Australian ITER Forum Website News Update 11/17

B.J.Green (20/11/17)

1. The hidden mechanics of magnetic field reconnection, a key factor in solar storms and fusion energy reactors

October 12, 2017

https://phys.org/news/2017-10-hidden-mechanics-magnetic-field-reconnection.html

In July 2012, a powerful solar storm almost struck Earth. Scientists estimate that had the storm, called a coronal mass ejection (CME), hit the planet, the impact would have crippled power grids worldwide, burning out transformers and instruments.

A NASA probe that happened to lie in the CME's path detected some of the charged particles it contained. Data the satellite collected showed the storm was twice as powerful as a 1989 event that knocked out Quebec's entire power grid, disrupted power delivery across the United States and made the northern lights visible as far south as Cuba. In fact, the recent storm might have been stronger than the first and most powerful CME known to hit the planet, the Carrington event. That 1859 storm sprayed sparks from telegraph lines, setting fire to telegraph stations. Researchers put the odds of a Carrington-size CME occurring by 2024 – and possibly hitting Earth – at 12 percent.

Such events occur when field lines in the sun's massive magnetic system snap and reconnect. "Magnetic fields are a reservoir of an enormous amount of energy, and major eruptive events occur in which this energy is liberated," says Amitava Bhattacharjee, a plasma physicist at the Princeton Plasma Physics Laboratory (PPPL), a Department of Energy facility in Princeton, New Jersey. "Charged particles tend to get tied to magnetic field lines like beads on a wire – when the wire breaks, the beads get thrown off at enormous speeds."

The phenomenon, known as fast magnetic reconnection, remains a mystery. No one knows how field lines break and rejoin fast enough to expel the billions of tons of material unleashed in a CME, or even in the smaller eruptions of common solar flares. In laboratory experiments and simulations, Bhattacharjee and his colleagues have revealed new mechanisms that help explain fast magnetic reconnection.

Bhattacharjee has been in pursuit of such mechanisms since graduate school, when he realized that plasma physics is "a beautiful, classical field with wonderful equations that were good things to analyze and do computer simulations with," he says. At the same time, he saw that plasmas – which constitute 99.5 percent of the visible universe – are also the key to "a very practical and important problem for humanity, namely magnetic fusion energy."

For decades, nuclear fusion machines, such as doughnut-shaped tokamaks, have promised a virtually limitless supply of relatively clean energy. But a working fusion device is still out of reach, partly because of fast magnetic reconnection. "Magnetic fusion reactors have magnetic fields in them, and these magnetic fields can also reconnect and cause disruptive instabilities within a tokamak fusion plasma," says Bhattacharjee, professor of astrophysical sciences at Princeton University and head of PPPL's Theory and Computation Division.

In the present model of reconnection, opposing magnetic fields are pushed together by some external force, such as plasma currents. A thin, flat contact area forms between the two fields, building tension in the field lines. In this thin region, called a current sheet, plasma particles – ions and electrons – collide with one another, breaking field lines and allowing them to form new, lower-energy connections with partners from the opposing magnetic field. But under this model, the lines reconnect only as fast as they are pushed into the current sheet – not nearly fast enough to explain the tremendous outpouring of energy and particles in a fast-reconnection event.

Since this slow reconnection model depends on plasma particle collisions, many research groups have searched for collisionless effects that might account for fast reconnection. Promising explanations focus on the behavior of charged particles in the current sheet, where field strength is close to zero. There, the charged properties of the massive, sluggish ions are suppressed, and the nimble electrons are free to carry the current and whip field lines into new configurations.

For laboratory experiments on hidden mechanisms, Bhattacharjee's team uses powerful lasers at the University of Rochester's Omega facility. To develop computer models, the group uses Titan, a Cray XK7 supercomputer at the Oak Ridge Leadership Computing Facility, a DOE Office of Science user facility, through the Office of Science's Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program. The Office of Science's Fusion Energy Sciences program and the DOE National Nuclear Security Administration sponsor the experiments.

In an early experiment led by PPPL research physicist Will Fox, the team pointed two intense Omega lasers at materials that yield plasma bubbles under the beams. Each bubble spontaneously generated its own magnetic field through an effect known as the Biermann battery. As happens in the sun and nuclear fusion devices, charged plasma particles lined up on the magnetic field lines. The bubbles plowed into each other, and a current sheet formed between them. The reconnection rate between the fields was fast – too fast for classical theory.

"That's where we were first establishing the underlying mechanism for reconnection happening in this machine," Bhattacharjee says. The team now had a model for fast magnetic reconnection, one applicable to earlier pioneering experiments conducted by groups in the United Kingdom and the United States. A simulation on Titan showed that more field lines were crammed together in the current sheet than anyone had realized, a phenomenon called flux pileup. The study showed that, in addition to previously suggested collisionless effects, flux pileup plays a role in fast reconnection.

In later experiments led by Gennady Fiksel, now at the University of Michigan, the team didn't want to rely solely on spontaneously generated magnetic fields. "We felt we needed greater control on the magnetic fields we were using for the reconnection process," Bhattacharjee says. "And so we used an external generator called MIFEDS (magneto-inertial fusion electrical discharge system), which produced external magnetic fields we could control."

To capture changes in this field, the team filled the space with a thin background plasma, generated by a third laser, and imaged it using a beam of protons, which magnetic fields deflect. When two plasma bubbles impinged on the external magnetic field, the team created the clearest image so far of events taking place in the region where field lines reconnect. The new configuration also showed flux pileup, followed by a reconnection event that included small plasma bubbles forming in the region between the bubbles and, finally, abrupt annihilation of the magnetic field.

"The mechanism that we found is that you form this thin current sheet that can then be unstable, in what we call a plasmoid instability that breaks up this thin current sheet into little magnetic bubbles," Bhattacharjee says. "The plasmoid instability is a novel mechanism for the onset of fast reconnection, which happens on a time scale that is independent of the resistance of the plasma."
Bhattacharjee and his colleagues are working to understand how their discovery fits into the big picture of solar activity, solar storms and nuclear fusion devices. Once they and the broader community of plasma physicists fully understand reconnection, the ability to predict CMEs and tame some of the plasma instabilities inside tokamak reactors, for example, may be within reach.

2. How machine learning can predict and prevent disruptions in reactors

October 11, 2017

https://phys.org/news/2017-10-machine-disruptions-reactors.html

Robert Granetz has been a research scientist in MIT's Plasma Science and Fusion Center for more than 40 years. He recently gave a talk hosted by the MIT Energy Initiative (MITEI) on using machine learning to develop a real-time warning system for impending disruptions in fusion reactors. A specialist in magnetohydrodynamic instabilities and disruptions, Granetz discussed how research in this area is bringing us one step closer to creating a stable, net-energy-producing fusion device.

Q: What makes plasma different from other states of matter? What are the challenges of working with plasma as an energy source?
A: In a gas at normal temperatures, the negatively-charged electrons and positively-charged nuclei are tightly bound into atoms or molecules, which are electrically neutral. Therefore, there are no forces exerted between particles unless they happen to actually collide. (The gravitational force acts between all masses, but gravity is much too weak to be relevant.)
When gas particles do collide, the collisions only involve a pair of particles at a time, and the kinematics of the collision are very simple, just like billiard ball collisions. So we can easily calculate the behaviors of gases. However, at the high temperatures that we need for fusion, the thermal energy of each atom or molecule is much, much greater than the binding energy that holds the electrons and nuclei together, so the neutral particles break up into their constituents, i.e. electrons and nuclei, which we call the "plasma state."
Therefore, in a plasma, all the particles are charged, and there are long-range electric and magnetic forces acting between the particles. A single electron or ion influences the motion of about a billion other electrons and ions simultaneously, and all of those billion other particles are simultaneously influencing every other individual particle. In addition, the electrons and nuclei have extremely different masses, so their velocities are very different. Also, since all the particles are charged, they can interact strongly with electromagnetic radiation. All of these complicating properties mean that in practice, we can't accurately calculate the detailed behavior of plasmas from the basic equations of physics.

Q: In the context of fusion reactors, what's a disruption?
A: To date, the tokamak concept for a steady-state fusion reactor outperforms all other concepts in terms of energy confinement. The tokamak relies on driving a large current—of the order millions of amperes—through the plasma to produce the magnetic field structure required to obtain good energy confinement. However, this large plasma current is somewhat unstable, and is subject to sudden termination, usually with very little warning. When a disruption occurs, the considerable thermal and magnetic energy contained within the plasma is suddenly released very quickly, which can lead to damaging thermal and electromagnetic loads on the reactor structure.

The whole goal of fusion energy is to develop large power plants to generate electrical power on the grid, and replace today's fossil-fueled utility power plants, and even replace fission nuclear power plants. But if a fusion power plant is subject to disruptions, its electricity output would suddenly turn off. Even if the most damaging consequences can be avoided, it could be hours or days before the plant can recover and get back online, only to be subject to another disruption at some later time. No utility would want to use fusion energy if that were the case. If we're going to rely on the tokamak concept for fusion reactors, we need to avoid or mitigate disruptions.
Q: How can machine learning address this problem?
A: The signs that a disruption is imminent are often quite subtle. Fusion researchers continuously measure a number of characteristic plasma parameters during a plasma discharge, and we have reason to believe, both from empirical experimental evidence and from theoretical understanding, that some of these measured plasma parameters may provide indications that a disruption is about to occur. But this information is not straightforward to interpret, not just with respect to the occurrence of an impending disruption, but also with regard to the timing of an impending disruption.
In an attempt to solve this problem, my team—which consists of myself, postdoc Cristina Rea, graduate students Kevin Montes and Alex Tinguely, and a dozen scientists at other U.S. and international labs—has built up large databases of measured parameters which we believe are relevant to disruptions, from several years' worth of experiments on several different tokamaks around the world. We are now applying machine learning techniques to these data to see if we can discern any patterns that would accurately predict whether or not a disruption will be occurring at a specific time in the near future. When dealing with large, complicated datasets, machine learning may be a powerful way of finding subtle patterns in the data that elude human efforts.

3. The ITER Project: Future of Endless Clean Energy?

physics-o-mania (58) in **steemstem** • last month

https://steemit.com/steemstem/@physics-o-mania/the-iter-project-future-of-endless-clean-energy

Hello Steemians, today I bring to you a topic which I was planning to write about for a long time. It is about the next generation power source which is endless and clean. Extensive research on the subject is underway all over the world. The following project is a collaboration of countries all over the world to get a solution for the future power need. Lets visit it to know more about it.

Read in my high school books, “***Sun is the ultimate source of energy on earth***”. That was only some combination of words for me at that time. Though lately, now I understand what that sentence means. I am a product of sun and I won’t have existed in absence of sun, no one on earth could.

The discovery of fossil fuel revolutionized the way of living of the world for the last few centuries. It fueled the industrialization of the world.

But the fossil fuel reserve is getting shallow over years and is expected to run out by the next few decades. May be its nature’s blessing to us in the form of a second chance to clean our atmosphere. Alternative sources to run the world is being studied all over the world like the solar energy, wind energy and nuclear energy. Energy sources like solar energy and wind energy need large infrastructure for operation for large scale energy production and their energy yield is comparatively low. While nuclear energy need relatively smaller set up which can generate a very large amount of energy.

ITER Project:

ITER which stands for International Thermonuclear Experimental Reactor is an international nuclear fusion research program and an engineering megaproject with an eye to fulfill the energy needs of the post fossil fuel period. The project is funded by seven nations namely India, Japan, USA, China, Russia, South korea and the European Union where European Union is the host and funds the major part of the total cost. The construction of the Tokamak type fusion reactor is underway at Saint-Paul-lès-Durance, France.
The readers can know more about the project from the official website of *ITER*[here]

While nuclear fission has already grown as a reliable source of clean energy, nuclear fusion is still in its infancy. The disadvantage of nuclear fission is that it produces a very large amount of radioactive wastes while the advantage of nuclear fusion is that the energy produced in this process is very large compared to nuclear fission. Also, the radioactive wastes produced in fusion process mostly have very short life.

The aim of the project is to construct a Tokamak fusion reactor and to operate it, to demonstrate the application of the experimental studies of plasma physics into a full-fledged energy production purpose through nuclear fusion.

At extreme temperatures electrons get torn apart from the nuclei and the system becomes a mixture of very high velocity electrons and nuclei. This state of the matter is called plasma and is called the fourth state of matter. The reactor is expected to produce 500 megawatts of power with only 50 megawatts to initiate it. The project started in 2013 and is expected to operate from 2025. It applies the concept of magnetic confinement plasma physics to operate it and will be the largest of its kind in terms of plasma volume used (approx. 840 cubic meters). The project will be followed by a commercial demonstration of a fusion power station named DEMO.

- **Nuclear Fusion:**

Nuclear fusion is an application of Einstein's concept for mass-energy conversion,

$$E=mc^2$$

In this process two or more atomic nuclei come close to each other and fuse together to form a larger nucleus and some subatomic particles like protons and neutrons with a release of energy. Nearly all isotopes lighter than Iron-56 and Nickel-62 which have the highest binding energy per nucleon, fuse with other isotopes, deuterium and tritium enjoys the most attention as it has the lowest activation energy (hence low temperature needed to fuse them together) and produce the largest amount of energy per unit weight.

The reaction results in a decrease in the mass in the system. This missing mass between the reactants and the products is manifested in the form of energy. The reaction needs a high energy to force the nuclei to fuse together which then yields a huge amount of energy compared to that used. This process is what powers the sun and many other stars. It seems the ITER team took it so seriously. They be like,"*If sun is the ultimate source of energy, why not make a mini-sun on earth itself*".

Nuclear fusion has many other advantages. The reactants which are isotopes of hydrogen i.e. deuterium and tritium are abundant on earth. Deuterium can be easily extracted from seawater while tritium is produced in the reaction itself. Moreover, the process produces no CO_2 or any other atmospheric pollutants.

Deuterium and tritium fuse to form a helium nucleus and a high energy neutron.

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\ MeV$$

We know, like charges repel. The protons in the two nuclei repel each other while in the process of fusing together. That is why the activation energy needed in the fusion process is very high which overcomes the electrostatic repulsion between the protons and allows the two nuclei to fuse. The optimum distance between the nuclei to undergo fusion is 100 femtometerswhen the nuclei undergo quantum tunneling. At this condition strong nuclear force and electrostatic forces are equal and the nuclei undergo the fusion process. Magnetic confinement and high temperature is used to achieve the small separation between the nuclei in the ITER Tokamak reactor.

At such a high temperature the particles in the reactor have high kinetic energy. These particles may escape the vessel if not confined well thus decreasing the plasma temperature. In ITER reactor these particles are confined within the container vessel using magnetic field induced by some coils around the container. Charges when move though a magnetic field experience a force in the perpendicular direction of their motion. It results in a centripetal acceleration of the charge and hence the charge continues in a circular or helical motion thus getting confined in the container vessel.

The container vessel for the reactor is subject to high velocity particles like the protons, neutrons, ions and many other particles due to the high temperature which may gradually degrade the container. A strong vessel which can sustain such an environment must be designed. The tests for such container material is a part of the ITER project and the IFMIF(**International Fusion Material Irradiation Facility**).

The high energy neutrons which will be radiated from the plasma crossing the magnetic field without any hindrance (since it is chargeless) is the primary source of the output energy of the ITER project. This energy will then be used to run an electricity-generating turbine which will generate electricity.

The project if successful may turn into a holy-grail of energy source and will open the door for future application of nuclear fusion and plasma physics for energy production which is clean and endless. It is hoped that it will end the long debated energy shortage of the world.

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4. THOMAS MORGAN TO LEAD WORK PACKAGE ON LIQUID METAL DIVERTORS

October 10th 2017

https://www.differ.nl/news/thomas_morgan_to_lead_work_package_on_liquid_metal_divertors

The EUROfusion research consortium has appointed DIFFER group leader Dr. Thomas Morgan as the leader of its new work package on self-repairing liquid metal walls for the exhaust of future fusion reactors. In the first two years of this European research package, Morgan wants to build on the field's current foundation in physics with a more engineering-oriented approach.

Future fusion power plants will mimic the nuclear fusion process at the heart of the sun to generate clean energy from abundant resources. Protecting the exhaust (*divertor*) of the fusion reactor against the harsh fusion conditions is one of the main challenges to realizing fusion energy. "One exciting concept is that of a liquid metal divertor, for example because it could be self-repairing", said Morgan, who is head of the Plasma Materials Interactions group at DIFFER. "In this design, a layer of liquid metal protects the underlying reactor wall against the harsh fusion environment, and this can be replenished as it is eroded."

By setting up a new work package dedicated solely to liquid metal divertors, EUROfusion wants to unify the research in a coherent program and set the direction for future research in Europe. Morgan will help set the direction in this work package together with his deputy Bradut-Eugen Ghidersa (Karlsruhe Institute of Technology), and he intends to adopt an engineering-based approach building on the solid physics background developed by the fusion community over the last decades.

Morgan: "At the end of the current package in 2019, we want the community to have developed several pre-conceptual designs - a set of options with CAD drawings, and operational limits defined, which can then be developed further for demonstration power plants."

DEVELOPING FUSION ENERGY

Researchers and companies all over the world are collaborating on the development of fusion energy; producing clean, safe energy from abundant resources by mimicking the nuclear fusion process in the heart of the sun. The international ITERexperiment under construction in southern France will be the first to produce more power from the fusion process than it consumes, with a demonstration power plant DEMO planned to operate by 2050.

In a fusion reactor, magnetic fields confine the 150 million degree fusion fuel and guide the reaction product helium to the exhaust or divertor region. The divertor of future fusion power plants has to handle harsh conditions such as an intense plasma bombardment and heat load. Designing a divertor that can stand up to these conditions 24/7 is one of the main research lines of the European research consortium EUROfusion.

EUROFUSION

EUROfusion coordinates the European research for the development of fusion energy and is a consortium of 30 research organisations and universities from 26 European Union member states plus Switzerland and Ukraine.

5. Is Infinite Clean Energy Near?

By Haley Zaremba - Oct 29, 2017, 2:00 PM CDT
https://oilprice.com/Alternative-Energy/Nuclear-Power/Is-Infinite-Clean-Energy-Near.html
fter decades of research and planning, a group of scientists in France are attempting to achieve the impossible: harnessing the heavens.

They are building a tokamak, a donut-shaped, man-made, artificial star that has the potential to bring the universe down to earth and provide millions of years of clean energy. Is this the dawn of a new era, in which we dominate nuclear fusion and solve the energy dilemma for millennia, or is it just a crackpot pipe dream? Every year we seem to be getting closer to the former.

While it once seemed impossible that we would be able to create, control, and confine plasma hotter than the sun, the development of tokamaks has created, for the first time, a viable avenue for nuclear fusion. Scientists have already been able to create plasma at the necessary ultra hot temperatures necessary. Now they just need to refine the process until they can create more energy than is consumed by the process to create the reactions—something that has never yet been achieved, but is growing closer to becoming a reality each year, thanks to international projects like the one currently taking place in France.
The International Thermonuclear Experimental Reactor (ITER), the massive tokamak fusion reactor under construction in Southern France, has been internationally funded with $14 Billion dollars (a number that will continue to rise) in capital. It's a combined effort by many nations in the European Union along with the United States, Russia, China, India, Japan, and South Korea. The scientists involved anticipate that the groundbreaking machine will make its inaugural run in 2025, 40 years after its inception, which was initiated after a fateful handshake between President Ronald Reagan and Soviet leader Mikhail Gorbachev in 1985.
Related: Which Of These 3 Hotspots Will Be The Next Big Thing In Oil?
There is a concern, however, that with the new administration in the United States, their annual $400 million contribution may be slashed or stopped altogether thanks to budget cuts and an aversion to investing in renewables. The Energy Collective has reported

that President Trump has allotted $63 million for ITER, however, the Senate's official budget does not publicly account for ITER funding at all.

Despite a new reluctance from the federal government, under past administrations the U.S. has been on the cutting edge of the technology that could help make the tokamak-based nuclear fusion a reality. Just this month the U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) have completed new simulations to study the behavior of these plasma bubbles and blobs, giving us a great understanding of how the heat moves and changes within the tokamak.

In order to fuse hydrogen atoms into helium, tokamaks must maintain the astronomical level of heat of the plasma (the hottest state of matter) they control. This is a particular challenge due to the percolating bubbles that arise and release this vital heat (think of boiling water). In order to function, a tokamak needs to maintain a temperature of around 100 million degrees Celsius.

In future simulations, the PPPL also plans to study how this behavior changes according to the shape of the tokamak, as well as the effects of density, temperature, and electromagnetic force affect the behavior of the blobs, crucial information in the development of the ITER.

Related: Kurdistan Proposes Immediate Ceasefire With Iraq

The UK is also gunning to be a major player in the development of nuclear fusion, and is currently working on designs for their own nuclear fusion power plant. Just this month it was announced that Atkins will partner with Tokamak Energy to create what they hope will be the world's first fusion facility (although it will be completed more or less at the same time as France's internationally-funded model) that generates more energy than it consumes. They aim to generate the first electricity by 2025 (the same year as ITER) and commercially viable fusion power by 2030.

Despite our tricky history with nuclear power, fusion holds the most promising (if not the only) viable future for clean and renewable energy worldwide. Despite popular belief, fusion actually holds little danger relative to traditional nuclear power, producing no long-lasting radioactive waste. Working as a complement to wind and solar, nuclear fusion would bring us much, much closer to creating a carbon-neutral planet, a goal that has never been more urgent.

By Haley Zaremba for Oilprice.com

6. FUSION ENERGY: HOW SCIENTISTS ARE CREATING PLASMA HOTTER THAN THE SUN IN QUEST FOR LIMITLESS CLEAN ENERGY

BY HANNAH OSBORNE ON 10/23/17 AT 4:48 AM

http://www.newsweek.com/fusion-energy-limitless-clean-power-plasma-hotter-sun-689225

Updated | Scientists believe that fusion energy—which generates electricity in the same way that the sun creates energy—has the potential to provide the world with an almost limitless, clean source of power. But while it is known that fusing two lighter atomic nuclei to form a heavier nucleus releases energy, it is far more difficult to harness that power. In order to do so, they would have to create plasma hotter than the sun that could be stably confined.

So far, researchers working across the globe have managed to achieve these temperatures to produce the plasma using two types of device—a tokamak and a stellarator (explained below). But as of yet they have been unable to generate more power from the fusion than it takes to create the reactions in the first place.

In a study published in *Nature Physics* in June, lead author Yevgen Kazakov, a researcher at the Laboratory for Plasma Physics in Brussels, Belgium, and colleagues showed how they had developed a new way to heat fusion plasma in tokamaks. By using radio frequency heating, they were able to raise ions to energies far greater than had previously been achieved.

The technique involves three ion species—hydrogen, deuterium and helium-3. Normally, only two species are used. By adding in a third, of which there were only trace amounts, researchers could focus in the energy on this species and heat it up to far higher energies.

Scientists now plan to build on this technique in the effort to achieve fusion energy.

In an email interview with *Newsweek*, John Wright, from the Massachusetts Institute of Technology (MIT), one of the study authors, spoke about the challenges he and other scientists are facing, and how they are working to overcome them.
People say nuclear fusion is always 30 years away—realistically will it be achieved within this time frame?
The answer to this question is always dependent on political and social will and funding to an extent. However, I am confident saying that the path to nuclear fusion has never been clearer. What is needed now is a next step experiment that enables us to test the robustness of the tokamak design to steady-state fusion plasmas.

The ITER device [which will be the world's largest fusion experiment] being constructed in the south of France by an international consortium is expect to begin operations late next decade. If it operates as expected, it will demonstrate net fusion power output in bursts of thousands of seconds.
During the period since ITER’s design, construction, and operation, technology and plasma physics have and will continue to progress. For example, recent developments in the field of high field high

temperature superconductors may permit the construction of tokamaks with higher magnetic fields and hence smaller and cheaper construction than ITER. Therefore, in concert with ITER construction and operations, other tokamaks should be built in parallel that focus on integrating new developments and capabilities to address other technical challenges outside of ITER's mission.

These experiments can easily happen within 30 years. With luck, and societal will, we will see the first electricity generating fusion power plants before another 30 years pass. As the plasma physicist Artsimovich said: "Fusion will be ready when society needs it."

What is the biggest difficulty in nuclear fusion?

Using the tokamak, the type of magnetic fusion confinement device discussed in the *Nature Physics* paper, we can already achieve the conditions needed for nuclear fusion. This configuration is well tested and its performance well understood and is the basis for most fusion programs around the world. While there are several technical challenges that must be addressed for economic fusion power, the biggest difficulty for the nuclear fusion program is the time it requires to address these one at a time. ITER is the first experiment to be built in over 30 years to address one of these issues—in this case the physics of a burning plasma in which its temperature is maintained by its own fusion reactions. The scale and cost of ITER is such that it requires a multinational consortium to build over a period of a couple decades.

A technical challenge that our paper tries to address using present day tokamaks such as Alcator C-Mod and JET is the understanding and control of the very energetic fusion product ions that must heat the core plasma as they make their way to the wall. Our work shows a method to efficiently raise the energy of a third species of ions to levels comparable to that of those produced by fusion in order to study their behavior in present day devices.

Why is temperature so important?

Fusion reactions take place at temperatures of 100s of millions of degrees Celsius. The products of a fusion reaction are at tens of billions of degrees Celsius. Temperature, therefore, plays two important roles in fusion.

Firstly, we must efficiently create and maintain a high temperature to enable the fusion reaction to take place. Our *Nature Physics* article focused on one method of doing this with microwaves launched from an antenna that heat the ions resonantly known as Ion Cyclotron Resonance Heating (ICRH). Through experiment and simulation, we established that a new method of using a third ion species at concentrations of less than one percent of the total plasma could be used to efficiently heat that species to very high energies and in turn heat the whole plasma. This method may have applications to more efficient heating of the plasma to the temperatures needed to begin the fusion burn.

The second important role of temperature is in the very high energy of the fusion products. Our heating technique is also capable of heating a small component of the plasma to temperatures comparable to that of the fusion products and so provides a way to study how the high energy fusion products interact with the plasma in experiments before burning fusion fuels are used. Like any fire, fusion burns hotter if the fire is bigger or better insulated, and our method addresses both of these aspects of fusion.

How does the latest study go towards helping reach these temperatures?

Our study uses two main ion species to control the level of efficiency at which a third species is heated. The result is a very efficient method to heat this third ion species to tens of billions of degrees to mimic fusion products or to heat the bulk plasma to 100s of millions of degrees to create the conditions to initiate a fusion burn.

What are the main differences between a tokamak and a stellarator?
A tokamak and a stellarator both have an overall toroidal (donut-like) shape. The tokamak is uniform in the toroidal direction (the long way around the donut). This symmetry improves its confinement—its efficiency and holding the plasma in its magnetic field—at the price of the need to produce a toroidal current needed to complete the confining magnetic field. Creating this current continuously is known as the steady state problem for tokamaks.

A stellarator has non-uniform shape and magnetic field in the toroidal direction that eliminates the need for toroidal current—hence is more robustly steady state than the tokamak. But this asymmetry reduces its confinement properties making fusion gain more difficult. It also is inherently more complex to construct. So the difference can be summarized as: stellarators give up the confinement benefits of axi-symmetry to solve the steady state challenge of tokamaks.

Which approach do you think is best for fusion?
While fusion research is focused on the tokamak with some efforts with the stellarator, there are many other approaches being pursued—some with private funds. This level of interest reflects the urgency felt to create new carbon free energy sources.

Of all these concepts, only the tokamak has demonstrated the properties necessary for fusion energy. With the completion and operation of ITER, the tokamak will be the device that first demonstrates a burning fusion plasma with net power gain. So in the near term, the tokamak provides the quickest path to fusion energy. But it is important to continue developing the stellarator and other concepts as secondary paths in the hopes they may eventually prove to be more efficient.

What is the next thing scientists will need to overcome?

Concepts other than the tokamak need to demonstrate the basic conditions for fusion: maintaining a hot enough core plasma to generate fusion reactions with a cool enough edge plasma to avoid damaging the wall materials. For tokamaks, the next thing scientists need to overcome are technical issues that affect the economics of a fusion reactor as a power plant.

The main obstacles are: 1) survivability of device components to minimize the need for replacement and refurbishment during, 2) efficient generation of the stabilizing toroidal current needed to complete the confining magnetic field, and 3) net production of Tritium fuel from Lithium in the reactor structures.

How could fusion help the planet?

Fusion can enable the transition to a carbon neutral power infrastructure. It produces no long lived radioactive waste and has a fuel that is plentiful and ubiquitous. Fusion can complement other carbon free energy technologies such as wind and solar by providing reliable base load power that can fit into the existing electrical grid infrastructure. After all, wind and solar derive their power from fusion in the Sun.

This article has been updated to include more information about the authors of the Nature Physics study.

7. Contact:
Laban Coblentz Laban.Coblentz@iter.org +33 6 14 16 40 85

https://www.iter.org/doc/www/content/com/Lists/list_items/Attachments/750/2017_11_IC-21.pdf

ST PAUL-LEZ-DURANCE, France (16 November 2017) – The outputs of new project performance metrics as well as the report of the 2017 Management Assessment were evaluated by the ITER Council in its most recent meeting. The Council confirmed that the ITER Project remains on track for success, despite the Project's extraordinary technical complexity. ITER Council Members jointly reaffirmed the importance of the mission and vision of the Project.
At its Twenty-First Meeting on 15 and 16 November 2017, the ITER Council reviewed a detailed set of reports and indicators covering both organizational and technical performance. Despite the extremely demanding construction and manufacturing schedule, and the challenging technical requirements of the ITER Tokamak and support systems, the ITER Project continues its strong performance, and remains on schedule for First Plasma 2025. The the ITER Agreement.

- Project milestones: Since 1 January 2016, all 26 scheduled Council-approved project milestones have been achieved, maintaining strict adherence to the overall project schedule and critical path. For each occasion in which specific milestones have shown a small amount of slippage, mitigation measures have been put in place to recover and maintain the First Plasma schedule, stimulating confidence in the increasing maturity of risk management practices.
- Measuring progress effectively: The Council was pleased by the ITER Organization's adoption of strengthened project performance metrics to measure physical progress in construction, manufacturing, assembly and installation. Specific percentages of completion are now in hand for each major building, system, and component under fabrication. Using this approach, the ITER Organization assessed total component manufacturing

through First Plasma to be 61% complete, and total construction work scope through First Plasma to be 49% complete, including ITER Organization assembly and installation activities.

- Management Assessment 2017: The ITER Council noted the recently received report of the Management Assessor for 2017, focused on the preparedness of the organization to deliver the project successfully.
- ITER Member support: The Council continued its candid discussions acknowledging continuing efforts made by each Member to overcome the value of the project, and its mission and vision, and resolved to work together to find timely solutions to ensure ITER's success.

The Council expressed its gratitude to outgoing Council Chair, Professor Won Namkung for his leadership and dedication, and congratulated Mr. Arunkumar Srivastava on his appointment to the Chairmanship for the following year.

8. The blob that ate the tokamak: Physicists gain understanding of how bubbles at the edge of plasmas can drain heat and reduce fusion reaction efficiency

By
Raphael Rosen
October 19, 2017
http://www.pppl.gov/news/2017/10/blob-ate-tokamak-physicists-gain-understanding-how-bubbles-edge-plasmas-can-drain-heat

To fuse hydrogen atoms into helium, doughnut-shaped devices called tokamaks must maintain the heat of the ultrahot plasma they control. But like boiling water, plasma has blobs, or bubbles, that percolate within the plasma edge, reducing the performance of the plasma by taking away heat that sustains the fusion reactions.

Now, scientists at the U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) have completed new simulations that could provide insight into how blobs at the plasma edge behave. The simulations, produced by a code called XGC1 developed by a national team based at PPPL, performed kinetic simulations of two different regions of the plasma edge simultaneously. This ability produces a more fundamental and fuller picture of how heat moves from plasma to the walls, potentially causing damage.

“In simulations, we often separate two areas at the plasma edge known as the pedestal and the scrape-off layer and focus on one or the other,” said PPPL physicist Michael Churchill, lead author of a paper describing the results in the journal *Plasma Physics and Controlled Fusion*. “XGC1 is unique because it is able to simulate both regions simultaneously, using kinetic ion and electron equations. In fact, it is important to include both regions in simulations because they affect each other.”

Simulations allow scientists to explore plasma, the fourth and hottest state of matter in which electrons are separated from atomic nuclei, without running physical experiments that could be costly. They also sometimes provide insights that physical experiments do not. Simulations of turbulence at the edge of the plasma, near where the plasma approaches a tokamak’s interior wall, are particularly important. The more that scientists understand such turbulence, the better able they will be to prevent moving blobs of plasma from forming in the plasma edge. If not controlled, these blobs could drain large amounts of heat from the confined plasma, and possibly either damage plasma-facing components or hinder the fusion reactions.

The XGC1 code simulated plasma in high-confinement mode, or H-mode, a set of conditions that helps plasma retain its heat. In H-mode, the results showed, a large number of blobs form between the pedestal and the scrape-off layer, two conditions near the edge, and move towards the outer edge, crossing the magnetic field lines as they go.

Blobs play an important role in the outward movement of particles in plasma. Blobs cause approximately 50 percent of the particle loss at the plasma edge, and researchers have observed blobs in a wide range of plasma devices, including tokamaks, figure-eight-shaped fusion devices known as stellarators, and linear machines. “The big picture is that blobs can pull energy and particles out of the plasma, and you don’t want that,” Churchill said. “You want to keep things confined.”

Scientists ran the simulation on America’s fastest supercomputer, called Titan, at the Oak Ridge Leadership Computing Facility, a DOE Office of Science User Facility in Oak Ridge, Tennessee. Much of the post-simulation analysis was performed at the National Energy Research Scientific Computing Center (NERSC), a DOE Office of Science User Facility at Lawrence Berkeley National Laboratory in Berkeley, California. Coauthors of the *Plasma Physics and Controlled Fusion* paper included PPPL physicists C.S. Chang, Seung-Hoe Ku, and Julien Dominski.

Future research will focus on how the blobs form and how their behavior is affected by the shape of the tokamak. Scientists must also fully determine how density, temperature, and electromagnetic force affect the behavior of the blobs.

PPPL, on Princeton University’s Forrestal Campus in Plainsboro, N.J., is devoted to creating new knowledge about the physics of plasmas — ultra-hot, charged gases — and to developing practical solutions for the creation of fusion energy. The Laboratory is managed by the University for the U.S. Department of Energy’s Office of Science, which is the largest single supporter of basic research in the physical sciences in the United States, and is working to address some of the most pressing challenges of our time. For more information, please visit science.energy.gov

9. **Plasma physics**

The Tao of Q

Laban Coblentz, Head of Communication

Both the mission and physics of ITER can be reduced to a single letter: Q. To understand the Q of ITER is to understand its most essential operating parameter as well as the *raison d'être* of the ITER Project.

https://www.iter.org/newsline/-/2845

What then is the meaning of Q?

Quantitatively, Q is the out-versus-in power amplification ratio of the fusion reaction: the ratio of the amount of thermal power produced by hydrogen fusion compared to the amount of thermal power injected to superheat the plasma and initiate the reaction. ITER is designed to produce plasmas having Q ≥ 10: meaning that injecting 50 megawatts of heating power into the plasma will produce a fusion output of at least 500 megawatts.

Qualitatively, the Q of ITER signifies the achievement of a "burning plasma"—a state of matter that has never been produced on Earth and that will usher in a new era of fusion research. In a burning plasma, the energy of the helium nuclei produced when hydrogen isotopes fuse (*see box below*) becomes large enough—because of the large number of reactions—to exceed the plasma heating that is injected from external sources. This is an essential condition for one day generating electricity from fusion power, and enabling scientists from 35 countries to study burning plasmas is the primary scientific motivation of the ITER Project.

Essentially, all other major aspects of tokamak plasma physics have been demonstrated and studied in smaller machines. In engineering terms, the construction of a tokamak capable of creating and sustaining a burning plasma for periods ranging from hundreds to thousands of seconds requires the development of "reactor-like" tokamak systems across virtually the entire range of fusion technologies. The study of burning plasmas in ITER is intended to demonstrate the feasibility of building commercial fusion power plants for electricity generation.

Plasma energy breakeven, or Q=1, has never been achieved in a fusion device: the **current record** is held by the European tokamak JET (UK), which succeeded in generating a Q of 0.67. ITER's Q value of ≥10 makes it a first-of-kind machine.
How did ITER's designers choose the specific Q value? Accounting for the size of ITER's vacuum vessel (830 cubic metres) and the strength of the confining magnetic field (5.3 Tesla), the ITER plasma can carry a current of up to 15 megaamperes. Under these conditions, an input thermal power of 50 megawatts is

needed to bring the hydrogen plasma in the vessel to about 150 million degrees Celsius. This temperature in turn translates to a high enough velocity, among a sufficient population of hydrogen nuclei, to induce fusion at a rate that will produce at least 500 megawatts of thermal power output.
During ITER's full deuterium-tritium fusion power operation, three heating systems will be employed: electron cyclotron resonance heating (ECRH), capable of injecting up to 20 megawatts; ion cyclotron radiofrequency heating (ICRF), with a similar 20 megawatt maximum heating capability; and the neutral beam (NB) heating system, capable of injecting a maximum of 33 megawatts into the plasma. Thus, 73 megawatts of plasma heating will be available to ITER operators, well above the 50 megawatts required.

Why stop at a Q of 10? Why not design ITER for a Q of 30, or 50? The answer is clear: expense. For tokamaks, size and magnetic field strength matter. In simple terms, increasing Q would require an increase in the major radius or in the magnetic field strength. Either approach would have increased the cost of the device unnecessarily, whereas the achievement of $Q \geq 10$ is sufficient to allow the primary scientific and technology goals of the project to be satisfied.

And a related question: Why not design ITER to produce electricity? This would also have required an increase in cost with no great benefit to the goals of the project. ITER is an experimental device designed to operate with a wide range of plasma conditions in order to develop a deeper understanding of the physics of burning plasmas, and to allow the exploration of optimum parameters for plasma operation in a power plant. The addition of the systems required to convert fusion power to high temperature steam to drive an electricity generator would not have been cost-effective, since the pattern of experimental operation of a tokamak such as ITER will allow for very limited generation of electricity.

Commercial fusion plants will be designed based on a power balance that accounts for the entire facility: the electricity output, sent to the industrial grid, compared to the electricity consumed by the facility itself—not only in tokamak heating, but also in secondary systems such as the electricity used to power the electromagnets, cool the cryogenics plant, and run diagnostics and control systems.

Not so with ITER. The ITER cryogenics plant and magnet conversion facilities are designed to operate efficiently, cooling the superconductor magnets to -269 °C and powering them to generate the necessary 15 megaamperes of plasma current. But the electricity consumed in these systems has no bearing on the thermal power balance of the plasma itself, and it is the burning (or largely self-heating) plasma that is of interest to ITER's scientists. With the physics of magnetically confined burning plasmas accessible for the first time in history, ITER's legacy will burn brightly in the fusion electricity plants of the years to come.

For ITER, it's all about the Q.

10. Measuring Material Changes During Shock Compression

https://lasers.llnl.gov/news/papers-presentations

Scientists have conducted the first in-situ diffraction experiments measuring deformation twinning at the lattice level during shock compression. The results were reported in a *Nature* paper published online on Oct. 25 by a team of researchers from LLNL and collaborators from the University of Oxford, Los Alamos National Laboratory, the University of York, and the SLAC National Accelerator Laboratory.

Shock compression is a challenging area of study, combining extreme conditions, such as high pressures and temperatures, with ultrafast time-scales. To simplify the problem, scientists often assume that solid materials behave like a fluid—flowing and changing their shape (plasticity) without resistance. Yet as a solid, most materials also retain a lattice structure. As a material flows, changing shape, the lattice somehow must change as well while still maintaining its regular lattice pattern. The study of plasticity at a most fundamental level then rests on understanding how the lattice changes while a material is deforming.

Dislocation-slip (where lattice dislocations are generated and move) and twinning (where sub-grains form with a mirror-image lattice) are the basic mechanisms of plastic deformation. Despite their fundamental importance to plasticity, diagnosing the active mechanism in situ (during the shock) has been elusive. Previous research has studied the material after the fact (in "recovery"), which introduces additional complicating factors and has led to conflicting results.

"In-situ diffraction experiments have been around for a few decades," said LLNL physicist Chris Wehrenberg, lead author on the paper, "but have gained prominence only recently as high-powered lasers and x-ray free electron lasers have made the measurements more widely available, more sensitive, and able to reach more extreme conditions. Our work highlights an untapped area of study, the distribution of signal within diffraction rings, which can yield important information."

The team's experiments were conducted at the new Matter in Extreme Conditions end station at SLAC's Linac Coherent Light Source, which represents the leading edge in a large, worldwide investment in facilities that can pair in-situ diffraction with high-pressure and high-strain rate techniques.

"In these experiments," Wehrenberg said, "you launch a shock wave with a laser, where a jet of laser-heated plasma creates an opposing pressure in your sample, and probe the state of your sample with an x-ray beam. The x rays will scatter off the sample at specific angles, forming diffraction rings, and the scattering angle provides information on the structure of the material."

Despite the growing popularity of in-situ diffraction experiments, most focus on the scattering angle and don't address the distribution of signal within a diffraction ring. While this approach may reveal when a material changes phases, it will not reveal how a material behaves outside of a phase transition.

Demonstrating Twinning and Slip

By analyzing the changes of signal distribution within the lines, the team was able to detect changes in the lattice orientation, or texture, and show whether a material was undergoing twinning or slip. In addition, the team could not only demonstrate whether the sample—tantalum, a high-density metal—twins or slips when shock compressed, but they also were able to demonstrate this for most of the entire range of shock pressures.

"LLNL is deeply engaged in material modeling as part of the science-based stockpile stewardship mission and has programmatic efforts to model tantalum at the molecular level, as well as plasticity modeling," Wehrenberg said. "These results are directly applicable to both of those efforts, providing data that the models can be directly compared to for benchmarking or validation. In the future, we plan to coordinate these experimental efforts with related experiments on LLNL's National Ignition Facility that study plasticity at even higher pressures."

While the techniques for analyzing x-ray diffraction data for changes to the texture and microstructure of a material have been practiced in quasi-static experiments, they are new to the field of shock experiments. This combination of techniques is relevant to many other fields.

For instance, planar deformation features in quartz caused by twinning and microfracture are a common indication of meteor impact sites, and these features also can affect the magnetization of other geological materials. Similarly, the twinning plays a crucial role in the self-sharpening behavior of ballistic penetrators and has been linked with increased ductility in high-performance ceramics for armor applications. Understanding high-rate plasticity is critical for hardening space hardware from hypervelocity dust impacts and even has implications for the formation of interstellar dust clouds.

For more information, see "Materials science: Atomistic views of deformation."

Joining Wehrenberg on the *Nature* paper were Amy Lazicki, Hye-Sook Park, Bruce Remington, Robert Rudd, Damian Swift, and Luis Zapeda-Ruiz from LLNL; David McGonegle, Marcin Sliwa, Matthew Suggit, and Justin Wark from the University of Oxford; Cindy Bolme from Los Alamos National Laboratory; Andrew Higginbotham from the University of York; and Bob Nagler, Hae Ja Lee, and Franz Tavella from SLAC.

11. Plasma Optic Combines NIF Lasers into 'Superbeam'

https://lasers.llnl.gov/news/papers-presentations

Since its introduction in the 1977 film "Star Wars," the Death Star has remained one of science fiction's most iconic figures. The image of Alderaan's destruction at the hands of the Death Star's superlaser is burned into the memory of millions of fans.

In the past, scientists and laser experts have maintained that this superbeam could never work due to the properties of lasers; theory says that rather than converging and combining their energy, the beams would just pass through one another.

That was true enough then. But now a team of LLNL researchers has added a plasma—a charged mixture of ions and free electrons—to the concept and successfully combined several separate NIF lasers into a "superbeam." Their work, recently published in *Nature Physics,* is a next step in the Laboratory's 50-year history of leadership in laser research and development.

While this superbeam isn't quite as super as the one depicted in science fiction, it stands as an important achievement—for the first time, nine of NIF's 192 laser beams were combined to produce a directed pulse of light with nearly four times the energy of any of the individual beams. Leveraging LLNL's expertise in optics research and development, the team used a Livermore-designed plasma optic to combine the beams and produce this first demonstration of its kind.

In certain experimental configurations, targets can be driven only by a single beam. Each beam has a limit on the amount of energy it can deliver. By combining multiple beams into one, LLNL's plasma beam combiner can break through that limit and push these experiments into new physics regimes. Beams with high energy and fluence are expected to advance a range of applications, including advanced x-ray sources and studies of physics at extreme intensities.

"In high-energy laser systems which use conventional solid optics, the maximum fluence (energy density) is limited by the damage of the (optics') material," said Robert Kirkwood, lead author on the paper and programmatic lead for the experimental campaign. "Because a plasma is inherently such a high energy density material, you don't destroy it. It can handle extremely high optical intensities."

"Beam combining has recently been done with solid-state lasers, but was limited by typical standard optics," added co-author Scott Wilks, one of the campaign's designers. "Because of this plasma optic, we can put a huge amount of energy into a very small space and time—serious energy, in a well-collimated (focused) beam."

Laser research and development is pushing into new regimes of power and energy, which are limited by conventional solid-state optics. Using a plasma optic, however, might appear counterintuitive.

"Plasma is generally bad for lasers—it is the bane of our existence," said co-author Brent Blue, program manager for NIF National Security Applications. "The team has turned that on its head and is intentionally harnessing plasmas for a benefit."

Plasma generally creates instabilities when combined with intense laser beams. By controlling an instability that causes the transfer of energy when beams cross, however, the researchers were able to combine the energy from multiple beams into a single powerful beam.

"We've known that plasma can deflect light and change the direction of energy flow, but it's been difficult to do it in a very precise way," Kirkwood said. "Here we've shown that we can control optical instabilities in plasma so that rather than randomly scattering energy, they put it where we want it and do so with good collimation and high intensity, producing a bright beam that can be delivered to another target. We can now control and predict what the plasma does, quite accurately."

The emerging beam has an energy of four kilojoules (over one nanosecond) that is more than triple that of any incident (pumping) beam, and a fluence that is more than double. Because the optic produced is plasma and is diffractive, it is inherently capable of generating higher fluences in a single beam than solid-state refractive or reflective optics.

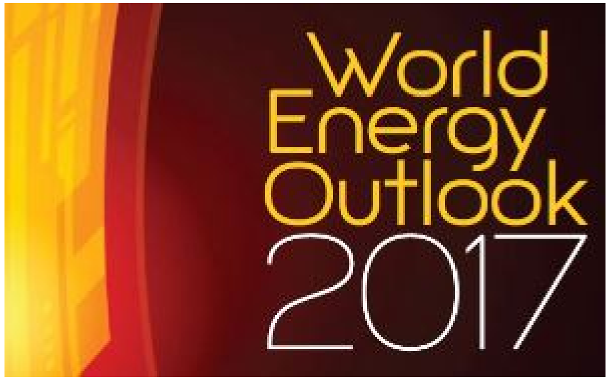
Transitioning to a new optic material with a much higher damage threshold than anything used before opens the door to higher laser intensities and energies. Looking forward, the team plans to scale up the experiment with the hope of combining up to 20 beams into one.

The campaign initially was funded by the Laboratory Directed Research and Development Program. Along with Kirkwood, Wilks and Blue, co-authors of the *Nature Physics* paper were LLNL's Thomas Chapman, Mordecai Rosen, Richard London, Louisa Pickworth, William Dunlop, John Moody, David Strozzi, Pierre Michel, Laurent Divol, Nino Landen, Brian MacGowan, Bruno Van Wonterghem, and Kevin Fournier; and David Turnbull of LLNL and the Laboratory for Laser Energetics at the University of Rochester.

12. Press Statements

Issued by the World Nuclear Association

http://www.world-nuclear.org/press.aspx



IEA: Nuclear generation to double to meet sustainable development goals (14 November 2017)

The World Energy Outlook 2017 report, published today by the International Energy Agency, foresees a substantially expanded role for nuclear energy if the world is to meet the challenges of people's development needs, while reducing greenhouse gas emissions to avoid dangerous levels of climate change.

13. Germany to miss 2020 carbon dioxide emissions target because of nuclear closure policy

Briefing Issued: 10 November 2017

http://www.world-nuclear.org/press/briefings/germany-to-miss-emissions-target-because-of-nuclea.aspx

If Germany had prioritized closing coal plants instead of nuclear plants it would have avoided the emission of 80 $MtCO_2$ by 2020, more than enough to make up the deficit needed to achieve Germany's emissions target. (3)

The 80 $MtCO_2$ emissions avoidance would be delivered if the nuclear plants were operating in a baseload, rather than load following, mode. Over the last seven years the increasing share of intermittent renewable generation has required coal, and on rare occasions those nuclear reactors still operating to curtail their generation. So would nuclear plant have been able to operate at close to full output to deliver the full emissions saving required? Analysis data from Fraunhofer ISE (6) shows that, for the twelve month period to the end of September 2017 this would be the case. Crucially, the output from coal was almost always higher than the output that would have been produced from the closed nuclear generation, so the closed nuclear plant could have operated at close to full capacity in place of coal.

Since 2010, Germany has increased its renewables capacity from 47.4 GW to 106.1 GW in 2016. Its fossil fuel capacity has also increased from 79.4 GW to 83.0 GW. The capacity of coal-fired generation as part of that fossil fuel total remains high, almost unchanged from 49.7 GW in 2010 to 49.2 GW in 2016. (4)

The additional output from renewables since 2010 has barely compensated for the loss of nuclear generation and growth in electricity output. Coal generation remained virtually unchanged, with lignite and hard coal producing 262.9 TWh in 2010 and 261.5 TWh in 2016. Nuclear generation fell from 140.6 TWh to 84.6 TWh, all renewables increased by 84.0 TWh and total electricity output increased by 15.9TWh. (5)

The impact of nuclear closures will worsen soon after 2020. A further 8GW of nuclear capacity is due to close in 2021 and 2022. Such a rapid loss of baseload capacity is unlikely to be compensated for by renewable generation, leading to further reliance on fossil fuel, particularly coal-fired generation.

Earlier this week the German government annouced a series of measures intended to reduce emissions by a further 78 million tonnes of CO_2 in an effort to meet their 2020 target. These included a reduction in emissions from coal plants of only 22 million tonnes of CO_2. Industry groups say these measures will harm jobs and the economy and Greens describe them as "a hodge podge of nothingness". (7) Even if the new measures are effective the existing programme of closing nuclear plants instead of coal plants will have resulted in the emission of half a billion tonnes of CO_2 by 2020.

The global nuclear industry has proposed the Harmony goal, advocating the decarbonisation of the world's electricity generation mix by 2050. It is proposed that nuclear generation supply 25% of all electricity demand in 2050, with the remainder coming from other low carbon generation.

Contact

Jonathan Cobb: +44(0)20 7451 1536
press@world-nuclear.org

14. Exascale Computing to help accelerate drive for clean fusion energy

by John Bashor, Lawrence Berkeley National laboratory Computing Sciences

https://www.hpcwire.com/2017/10/02/exascale-computing-help-accelerate-drive-clean-fusion-energy/

October 2, 2017

Editor's note: One of the U.S. Exascale Computing Project's mandates is to explain how exascale computing power will enhance scientific discovery and society broadly. This article from ECP not only examines the need for exascale computing power to advance research on fusion reactor design but it also highlights the potential for collaboration with industry partners who will require this kind of power.

For decades, scientists have struggled to create a clean, unlimited energy source here on Earth by recreating the conditions that drive our sun. Called a fusion reactor, the mechanism would use powerful magnetic fields to confine and compress gases four times as hot as our sun. By using the magnetic fields to squeeze the gases, the atoms would fuse and release more energy than was used to power the reactor. But to date, that has only worked in theory.

Achieving fusion energy production would benefit society by providing a power source that is non-polluting, renewable and using fuels such as the hydrogen isotopes found in seawater and boron isotopes found in minerals.

Early fusion research projects in the 1950s and '60s relied on building expensive magnetic devices, testing them and then building new ones and repeating the cycle. In the mid-1970s, fusion scientists began using powerful computers to simulate how the hot gases, called plasmas, would be heated, squeezed and fused to produce energy. It's an extremely complex and difficult problem, one that some fusion researchers have likened to holding gelatin together with rubber bands.

Using supercomputers to model and simulate plasma behavior, scientists have made great strides toward building a working reactor. The next generation of supercomputers on the horizon, known as exascale systems, will bring the promise of fusion energy closer.

The best-known fusion reactor design is called a tokamak, in which a donut-shaped chamber is used to contain the hot gases, inside. Because the reactors are so expensive, only small-scale ones have been built. ITER, an international effort to build the largest-ever tokamak-in the south of France. The project, conceived in 1985, is now scheduled to have its first plasma experiments

in 2025 and begin fusion experiments in 2035. The estimated cost is 14 billion euros, with the European Union and six other nations footing the bill.
Historically, fusion research around the world has been funded by governments due to the high cost and long-range nature of the work.

But in the Orange County foothills of Southern California, a private company is also pursuing fusion energy, but taking a far different path than that of ITER and other tokamaks. Tri Alpha Energy's cylindrical reactor design is completely different in its design philosophy, geometry, fuels and method of heating the plasma, all built with a different funding model. Chief Science Officer Toshiki Tajima says their approach makes them mavericks in the fusion community.

But the one thing both ITER and similar projects and Tri Alpha Energy have consistently relied on is using high-performance computers to simulate conditions inside the reactor as they seek to overcome the challenges inherent in designing, building and operating a machine that will replicate the processes of the sun here on Earth.
As each generation of supercomputers has come online, fusion scientists have been able to study plasma conditions in greater detail, helping them understand how the plasma will behave, how it may lose energy and disrupt the reactions, and what can be done to create and maintain fusion. With exascale supercomputers that are 50 times more powerful than today's top systems looming on the horizon, Tri Alpha Energy sees great possibilities in accelerating the development of their reactor design. Tajima is one of 18 members of the industry advisory council for the U.S. Department of Energy's (DOE) Exascale Computing Project (ECP).
"We're very excited by the promise of exascale computing – we are currently fund-raising for our next-generation machine, but we can build a simulated reactor using a very powerful computer, and for this we would certainly need exascale," Tajima said. "This would help us accurately predict if our idea would work, and if it works as predicted, our investors would be encouraged to support construction of the real thing."

The Tri Alpha Energy fusion model builds on the experience and expertise of Tajima and his longtime mentor, the late Norman Rostoker, a professor of physics at the University of California, Irvine (UCI). Tajima first met Rostoker as a graduate student, leaving Japan to study at Irvine in 1973. In addition to his work with TAE, Tajima holds the Norman Rostoker Chair in Applied Physics at UCI. In 1998, Rostoker co-founded TAE, which Tajima joined in 2011.

In it for the long run

It was also in the mid-1970s, that the U.S. Atomic Energy Commission, the forerunner of DOE, created a computing center to support magnetic fusion energy research, first with a cast-off computer from classified defense programs, but then with a series of ever-more capable supercomputers. From the outset, Tajima was an active user, and still remembers he was User No. 1100 at the Magnetic Fusion Energy Computer Center. The Control Data Corp. and Cray supercomputers were a big leap ahead of the IBM 360 he had been using.

“The behavior of plasma could not easily be predicted with computation back then and it was very hard to make any progress,” Tajima said. “I was one of the very early birds to foul up the machines. When the Cray-1 arrived, it was marvelous and I fell in love with it.”

At the time, the tokamak was seen as the hot design and most people in the field gravitated in this direction, Tajima said, and he followed. But after learning about plasma-driven accelerators under Professor Rostoker, in 1976 he went to UCLA to work with Prof. John Dawson. “He and I shared a vision of new accelerators and we began using large-scale computation in 1975, an area in which I wanted to learn more from him,” Tajima said.

As a result, the two men wrote a paper entitled “Laser Electron Accelerator,” which appeared in Physical Review Letters in 1979. The seminal paper explained how firing an intense electromagnetic pulse (or beam of particles) into a plasma can create a wake in the plasma and that electrons, and perhaps ions, trapped in this wake can be accelerated to very high energies.

TAE’s philosophy, built on Rostoker’s ideas, is to combine both accelerator and fusion plasma research. In a tokamak, the deuterium-tritium fuel needs to be heated and confined at an energy level of 10,000 eV (electron volts) for fusion to occur. The TAE reactor, however, needs to be 30 times hotter. In a tokamak, the same magnetic fields that confine the plasma also heat it to 3 billion degrees C. In the TAE machine, the energy will be injected using a particle accelerator. “A 100,000 eV beam is nothing for an accelerator,” Tajima said, pointing to the 1G eV BELLA device at DOE’s Lawrence Berkeley National Laboratory. “Using a beam-driven plasma is relatively easy but it may be counterintuitive that you can get higher energy with more stability — the more energetic the wake is, the more stable it becomes.”

But this approach is not without risk. With the tokamak, the magnetic fields protect the plasma, much like the exoskeleton of a beetle protects the insect’s innards, Tajima said. But the accelerator beam creates a kind of spine, which creates the plasma by its weak magnetic fields, a condition known as Reverse Field Configuration. One of Rostoker’s concerns was that the plasma would be too vulnerable to other forces in the early stages of its formation. However, in the 40-centimeter diameter cylindrical reactor, the beam forms a ring like a bicycle tire, and like a bicycle, the stability increases the faster the wheels spin.

“The stronger the beam is, the more stable the plasma becomes,” Tajima said. “This was the riskiest problem for us to solve, but in early 2000 we showed the plasma could survive and this reassured our investors. We call this approach of tackling the hardest problem first ‘fail fast’.”

Another advantage of TAE’s approach is that the main fuel, Boron-11, does not produce neutrons as a by-product; instead it produces three alpha particles, which is the basis of the company’s name. A tokamak, using hydrogen-isotope fuels, generates neutrons, which can penetrate and damage materials, including the superconducting magnets that confine the tokamak plasma. To prevent this, the tokamak reactor requires one-meter-thick shielding. Without the need to contain neutrons, the TAE reactor does not need heavy shielding. This also helps reduce construction costs.

Computation Critical to Future Progress

With his 40 years of experience using HPC to advance fusion energy, Tajima offers a long-term perspective, from the past decades to exascale systems in the early 2020s. As a principal investigator on the Numerical Tokamak project in the early 1990s, he has helped build much of the HPC ecosystem for fusion research.

At the early stage of modeling fusion behavior, the codes focus on the global plasma at very fast time scales. These codes, known as MHD codes (magnetohydrodynamics), are not as computationally “expensive,” meaning they do not require as many computing resources, and at TAE were run on in-house clusters.

The next step is to model the more minute part of the plasma instability, known as kinetic instability, which requires more sophisticated codes that can simulate the plasma in greater detail over longer time scales. Achieving this requires more sophisticated systems. Around 2008-09, TAE stabilized this stage of the problem using its own computing system and by working with university collaborators who have access to federally funded supercomputing centers, such as those supported by DOE. “Our computing became more demanding during this time,” Tajima said.

The third step, which TAE is now tackling, is to make a plasma that can “live” longer, which is known as the transport issue in the fusion community. “This is a very, very difficult problem and consumes large amounts of computing resources as it encompasses a different element of the plasma,” Tajima said, “and the plasma becomes much more complex.”

The problem involves three distinct functions:

- The core of the field reverse configuration, which is where the plasma is at the highest temperature
- The “scrape-off layer,” which is the protective outer layer of ash on the core and which Tajima likens to an onion’s skin

- The “ash cans,” or diverters, that are at each end of the reactor. They remove the ash, or impurities, from the scrape-off layer, which can make the plasma muddy and cause it to behave improperly.

“The problem is that the three elements behave very, very differently in both the plasma physics as well as in other properties,” Tajima said. “For example, the diverters are facing the metallic walls so you have to understand the interaction of the cold plate metals and the out-rushing impurities. And those dynamics are totally different than the core which is very high temperature and very high energy and spinning around like a bicycle tire, and the scrape-off layer.”

These factors are all coupled to each other using very complex geometries and in order to see if the TAE approach is feasible, researchers need to simulate the entirety of the reactor in order to understand and eventually control the reactions.

“We will run a three-layered simulation of our fusion reactor on the computer, with the huge particle code, the transport code and the neural net on the simulation – that’s our vision and we will certainly need an exascale machine to do this,” Tajima said. “This will allow us to predict if our concept works or not in advance of building machine so that our investors’ funds are not wasted.”

The overall code will have three components. At the basic level will be a representative simulation of particles in each part of the plasma. The second layer will be the more abstract transport code, which tracks heat moving in and out of the plasma. But even on exascale systems, the transport code will not be able to run fast enough to keep up with real-time changes in the plasma. Instabilities which affect the heat transport in the plasma come and go in milliseconds.

“So, we need a third layer that will be an artificial neural net, which will be able to react in microseconds, which is a bit similar to a driverless auto, and will ‘learn’ how to control the bicycle tire-shaped plasma, Tajima said. This application will be run on top of transport code and it will observe experimental data and react appropriately to keep the simulation running.

“Doing this will certainly require exascale computing,” Tajima said. “Without it we will take up to 30 years to finish – and our investors cannot wait that long. This project has been independent of the government funding, so that our investors’ fund provided an independent, totally different path toward fusion. This could amount to a means of national security to provide an alternative solution to a problem as large as fusion energy. Society will also benefit from a clean source of energy and our exascale-driven reactor march will be a very good thing for the nation and the world.”

Advanced Accelerators are Pivotal

Both particle accelerators and fusion energy are technologies important to the nation’s scientific leadership, with research funded over many decades by the Department of Energy and its predecessor agencies.

Not only are particle accelerators a vital part of the DOE-supported infrastructure of discovery science and university research, they also have private-sector applications and a broad range of benefits to industry, security, energy, the environment and medicine.

Since Toshiki Tajima and John Dawson published their paper “Laser Electron Accelerator” in 1979, the idea of building smaller accelerators, with the length measure in meters instead of kilometers, has gained traction. In these new accelerators, particles “surf” in the plasma wake of injected particles, reaching very high energy levels in very short distances.

According to Jean-Luc Vay, a researcher at DOE’s Lawrence Berkeley National Laboratory, taking full advantage of accelerators’ societal benefits, game-changing improvements in the size and cost of accelerators are needed. Plasma-based particle accelerators stand apart in their potential for these improvements, according to Vay, and turning this from a promising technology into a mainstream scientific tool depends critically on high-performance, high-fidelity modeling of complex processes that develop over a wide range of space and time scales.

To help achieve this goal, Vay is leading a project called “Exascale Modeling of Advanced Particle Accelerators” as part of DOE’s Exascale Computing Project. This project supports the practical economic design of smaller, less-expensive plasma-based accelerators.
As Tri Alpha Energy pursues its goal of using a particle accelerator (though this accelerator is not related to wakefield accelerators) to achieve fusion energy, the company is also planning to apply its experience and expertise in accelerator research for medical applications. Not only will this effort produce returns for the company’s investors, but it should also help advance TAE’s understanding of accelerators and using them to create a fusion reactor.

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overall project cost was approved ad referendum, meaning that it will now fall to each Member to seek approval of project costs through their respective governmental budget processes."

8. Wendelstein 7-X: Second round of experimentation started

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https://phys.org/news/2017-09-wendelstein-x-experimentation.html

The plasma experiments in the Wendelstein 7-X fusion device at Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany, have been resumed after a 15-month conversion break. The extension has made the device fit for higher heating power and longer pulses. This now allows the optimised concept of Wendelstein 7-X to be tested. Wendelstein 7-X, the world's largest fusion device of the stellarator type, is to investigate its suitability for a power plant.

Besides new heating and measuring facilities, over 8,000 graphite wall tiles and ten divertor modules have been installed in the plasma vessel since March last year, i.e. the scheduled end of the first experimentation phase. This cladding is to protect the vessel walls and allow higher temperatures and plasma discharges lasting 10 seconds in forthcoming experiments.

A special function is exercised here by the ten sections of the divertor: As broad strips on the wall of the plasma vessel, the divertor tiles conform exactly to the twisting contour of the plasma edge. They thus protect especially those wall areas to which particles escaping from the edge of the plasma ring are specifically directed. Along with unwanted impurities the impinging particles are neutralised and pumped off. The divertor is thus an important tool for regulating the purity and density of the plasma.

The smaller predecessor, the Wendelstein 7-AS stellarator at IPP in Garching, had already yielded encouraging results in divertor tests. But not till the much larger successor, Wendelstein 7-X at Greifswald, did the geometry conditions come up to power plant size, particularly the ratio of the divertor area to the plasma volume. "We are therefore very excited that we are now able for the first time to investigate whether the divertor concept of an optimised stellarator can really work properly", says Project Head Professor Thomas Klinger. These tests will play a major role: Many detailed investigations will carefully check how to guide the plasma and what magnetic field structures and heating and replenishing methods are most successful.

Newly enlisted measuring instruments will also allow observation of turbulence in the plasma for the first time: The small eddies entailed influence how successful magnetic confinement and thermal insulation of the hot plasma are, these being important parameters for a future power plant, because they determine the size of the plant and hence its economical merit. "We shall be able for the first time to check whether the promising predictions of theory for a completely optimised stellarator are correct. In comparison with previous devices, Wendelstein 7-X is expected to yield quite new, possibly even better, conditions", says Thomas Klinger.

As all ten microwave transmitters for the microwave heating of the plasma are meanwhile ready for use, this will allow a higher energy throughput and plasmas of higher density. It will now be possible to raise the energy to 80 megajoules once all versions of the microwave heating have been tackled and tested, as compared with 4 megajoules in 2016. The rather low plasma density hitherto can now be more than doubled to attain values meeting power plant requirements.

This has significant consequences: First the density of the plasma has to be sufficient to allow electrons and ions to exchange energy effectively. Previously, the microwave heating had only been able to heat essentially just the electrons. Instead of hot electrons with 100 million degrees and cold ions with 10 million degrees as hitherto the electrons and ions in the new plasma will have almost equal temperatures of up to 70 million degrees. This should also enhance the thermal insulation of the plasma. Whereas it was hitherto just upper average in relation to the size of the device, the effect of optimising Wendelstein 7-X should now become visible: "It's getting very exciting", states Thomas Klinger.

Background

The objective of fusion research is to develop a power plant favourable to the climate and environment. Like the sun, it is to derive energy from fusion of atomic nuclei. As the fusion fire does not ignite till temperatures exceeding 100 million degrees are attained, the fuel, viz. a low-density hydrogen plasma, ought not to come into contact with cold vessel walls. Confined by magnetic fields, it levitates inside a vacuum chamber with hardly any contact.

The magnetic cage of Wendelstein 7-X is formed by a ring of 50 superconducting magnet coils about 3.5 metres high. Their special shapes are the result of sophisticated optimisation calculations. Although Wendelstein 7-X is not meant to produce energy, the device should prove that stellarators are suitable for power plants. For the first time the quality of the plasma confinement in a stellarator is to attain the level of competing devices of the tokamak type.

For this purpose, further stages of modification are being planned. For example, the graphite tiles of the divertor are to be replaced in a few years by carbon-fibre-reinforced carbon elements that are additionally water-cooled. This will allow discharges lasting up to 30 minutes in which it can be tested whether Wendelstein 7-X will achieve its optimisation targets in the long run: In this way the device is to demonstrate the essential advantage of stellarators, viz. their capability for continuous operation.

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