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Welcome to IFL Science, The Big Questions. The podcast where we invite the experts to explore the biggest mysteries of science with your host, Dr Alfredo Carpineti.

I: **Welcome to IFL Science, The Big Questions. A series where we ask experts some of the most pressing mysteries of science, technology and humanity. I'm your host, Dr Alfredo Carpineti, IFL Science Senior Science Writer, and it's my great pleasure to welcome Dr Elise Delchambre, Risk and Opportunity Management Officer at ITER (International Thermonuclear Experimental Reactor), an experimental nuclear fusion power plant being built in the south of France. The question this time is can we achieve unlimited energy and the key to that could be in humanity's mastery of nuclear fusion. Dr Delchambre, it's a pleasure speaking to you today. Could you please introduce yourself and tell us a little bit about your work at ITER?**

R: Thank you, Alfredo. I'm really delighted to discuss with you this morning about fusion energy. So I am Elise Delchambre. I am French as you can hear. I did a PhD 18 years ago now in Plasma Physics. I did it in France in the south of France at CEA, on an experimental fusion device called Tore Supra. After my PhD I went to UK to work on MAST, The Mega Ampere Spherical Tokamak, at the Culham Science Centre in the south of Oxford and then I went back to France and I started my career. I was a Physicist, mainly working on infrared thermography, which is a methodology to measure temperature using radiation from a carbon surface. I also was a physicist in visible spectroscopy. Almost nine years ago I moved from physics to project management because I like to see an idea becoming a reality.

In 2018 I joined the ITER project as a risk and opportunity management officer and in particular in the machine construction department., My job is mainly to interact with the engineer in charge of the assembly, the construction of the machine and to identify events that could impact positively or negatively the schedule, the performance or the cost of the project.

I: **Fantastic, thank you very much. With your expertise can you tell us a little bit about how nuclear fusion works?**

R: Let's start by saying that reaction fusion is a natural event that occurs in the universe since 13.8 billion years, since the beginning of the universe. It's a reaction that fuels and powers, stars. For example, our sun and the weight of our Sun is 300,000 heavier than Earth, and thanks to that, with the gravitation, inside the core of the Sun you have a big temperature. The temperature in the core of the sun is 15 million degrees. With that temperature, you have a new state of matter and this new state of the matter is called plasma. Plasma is a fourth state of the matter. You know solid, you know liquid, you know gas and when you heat up a gas, actually electrons and nuclei are free to move. Since we have electric charge, so negative electric charge for electrons and positive electric charge of nucleus, when you put electric charge in the magnetic field you can shape the move and the trajectory and you can control the plasma.

In the sun we know that since the last century, 1920 actually, Eddington - who proposed that the sun fused hydrogen into helium - the difference of mass between two hydrogen and one helium is energy, thanks to the relation $E=MC^2$. Basically it is a big source of energy, the energy inside the nucleus and it is something, as I said that's natural because plasma constitutes 99% of the universe. Actually, thanks to fusion we are made of stardust. This is why it's a big quest and big dream to recreate on Earth what happened in all the stars in the universe because the aim is to recreate from very light atoms, bigger atoms and in the sun it's hydrogen transforming into helium.

I: If I understand correctly, the sun uses hydrogen, regular hydrogen, one proton, one electron, and fuses into helium but that's not what the nuclear fusion power plant will use, they will be using Deuterium, which is this heavier version of hydrogen, which is one proton and one neutron and Tritium that has one proton and two neutrons. It's the same process but slightly different materials that we try…

R: What we want to do in the research in magnetic fusion is to do on Earth is deuterium, tritium fusion reaction. While in the sun you have big gravity and big density and high temperature you can trigger fusion reaction. On Earth it's a bit more complex because we have to recreate favorable conditions to trigger fusion. To do that, it's a bit different. It's a gas, so it's ionized gas of plasma with very low density but with bigger temperature. In the core of the sun, you have 15 million degrees and on Earth we need to have 150 million degrees, so ten times hotter than in the core of the sun. To do that in concrete terms, we need to inject the gas, basically in the ITER devices, 2 grams of the deuterium tritium in a big vacuum, so $800m^3$, so big, big volume and a little quantity of gas, of 2g.

We inject in the magnetic cage and in the magnetic field particles start to move and this creates a current, what we call plasma current. When there is a current, there is naturally, like in a copper conductor. You heat up the plasma, you heat up and you also use additional heating because the aim is really to have 150 million degrees. We heat up with antennas, like a microwave, the one we have in the kitchen. We also have a different kind of heating system with a natural beam and thanks to that we can switch on the plasma and start nuclear fusion, either with hydrogen, but what is interesting for electricity, for a source of electricity, is to control the fusion of the deuterium and tritium.

I: That is absolutely fascinating. I am always blown away by how much in just over a century we have learned from barely what the inside of an atom was to actually understanding its components and actually manipulating it. Knowing really so much about nuclear fusion, how are we doing, how good are we at this? Have we got any way into mastering this energy source?

R: What you need to know is when we are talking about sustainable energy with fusion it is because of future fusion devices, we need two principle fuels. The first one is deuterium and deuterium is just a heavy hydrogen atom and we also need lithium and lithium, as well as deuterium, can be found in seawater. That's why it's an amazing source of energy and that's why we are talking about sustainable. Having said that, in order to face the climate emergency and also the increase in terms of electricity demands, we need to play with several darts on the chessboard. Let's say that fusion is one down on the chessboard, and working in fusion is really to expect that before the end of the century we will be able to produce electricity based on the fusion reaction of the deuterium and tritium.

I: What are the challenges in making nuclear fusion happen?

R: Fusion community needs to control and have different challenges and we have five main challenges to succeed in fusion. The first one is to maintain and control hot turbulent plasma over a long period of time. This is the first thing we have to handle. We have to absorb the energy of the neutron because the fusion direction between deuterium and tritium creates helium particles and the neutron. Helium particles is a gas and it's like in a balloon and it's important to maintain the temperature of the plasma. Neutrons, this is what we want because with the neutron we can heat up the system of water cooling and then produce electricity. The big challenge is to absorb this neutron energy without damaging the vacuum around and all the components around it. In terms of technology, it's also a big challenge. The third challenge also is to create tritium inside the machine. We want to do the deuterium-tritium, the deuterium is coming from seawater but tritium is not something natural on Earth and is radioactive.

We need to create inside the machine the tritium and to do that we need lithium. With one neutron and one lithium we can create tritium. The third challenge is to have a specific competence so that we call the tritium module blanket that can transform lithium into tritium and then inject that tritium into the machine. The fourth challenge is the power exhaust because as we have hundreds of millions of degrees inside the plasma, on the edge we have a superconductive coil, that actively cools at 4 Kelvin, so it's quite cold. We need to enable to use that energy, that power load and control that and to exhaust this power load. This is a scientific and technological challenge in terms of plasma facing confidence. The last challenge also is the maintenance of such a device. ITER basically will be the first Tokamak - because Tokamak is the name for magnetic chamber for fusion - and ITER will be the first Tokamak to handle all these challenges. It's an integrated approach and this is the first time.

ITER, what is also important to know about ITER, is that it will be the biggest Tokamak in the world. Why it's big, why it's so big is because when I started in fusion, what we knew is that to increase the probability of particles to collide and to fuse, we need a big volume. We need a big volume to increase this probability of collision and fusion. We started with that. ITER, in that sense with bigger capability compared with the current devices in the world, can reach what we call burning plasma. Okay, so also important, ITER will not produce electricity. ITER is a big Tokamak but it's an experimental reactor. The aim for ITER, for the scientific community, is to prove the feasibility of fusion as a source of energy for the production of electricity. ITER is an experimental reactor, the step after that is to have an initial prototype that will produce electricity. The first step is ITER.

To do fusion reaction we know how to do it and we did it already and we did it with the deuterium-tritium, for instance, TFTR, Tokamak in the US, but also JET in the UK, already did fusion reaction with deuterium-tritium. JET also was very close to producing the same amount of energy that the machine itself used to switch on the direction and to produce as much energy as we use and this is called ignition. This is factor one, let's say factor one. For JET, it was 0.7, so we were quite close to succeeding with that. We need now a bigger and bigger machine and this is called ITER. The future objective of ITER during the operation will be to have a gain factor of ten, that means it can produce ten times energy than we use. This is a bigger challenge and the machine will start in 2025 and we will have a second phase of assembly because we need also to install inside the vacuum the cellar of specific components to sustain the high temperature and for the poor exhaust. We will then have a second run, what we call the DT operation, the deuterium-tritium operation in 2035. We expect to have a burning plasma in 2025 with full power in 2038 and when I'm talking about burning plasma it means also that at some point we need energy to switch on the plasma and to initiate and to trigger a fusion reaction.

Then we need a self-heated plasma. Within ITER burning plasma it means that we can initiate fusion. We create helium particles, high-energy helium particles and the helium particles maintain the temperature and then you can switch off your heating system. The plasma is self-heated and this is what we call a burning plasma, which is the biggest waste in scientific community, in fusion.

I: That is fantastic. Based on the dates, I kept thinking of this old joke. I am a physicist by background and I've heard this since I started, so almost a decade, that nuclear fusion is almost 20 years away and it's something I think that has been said since the '70s. With your timescale of getting up self-sustained burning plasma by 2038, it feels that maybe we really are just 20 years away from, maybe not a fully built fusion power plant, but something really close to it. Do you think that is possible that by 2050 we will be having commercial fusion power plants?

R: When I started, to be honest, it was 50 years away. It was even longer. If we carry on with ITER, let's say that, well I'm convinced that we will have a burning plasma in ITER in the decade. After that, we need to deploy a fusion reaction at an industrial level and if you project in the time scales, based on the current ITER configuration, a power plant, based on fusion will be more end of the century.

We need also to understand that it is a bit too late to provide an answer for climate change. When I started physics and fusion what we knew is that the size of the machine must be big. Now we have new scientific breakthroughs. I think that they demand something happens in the fusion community, something really big and while ITER is paving the way for industrial scale, clearly during the construction of the machine we are managing and very well handling technical challenges. Its big massive components, specifically for instance, for actively cooling the superconductive coils. This is the first time we are building such a big coil. We know how to build superconductive but at such a scale this is the first time. Already we have a bunch of qualified industries in the work, capable of producing such a critical component for fusion. This is already good news. In parallel, the UK, but also the United States, are working in parallel on a new technology and this could change the future progress of fusion because now we are able, so that's why I'm talking about scientific breakthrough, we are able to build superconductive coils at high temperature. Now, before the beginning of ITER, we have a kind of limitation in terms of the magnetic field. Now with the new technology and with combining scientific approaches and industry we will be soon able to produce a new type of superconductive coil working at higher temperatures with a bigger magnetic field. To have a burning plasma and to have a self-heating plasma we have two choices, either we increase the size of the machine or we increase the magnetic field. Now, it may be possible to study different types of devices, that's why the UK is proposing to work on the project called STEP and to build as soon as possible during the coming decade the fusion device capable of directly producing electricity.

In the US you also have MIT working with a start-up commonwealth fusion system, I think, and they are designing a new type of Tokamak, a smaller one, with a higher magnetic field called SPARC. Fifty years away, maybe not, and I think we will see a big change in this century but in the landscape of renewable energy, I think we need also to consider all sources of low carbon energy. It's an energy mixed really. I think we need to consider fusion also, because it's a low carbon energy and it's difficult to get rid of that because it can help for the climate emergency. We also need to combine with photovoltaic and hydroelectricity and wind, also. There is no one big solution. There is a mix of solutions that you have to adapt, depending on the place in the Earth, if you have space for wind and photovoltaic, and also depending on the local demand. Also, the capability to store energy and also the capability to connect to the grid. This is my vision, and I think in ITER the main message is really fusion will be part of the energetic mix in the coming decade.

I: Wonderful, thank you very much. I have just one final question. What is something you would want everyone to know about nuclear fusion?

R: Nuclear fusion is completely different from fusion reaction. Of course, we are talking about energy inside the nucleus, but it is completely different. The main difference, and that's why the whole community involved is working hard to find a solution, is because, for instance, there is no runaway in fusion reactor. If you switch on the machine you just shut down fusion reaction. If you stop injecting gas inside the machine the plasma switches off also. It's so hard to create the best condition for fusion reaction. You need to have the best time confinement, the best temperature, best density, control the turbulence and there is very low density, only 2g of deuterium-tritium in a big volume. There is no risk of runaway, like in fusion, and also there is no long-term, high radioactive waste. This is also the reason why I started in fusion because 20, 30 years, and 50 years ago it was already a way to see nuclear energy. It was the future of nuclear energy without any high radioactive waste. It is worth spending time, spending money and spending best effort and putting industry and science all together to try and to try hard.

I: Wonderful. Thank you very much for speaking to me today about the future of energy. Thank you so much for your time.

R: Thank you.

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Thanks for listing to IFL Science, The Big Questions. Don't forget to subscribe so you don't miss any future episodes and join us next time when we'll be examining the composition of the cosmos, have a great day.

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