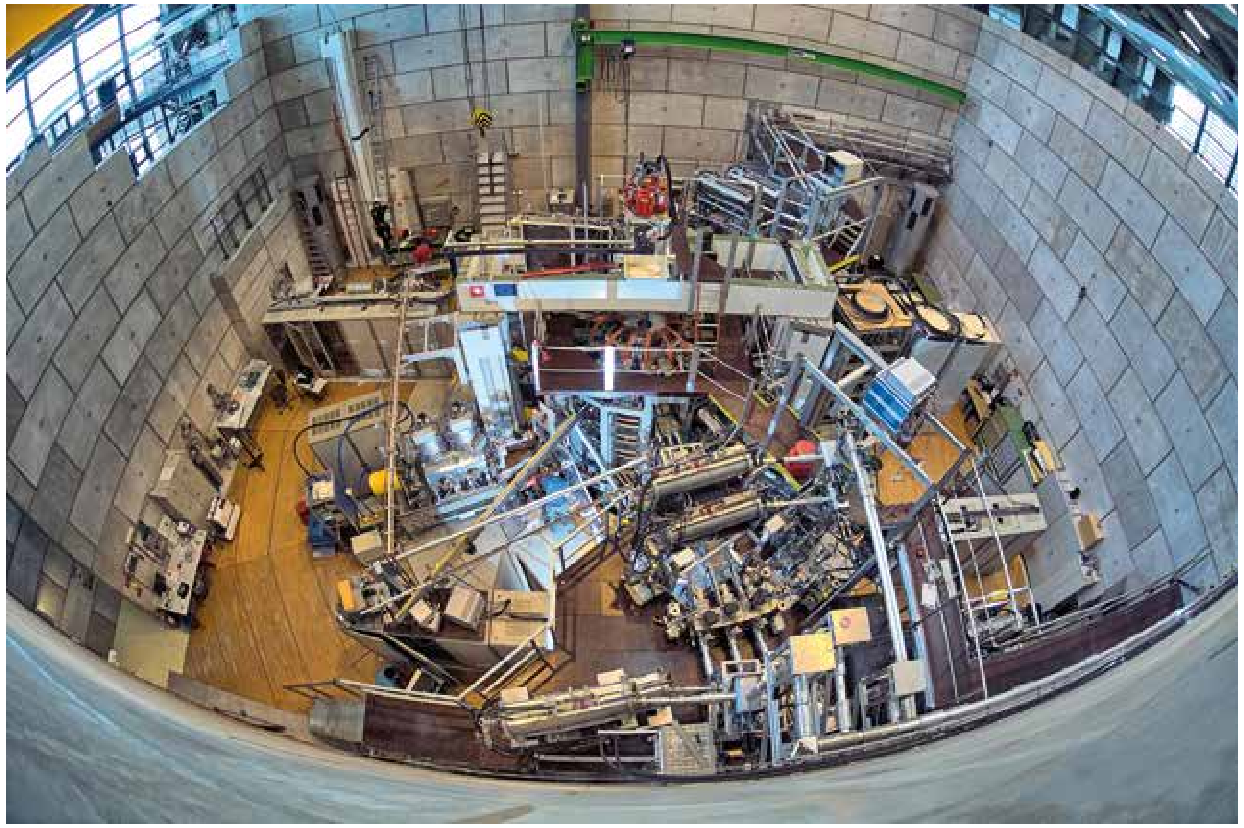
Picture: private

Amita Joshi

Age: 28
Origin: Indian
Currently based in: Germany

> *As they say, 'A picture speaks a thousand words'. Keeping this quote in mind I worked as illustrator for this edition of EuroFUSION too and tried to convey technical stuff through a comic strip to make it lucid. This was my second year with EuroFUSION team, I wish the bond strengthens. I thank Anne again to give me this opportunity. Cheers!*

A **SNOWFLAKE** FOR FUSION?



The Swiss Tokamak à configuration variable (TCV) from above.
Picture: Christophe Roux/EUROfusion

Picture: private

Carrie Beadle

Age: 23

Origin: British

Currently based at: Swiss Plasma Center, Lausanne

> *“I am a PhD student studying plasma turbulence in the outermost region of the tokamak via numerical simulation. I find fusion plasma physics exciting because it has so many different aspects, challenges and problems to be solved! My article is about the problem of overheating materials where they interact with the plasma and how we can change the magnetic field configuration to keep vessel walls from melting.”*

A snowflake might not be the first thing you associate with a hot fusion plasma. But it is a concept designed to handle the heat where the plasma touches the vessel wall. It is not surprising that this task presents technical difficulties. However, the scale of the problem is remarkable: the predicted heat load on the ITER targets is greater than that on the soil beneath a launching rocket!

PROBLEMS AT THE EDGE

Two of the biggest scientific and technological challenges facing ITER and DEMO are associated with plasma-wall interaction. Firstly, how to minimise the heat load on the target plates. Secondly, how to prevent impurity particles from entering the core plasma and causing heat loss. For this reason, such troublesome particles should be kept to a finite, well-defined area.

BEYOND THE LIMITED CONFIGURATION

Early tokamaks achieved this aim using a limiter – typically a rail extending a short way inwards from the inner wall of the tokamak. In this configuration, it is relatively easy for the impurity particles to re-enter the core plasma. A solution was proposed as early as in the 1950s, split the flux surfaces at a certain point. The field lines will cross each other and end at two divertor plates, some distance away from the last closed flux surface, keeping the core plasma “safe and clean”. However, it wasn’t until the 1980s that this more complex configuration started to be used in fusion devices.

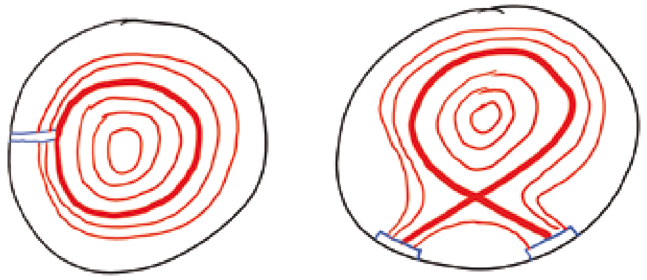
DETACHING THE PROBLEM

The diverted configuration also tackles the tremendous heat load problem. No material would be able to withstand such harsh conditions. The greater distance between the target and the flux surface allows density and temperature gradients to form along the magnetic field lines, thus reducing the temperature at the target to well below that in the core. The heat load can also be reduced by either spreading the same total heating power over a greater plate area, or by radiating more heat before it reaches the target. This requires a strongly radiating “cushion” of dense neutral gas between the target and X point. It remains very difficult to simultaneously reach the detached regime for the targets and maintain the high-confinement mode, which optimises the core plasma performance.

ADVANCED DIVERTORS

ITER must operate in both high confinement mode and the detached regime. The challenge is to maintain the detachment front in a stable way. It is here that the shape of the flux surfaces close to the target becomes important. So, we need a new concept: advanced divertors.

These are magnetic configurations in which there is not one but two magnetic X points. The second X point modifies the angle at which the field lines arrive at the target as well as the change in separation between the flux surfaces as they approach the target. Current experiments are trying to find the magnetic field which provides the most effective heat load reduction.



Limited vs diverted configuration. The limited configuration is shown on the left, with the limiter itself in blue, last closed flux surface in bold red and flux surfaces in red. On the right is the diverted configuration, with the target in blue and magnetic surfaces as before. Snowflake flux surfaces on TCV.

IT’S JUST THE BEGINNING

One such advanced configuration is called the “snowflake”. It is named after its 6-fold symmetry, achieved by a secondary X point close to the primary X point. Researchers have discovered that this reduces the heat drastically. The area that receives the heat becomes much larger. Also, the distance along a field line from the X-point to the target is now longer, allowing a much greater drop in temperature along the line. It is clear that we need to understand the effect of divertor geometry on the heat load. Theoretical modelling of diverted geometries is just beginning, but already there are hints that first principles models can recover results of experiments such as those carried out on Tokamak à configuration variable (TCV). So, watch this space! ■

DIVERTOR

A **divertor** is the in-built vacuum cleaner of a fusion reactor and is situated along the chamber floor. Build-ups of helium ash and impurities in the plasma must be removed during operation. These heavier particles are pushed to the edge of the plasma by centrifugal forces, where they escape through a specially designed magnetic “gap” at the bottom of the plasma and fall into the divertor. The divertor shape and materials are also constructed to bear the brunt of the heat load from the plasma, thus protecting the surrounding walls.

THE NEED OF THE HOUR: **NUCLEAR FUSION**

As a child, I witnessed innumerable incidents of load shedding in Delhi, especially during summers. This meant no electricity at home and studying by candlelight for hours. Even today 24/7 power supply remains a dream that is unfulfilled. Just imagine, there are around 396 million people with no access to electricity in India! Around 75% of the world population is living in developing countries with energy demands that are expected to surpass that of developed nations in the next 50 years. My big question is: “How do we tackle this energy crisis?” We will be running out of non-renewable resources in the next 40 to 80 years. But, coal, oil and natural gas currently supply most of the world’s energy.

Picture: Istock/Sean Kuma

Picture: private

Priyanjana Sinha
Age: 25
Origin: Indian
Currently based at:
Greifswald, Germany

> *“I am a PhD student, but also a science enthusiast with a passion for writing. I believe that nuclear fusion undeniably holds the key to solving the current global energy crisis. EUROfusion presents a perfect platform for young researchers like me to speak out and dispel the misconceptions as well as raising awareness about nuclear fusion amongst the general public.”*

THE DILEMMA OF CHOICE

The general scepticism about nuclear energy is well known. Like most countries, India has also witnessed raging controversy regarding the suitability of nuclear power as the solution to ever growing energy requirements. I too was drawn into this debate and thus developed a strong desire to contribute something towards the promotion of clean and abundant energy. It engendered in me a deep interest in nuclear physics and engineering. It was only during my master’s studies that I understood in-depth the prospect of employing fusion power as an almost inexhaustible source of energy for future generations. Now, I am proud to work at one of the most developed fusion experiments in this world: the stellarator Wendelstein 7-X (W 7-X).

CONFINEMENT IS KEY

Fusion reactions take place at high temperatures of around 10 keV (~100 million Kelvin) where the fuel is in a fully ionised state, also called plasma. The particles have a large thermal velocity with a tendency to escape from the machine. Hence, some method of confinement of particles is essential. Magnetic field confinement using high powered magnets is one of the solutions. Tokamaks and stellarators, two types of fusion experiments, are both based on this concept.

THE COMEBACK OF STELLARATORS – WENDELSTEIN 7-X

In the past, research into stellarators has been overshadowed by interest in the other concept, the tokamak. However, recent advances in computational power and engineering expertise have revived it. So, the inauguration of Wendelstein 7-X (W7-X), the world’s newest stellarator, has put stellarator research back on the fusion table.

See also the article “A snowflake for fusion?” by Carrie Beadle on the pages 28 – 29.

A recent publication in Nature Communication, by Prof Thomas Sunn “from my institute”, the Max Planck Institute for Plasma Physics, highlights the success achieved in W7-X. Sunn Pedersen discussed how he and his colleagues managed to tackle the challenges.

A LIKELY SAVIOUR: CONNECTION LENGTH

The main obstacle in reaching high power density in fusion devices is the limited capability of the divertors. Divertors are the ashtrays of fusion experiments and need to withstand immense heat and particle loads. My present goal is to develop of special magnetic configurations that should help to manage the heat flux. They will be tested in

Inside the stellarator Wendelstein 7-X.
Picture: Christophe Roux/EUROfusion

Picture: private

> *Fusion will, I hope, one day create energy for everybody.*

an operational campaign in W7-X. This should further assist us in comprehending the impact on the exhaust physics in a stellarator. Once the riddle of tackling the tremendous power exhaust from fusion plasma has been solved, we will have moved one large step closer to a fusion power plant.

THE SILVER LINING: NUCLEAR FUSION

The previous operation phase of W7-X has concluded in March 2016 and delivered promising results. We found parameters, for example, for plasma temperatures and densities, that enhance the performance of a stellarator plasma, exceeding predicted values from simulations. There is, of course, still a lot of research that must be done before nuclear fusion becomes a viable commercial option. Nevertheless, I feel like I am participating in the creation of the future solution for the demanding energy needs of the world. Fusion will, I hope, one day create energy for everybody. ■

TOKAMAKS vs STELLARATORS

Tokamaks are the most well developed reactor type due to their simple flat magnetic coil design. They have an induced electric current that confines particles on a helical path, but this current also means pulsed operation and results in unwanted instabilities. Stellarators have a complicated twisted coil design, which has been made possible thanks to modern computer modelling. These twisted coils produce a natural helical path thus avoiding the current instabilities and resulting in a much desired steady-state operation.

BUILDING THE FUTURE WITH S.T.E.A.M.

CIENCE ECHNOLOGY NGINEERING RT ATH

The Ev3storm roboter is one of the models the school children learned to programme. Picture: The Lego Group

There is a great demand for technically skilled people in our information-driven society. S.T.E.A.M., an acronym that stands for Science, Technology, Engineering, Art and Maths, is an interdisciplinary approach to learning. Being both physicists and robotics instructors, we decided to launch a project for young enthusiasts, specifically including girls, who are traditionally underrepresented in the sciences.

NEXT GENERATION OF INNOVATORS

In the end, we achieved our aims, we have prepared the next generation of innovators. By teaching science and technology literacy, we have increased the level of interest in all those who might, one day, wish to work in fusion or other future-relevant subjects.

CREATE-EVALUATE-IMPROVE

“Transformers visit my school” is a scheme designed for primary and middle school pupils. With the help of Lego Mindstorms robotics kits, the children have learned how to design and construct a robot, attach sensors, think in terms of algorithms and program the tiny machine.

The partakers even approached difficult scientific concepts, such as the physics of sensors, more easily. Hands-on activities are used to fill the gaps left by traditional education methods. Our participants enjoyed their practical challenges including building, testing, programming and troubleshooting. They worked excitedly and creatively and let their team spirit guide them. Our role, in the meantime, was to mentor and lead them, allowing the young engineers to take their own initiatives and creative risks, and to explore their different levels of expertise and imagination. We discovered that the satisfaction of accomplishment was a further motivation to the teams. They finally realised that science is everywhere and ready to be discovered!

ELEMENTARY KNOWLEDGE

Nowadays, success results from what we are able to do with knowledge acquired. Hence, in addition to preparing our future workforce, it is essential to spread the benefits of S.T.E.A.M. education.

Engaging children from an early age in special processes, enables them to cultivate and capitalise on their own interests and, moreover, their curiosity. By watching them confront the technical difficulties with the Lego robots, we understood how they learned to investigate.

“I enjoyed that we worked as a team in the Robotics First Lego League in Greece. Everyone had a distinct role, but we needed to collaborate and share our ideas in order to complete the tasks”, says nine year old Eudoxia Karlati-Koufopoulou.

> “*I learnt to take risks.*
> *I evaluated my constructions and improved them.*”
>
> *Lucas Lenard*

Another fascinating aspect was that ignorance aids learning and further improvement. By this we mean, failures are considered to be part of the discovery process thus leading to a better approach. “I learnt to take risks. I evaluated my constructions and improved them”, states Lucas Lenard, a sixth grade primary student.

CONNECTING ART AND S.T.E.M.

Can there ever be a connection between Art and S.T.E.M.? According to Leonardo Da Vinci, we need to “realise that everything connects to everything else”. Those additional skills make sciences applicable and innovative in real life. Mathematical concepts such as spatial awareness or geometry are easily approached by art while cultivating a basic scientific tool: the power of observation. Children become open minded and quickly assimilate new ideas.

> “*According to Leonardo Da Vinci, we need to ′realise that everything connects to everything else′*”

GIRL‘S PIPELINE ISSUES

As was mentioned earlier, it is not news that girls are underrepresented in scientific and technological fields. This will have an impact on the future staff pool. Young women are often engaged in traditionally “girly” stuff. Early intervention with S.T.E.A.M. subjects encourages them to participate. Our project boosted the self-confidence of female participants as they took on the technical challenges. We realised that when girls overcome their fear of failure or non-qualification, they even gear up. In many cases, they were chosen to be team leaders during our competition. In summary, it is important that these positive projects do not remain single events only. Key influencers, such as parents, teachers and specifically women-leaders should further encourage girls to continue in technical fields.

> “*Key influencers, such as parents, teachers and specifically women-leaders should further encourage girls to continue in technical fields.*”

THE FOUNDATION OF A VISION

Technical education can be applied widely and creatively in order to overcome stereotypes. Working practically with children and encouraging them to explore, enables them to gain a deeper understanding of technological fields. Science has simply become more relevant to them. Indeed, our pupils gained additional skills. They finally realised that S.T.E.A.M is a key way to make their own and others’ lives better". ■

S.T.E.A.M.
CIENCE
ECHNOLOGY
NGINEERING
RT
ATH

Irene Papa

Picture: private

Age: 28
Origin: Greek
Currently based at: Athens, Greece

“*I am an undergraduate physicist and a Robotics instructor. Wanting to pursue a career in fusion, I believe that the answer to the question of safe and clean energy is written in the stars! Fusion and its attractive prospects promises a better future, so I would like to participate in the diffusion of this effort.*”

Nikos Moraitis

Picture: private

Age: 30
Origin: Greek
Currently based at: Athens, Greece

“*I am a physicist and my field of expertise is Medical Physics. I have been fascinated by the subatomic world and the power of the nucleus. Fusion is a great example of this power and I think we all must corporate in order to achieve the promising future of vast and clean energy.*”

THE GREAT FUSION **ENDEAVOR**

It has been said that the nuclear fusion conundrum will be solved within 30 years … but they have been saying that for the last 50 years already. Now, we humbly expect the first feasible fusion power plant prototype to start operations sometime in the 2060s. Producing electricity from fusion is the greatest engineering and scientific challenge of our century. A scientific journey that is greater than achievements such as the building of the Great Pyramids or the Great Wall of China, or landing on the Moon … and this time, humankind depends on it.

A QUEST FOR CLEAN ENERGY

Our use of fossil fuels has an accelerating countdown timer. Either we completely deplete our available reserves or we damage the environment just enough to prevent human society from continuing as we know it. We have to find alternative sources of clean energy, whatever they may be. As the head of the Electron Cyclotron Section of ITER and advocate of fusion energy, Dr. Mark Henderson, puts it: ”We are addicted to carbon. We have to prove, as a species, that we are collectively intelligent enough to prevent our own extinction.” Fusion looks like a promising answer.

> “*We are addicted to carbon. We have to prove, as a species, that we are collectively intelligent enough to prevent our own extinction.*”
>
> Dr. Mark Henderson

Mark Henderson

NOT THERE YET

Fusion power plants will create artificial stars and become the clean energy source that will power our way of life in the future. But we are not quite there yet. At the moment, it takes a lot of energy to confine the plasma and a lot more to heat it up to the temperature required for fusion to occur. At this time, we are building ITER to prove that we will be able to obtain a net gain of energy output from a fusion reaction, sometime in the next 20 years. Then, DEMO, a prototype power plant, will be built in order to transform the excess output fusion energy into usable electricity, based on everything we learn from ITER.

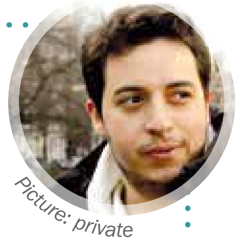
LONG TERM COMMITMENT

Generations of scientists have dedicated their whole careers to fusion research, but there is still a long way to go. The end goal is so far into the future that those who finally make fusion happen may not have even been born yet. The tens of thousands of scientists and individuals working towards fusion today are well aware that they might not be remembered in thirty or forty years, and that is okay. Believing in fusion is looking beyond the importance and the lifetime of our generation. Mark presumes that "as fusion scientists we have the chance to impact the future of the hundreds or thousands of generations to come."

> *"As fusion scientists we have the chance to impact the future of the hundreds or thousands of generations to come."*
>
> Dr. Mark Henderson

FUSION IS PART OF OUR FUTURE

Nuclear fusion is the epic scientific quest of our time. "We have to face the fact that fusion is extremely complicated", warns Mark. "We need to orient the scientific community and the population towards it. Otherwise, look at the consequences". Fusion is one of our best hopes, as a species, to have a sustainable and reliable near-limitless source of clean energy within the 21st century. "I believe we will have multiple clean sources of energy in the future: solar, wind – but fusion will be the basis", says the ITER expert. ■



Picture: private

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"I am an electronics engineer currently doing a PhD in the Advanced Plasma Science and Engineering programme. I develop microwave reflectometry diagnostics that aid other physicists understanding plasma behavior in nuclear fusion research. I advocate for Open Science and thank EUROfusion for the support in publishing Open Access."

The tokamak pit of ITER some years ago.
Pictures: Eyesteelfilm

PREPARING **EARLY**

Picture: Istock/PashaIgnatov

The prospect of a fusion power plant is edging closer to reality. Work is underway to ensure that these plants will be designed to mitigate low-level proliferation risks.

Picture: private

Thom Dixon

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"I am interested in communicating how emerging technologies reshape the world and challenge the status quo. Fusion power will do away with the limits of energy supply and fundamentally rewrite our understanding of power generation. Though this is not without risk, the risks are minimal and need to be communicated before they are misunderstood."

RISK SCENARIOS

The breakout scenario has long been a concern for the international community but it's never been a major concern when it comes to fusion research. There simply haven't been significant levels of fertile material in fusion. However, with fusion power plants looming on the horizon, the risk calculus will change. Research and development is now underway to mitigate these low-level risks.

Dr Richard Kamendje, Responsible Office of the EUROfusion ITER Physics Department
Picture: EUROfusion

Dr Richard Kamendje from EUROfusion, who previously dealt with proliferation issues at the IAEA, anticipates that over the coming decades the international community will need to incorporate some safeguards to mitigate the low-level risks in fusion.

TRITIUM IN NUCLEAR WEAPONS

Fusion boosted bombs fuse deuterium and tritium as a trigger to spark lots of early neutrons, which chain-react to make the primary fission explosion more efficient and about twice as powerful. This is a relatively simple weapons technology, and it is suspected that North Korea currently have this type of bomb. A pure fusion bomb is a hypothetical weapon. In comparison with fission fueled bombs, weapons using 100% deuterium-tritium fuel could more easily evade current non-proliferation measures.

WHAT ARE THE LONG-TERM PROLIFERATION SCENARIOS FOR FUSION?

As the largest fusion experiment on Earth, ITER will test breeding blankets for the production of tritium. One future breakout scenario involves a state that introduces fertile material to the breeding blankets. However, not only would doing this have implications for the tritium breeding ratios – every cubic centimetre counts – but it would alter the power consumption of the plant and the detectable signatures of the tritium. Both of these changes can be tracked by satellites using current technology and the presence of fertile material would quickly be discovered.

Another breakout scenario is the introduction of fertile material into the coolant flow. Again, this scenario can be mitigated by monitoring changes in background radiation. While further research and development is required to confidently mitigate this risk, there is plenty of time left to do so and ITER will provide the perfect opportunity.

> *“There is an awareness of the risks, they're manageable and the international community is taking steps to anticipate them.”*
>
> *Dr Richard Kamendje*

SAFEGUARDS BY DESIGN

New designs for nuclear power plants are sent to the IAEA for approval and must incorporate safeguards in the designs. While there are no current designs for fusion power plants, there is little doubt they will go through a similar process. The next 20 – 30 years will see the research, development and design of such reactors. At each step along the way, the long-term low-level risks will be known and planned for.

ITER has enabled international scientific collaboration on a scale that has rarely been seen before. This stands in marked contrast to competitive nuclear weapons research and the construction of their supporting facilities. Careful and considered research over the coming decades will ensure that fusion remains the low-level proliferation concern it always has been. ■

PUTTING PLANET EARTH FIRST?

REVISITING THE DEBATE ABOUT THE FUTURE OF GERMANY'S ENERGY SUPPLY

Picture: Istock/lukbar

The future scenario in Germany appears obvious: Renewable energies are to be expanded and conventional power stations are to be closed down. Simply add on a few storage systems and power grids and the German energy transition is complete – but is it really that simple?

WHERE TO ENERGISE?

For decades, the German population has feared nothing more than a nuclear disaster. After the Fukushima accident Chancellor Merkel and her government finally decided to close down all of the remaining nuclear power plants within eleven years.

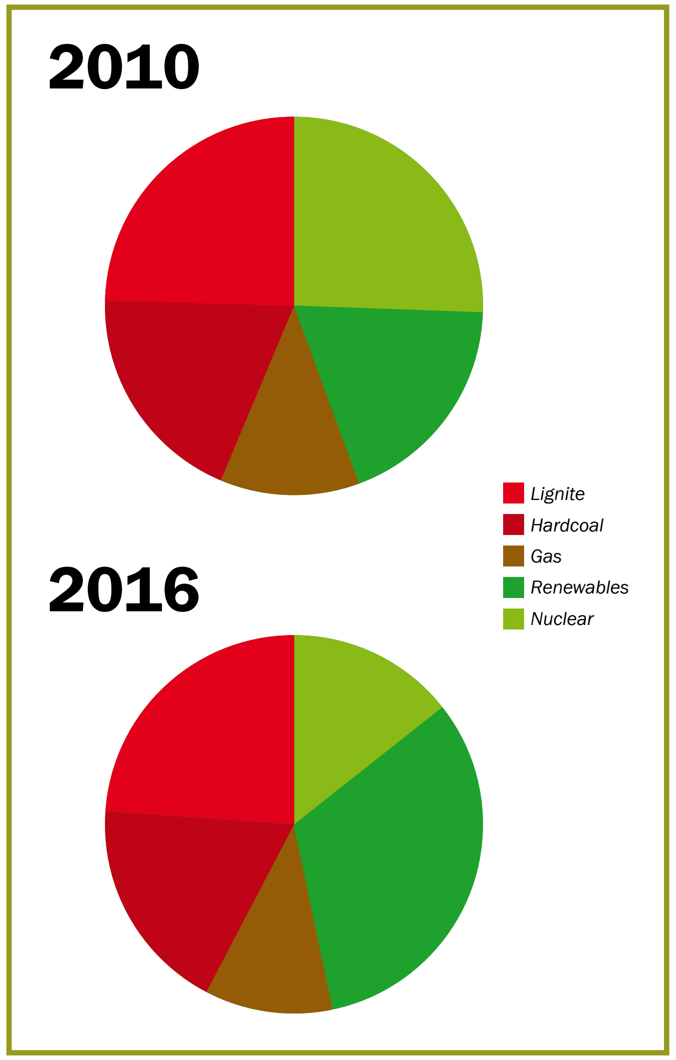
But climatologists have been warning us about climate change since the early 70s. As a result, the government has also been forced to develop a plan designed to help decrease CO_2-emissions until 2050. As a consequence of this, and in order to reduce greenhouse gases, Germany has also decided to shut down its fossil fuel power plants.

IMPOSSIBLE GOALS?

Now the country has to fight a battle on two fronts. Renewable energies primarily replace another CO_2-free one, viz. nuclear, while the use of fossil fuels decreased slightly (see Graphic). This is one of the reasons why it is very probable that the next climate change goal in 2020 will not be met. Additionally, in order to compensate for the remaining nuclear power plants, Germany must theoretically double its wind power capabilities. To achieve these aims, the rate of expansion of renewable energy had to be about one order of magnitude larger (see www.energy-charts.de).

DON'T BE TOO OPTIMISTIC!

Is it possible for Germany to be fully powered by renewable energies by the end of this century? There are a few optimistic, yet non-reviewed studies, like Greenpeace's "Plan B" or "Kombikraftwerk2" produced by the Agency of Renewable Energies. They predict that it can be achieved by way of relatively small efforts, by installing plants, storage and backup systems. Anyhow, most of these studies have critical issues: they ignore, for example, changing weather conditions or assume an unrealistic decrease in the amount of energy consumed.
I propose to consider the calculations made by Fritz Wagner, retired German plasma physicist and former director at the IPP. He has generated simulations for a fully renewable supply that also takes into consideration sector-coupling or an international power grid.



Germany's energy mix before Fukushima and now. The red component represents the climate impact of each source. (Based on www.energy-charts.de and VDI 2007)

The famous banner of the anti-nuclear movement at a protest-camp against coal mining near Cologne, Germany in 2017. Is it in times of climate change still legitimate to reject nuclear fission and fusion?

Even in the best case scenario it is more likely that Germany will need to multiply the level of power generated from renewable sources by ten or twenty times the current rate. Wagner also warns about the underestimation of dimensions of storage systems and their operational limitations.

THE STAGNATING DEBATE

About 71 % of Germany's population (according to an Emnid study from 2017) agrees that climate change is one of the biggest threats to today's society. But in 2016, 70 % of Germans also wanted to avoid nuclear fission according to a study from YouGov.
Fusion seems fascinating but does not play a major role: for example, when Wendelstein 7-X created its first hydrogen plasma in 2016, fusion was a trending topic in the German news for about a week. However, in the government's declaration on the energy policy, fusion is not even mentioned. So, nuclear power of any kind appears to remain something of a hot potato in this country. In most cases, it is only associated with potential risks and nuclear leftovers. The contradiction between phasing out nuclear power and attaining climate goals is often downplayed by politicians, independently of their party membership (see both the government's declarations and the party programmes of CDU, SPD, Alliance 90/The Greens, The Left).
Meanwhile, the European Union is keeping its nose out of this struggle. The Parliament in Brussels has declared that each country is free to choose the method of supply it prefers, just as long as the EU member states accomplish the international climate goals.

NEW IDEAS FOR THE FUTURE OF ENERGY

Given the problems explained above, I think, we need to embark upon a renewed debate of Germany's energy future. In an unbiased discussion, we need to figure out an energy mix that will minimise the risks for both humans and the environment.

> *"In an unbiased discussion, we need to figure out an energy mix that will minimise the risks for both humans and the environment."*

I personally have come to the conclusion that we initially should focus on phasing out the use of fossil fuels for power. Nuclear power will be necessary as long as the problems of pollution are as present as they are today. I know that continuing to use nuclear as a source of power will be a tough decision. The full argumentation would explode beyond the scope of this article.

In the long run, nuclear fusion should, together with renewable power, play a crucial role. It may be able to supply the growing energy demand world-wide much more adequately than a complex system based ONLY on renewable sources. Anyway, we must accept that fusion will not help us to reduce the CO_2 emissions before 2070 or even later. Though emissions have to be rapidly decreased already in the coming years, if we want to succeed in stopping climate change. Fusion can help in the longer run to meliorate the two major disadvantages of wind energy and Photovoltaics, which is low power density and intermittency.

TO PREVENT THE WORST CASE SCENARIO

On the other hand, we might also stick to the current strategy, which means: we continue to hope that sometime within this century renewable energy will be sufficient for our needs. However, if we are to fail, the result would be a simple one: the power supply, even that of 2100 will be a dirty and noxious one, if sufficient at all. That would be putting "Planet Earth last".

Picture: private

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"I am a student of Physics and I will be initiating my master's thesis in fusion research by the end of this year. I intend entering into the theoretical fields, because the mathematical description of nature has always been an interesting challenge. For me, convincing society of visions of a sustainable future is more exciting than maths itself. That's why I have enjoyed debating this topic even since my days at school."

DO WE ACTUALLY NEED **FUSION ENERGY** AT ALL?

Will it be possible to use just renewable energies to reduce the world‘s fossil fuel consumption? Could fusion power help to reduce the world‘s CO$_2$ emissions? Sometimes the simplest questions are the most important – and the most difficult – to answer. A small excursion into recent energy problems and cutting-edge energy predictions may help to put these questions into the right focus and to provide proper answers.

PARIS CLIMATE AGREEMENT

The 2016 **Paris Agreement** is a major international accord on tackling climate change, supported by almost 200 countries. It aims to restrict the global average temperature to less than 2° C above pre-industrial levels, mainly by way of cutting greenhouse gas emissions. 2° C is seen to be a tipping point, beyond which irreversible climate changes will occur, leading to a devastating rise in sea levels, extreme droughts and wildfires. Fusion could provide an essential source of zero emission energy needed to achieve the goals of the Paris Agreement.

Picture: EUROfusion/Shutterstock

A NEW ENERGY CONSUMING LIFE-STYLE

My grandparents generation will probably be remembered as the one that experienced the most incredible changes during their lives: they were born in a society where phone boxes were the only way to make calls, where travelling was a luxury reserved for the rich, where clothes were washed only by hand. Now, their generation uses mobile phones, travels by plane and owns washing machines. The changes that my grandparents have experienced during their lifetime are not without consequences for our society. The world energy consumption has grown enormously in the past 90 years, increasing to seven times that of 1930. This dramatic jump is not only related to the population growth. The world‘s per capita energy-consumption has doubled the value from 1930: hence, our life-style has become much more energy-consuming in a very short period of time.

HIGH FOSSIL FUEL CONSUMPTION: NEED FOR AN ENERGY TRANSITION

To satisfy this thirst for energy, fossil fuel consumption was increased dramatically. Coal, oil and natural gas rapidly began to dominate the energy market. Now everyone is familiar with the effects of this “energy revolution”: the increased emission of greenhouse gases is affecting the natural environmental balance that has ruled on Earth for more than 100,000 years. A relentless global warming process is causing the ice to melt and the climate to change and has resulted in disastrous impacts on our lives. At the same time, the concentration of fossil fuels in few regions (Middle East, Russia etc.) is seriously undermining geopolitical stability. Hence, a society with low fossil fuel consumption has become a fundamental goal that must be achieved in order to restore the world‘s natural and geopolitical stability. The Paris agreement of 2016 is pushing towards this aim, even if it has some limitations.

RENEWABLE ENERGIES ALONE ARE NOT ENOUGH

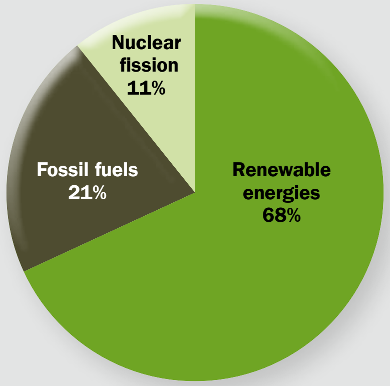
In this context, renewable energies play a crucial role. Wind farms, solar panels, biomass, geothermal and hydro power plants represent valid energy sources that can help to reduce fossil fuel consumption. Nevertheless, a socio-economic study of EUROfusion published in 2016 estimates that by 2100 renewable energies will cover 68 % of the total electricity production, while 21 % will still be provided by fossil fuels and 11 % by nuclear fission. This scenario sets low CO_2 emission targets, a condition that is helping the penetration in the market of renewable energies and does not consider fusion energy to be an option at all. Hence, it seems clear that renewable energies alone will not be able to completely conquer this energy transition.

A FULL ENERGY TRANSITION COULD BE ACHIEVED IN 2100

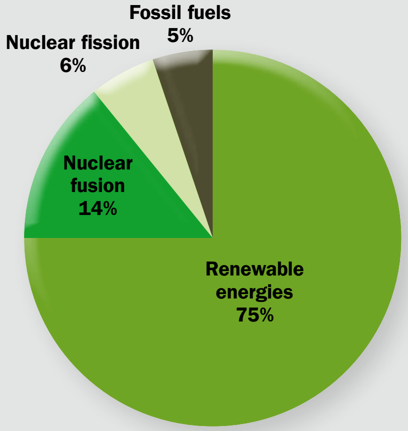
The same EUROfusion socio economic study also analyses a different scenario, one which considers a drastic reduction of the world per capita energy consumption, a low CO_2 emission target and the first fusion power plant connected to the grid to be in operation by 2070. Considering that we are talking about developments that may be implemented in 50 years' time, we should always be cautious with such timelines. Nonetheless, this study has interesting results: it predicts that, in 2100, 75 % of the total electricity production will be generated by renewable energies, 14 % by fusion power plants, 6 % by nuclear fission and only 5 % using fossil fuels.

These estimations are telling us something quite intuitive: if we will bring about a drastic reduction of our per capita energy consumption, if we aid the development of renewable energies and if fusion power plants are able to start operating soon enough, the energy transition could be achieved fully by 2100. Fusion energy, then, would not be a childish tantrum of stubborn scientists that do not want to throw in the towel, but it seems it will be necessary in order for our society to restore the world's natural and geopolitical stability. ■

2100 – FUSION failure



2100 – with FUSION



Source: D. Silvagni

Picture: private

Davide Silvagni

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“I am a former student of the European Master of Science in Nuclear Fusion and Engineering Physics and I recently started a PhD at the Max Planck Institute for Plasma Physics in Garching. As an energy engineer, I believe that engineers should develop “appropriate technologies” for mankind. Fusion is one of these, since it may help to reduce CO_2 emissions and the high fossil fuel dependency of our society, as I explain in my article.”

EUROfusion

EUROPEAN CONSORTIUM FOR THE DEVELOPMENT OF FUSION ENERGY

REALISING FUSION ELECTRICITY

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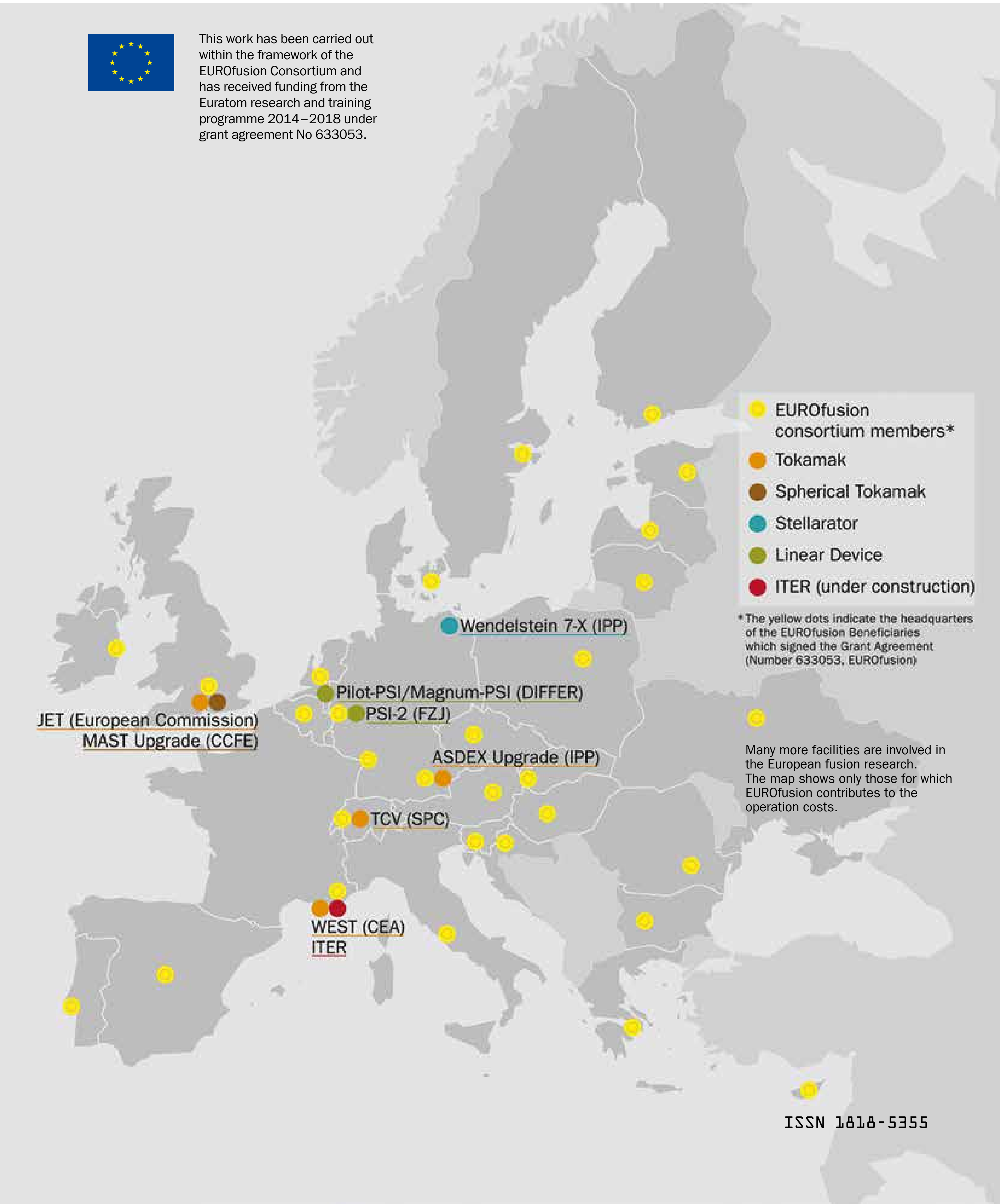

*The yellow dots indicate the headquarters of the EUROfusion Beneficiaries which signed the Grant Agreement (Number 633053, EUROfusion)

Many more facilities are involved in the European fusion research. The map shows only those for which EUROfusion contributes to the operation costs.

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