Andlinger Center Speaks: fusion’s hot moment

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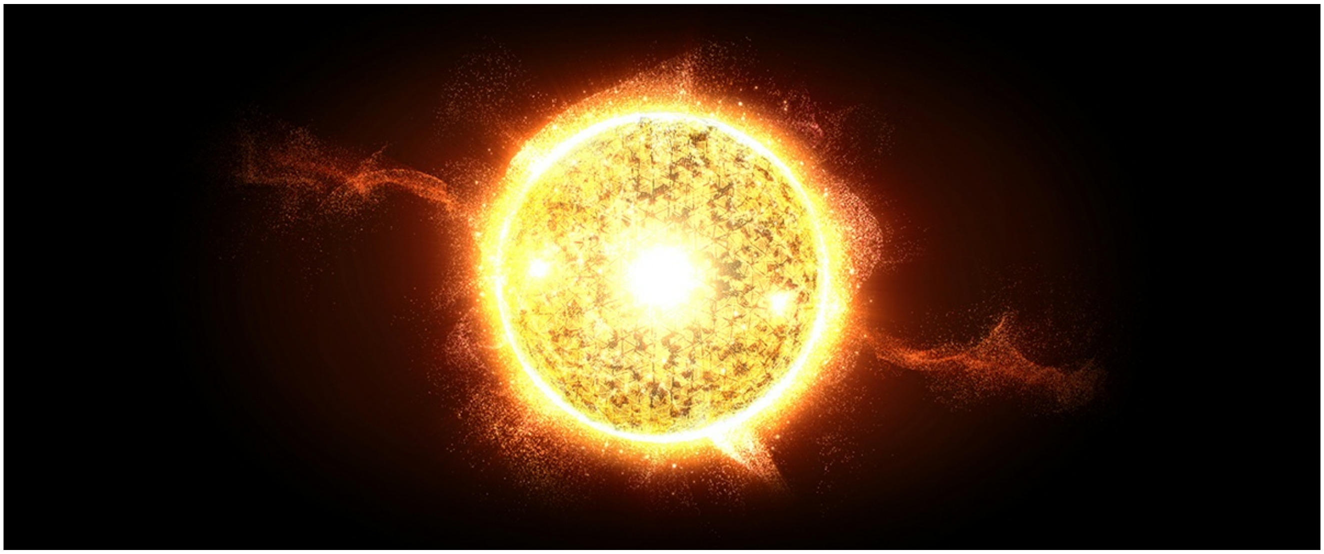

By Molly A. Seltzer

Harnessing fusion energy, the reaction that powers the sun, is a herculean scientific and engineering task. Fusion research has recently gained new attention with big investments from energy agencies and private investors, such as Bill Gates and Jeff Bezos, who are funding fusion startups. As of January 2020, the world entered the decade in which the International Thermonuclear Experimental Reactor (ITER), a 35-country collaboration to build a 500-MW fusion plant in southern France, is scheduled for testing. It is slated to be the first fusion experiment to produce more energy than it consumes. In this Andlinger Center Speaks, experts discuss the new momentum in fusion research, the development of a private fusion industry, and the path to commercial reactors.

Steven Cowley is the director of the Princeton Plasma Physics Laboratory (PPPL) and professor of astrophysical sciences. Cowley is a fusion theorist and previously served as chief executive of the United Kingdom Atomic Energy Authority and director of the Culham Centre for Fusion Research. Egemen Kolemen is an assistant professor of mechanical and aerospace engineering and the Andlinger Center for Energy and the Environment, and a physicist at PPPL. Kolemen specializes in plasma control systems and tokamaks, and has worked on reactors in China, Korea, France, and the United States. He has been affiliated with PPPL since 2008.

How would you describe the state of research and technology for fusion power?

Cowley and Kolemen

Kolemen: There is a lot of excitement in fusion these days. Consistent progress in the last few decades has brought the possibility of fusion power reactors within striking distance. With a better understanding of the dangers of global warming in recent years, there is an increased thrust in the search for non-fossil-based energy sources. The angel investment and startup culture has penetrated the energy sector and has led to many fusion energy startups. There are so many startups that in 2018 they formed a lobby group, the Fusion Industry Association. The U.S. Department of Energy and governments around the world responded to these developments and started programs to enhance public-private collaboration, which is focused not only on the science of fusion, but on paving the way to reach commercial fusion reactors as soon as possible.

Cowley: There has been a real resurgence of momentum in the last two years, probably as people have started to see ways to bring down the cost of fusion. We know how to do fusion, but we do not know how to do fusion at a cost that the consumer wants to pay for electricity. The challenge is finding ways to make it simpler and cheaper. How do you go about that? Part of it is applying new technologies. There has been work on using high temperature superconductors, permanent magnet systems, and artificial intelligence to help fusion systems work better. Experimenting with new technologies and processes is important because we know that, theoretically, we ought to be able to do fusion in a lot smaller and simpler devices than the ones we make today. There is a need for research to focus on experimental technologies to drive innovation in the field.

How is fusion power different from current nuclear power generation and what are its benefits?

Kolemen: Currently deployed nuclear reactors use fission, which splits very heavy atoms, like uranium to release energy. Fusion, in contrast, fuses light atoms, like hydrogen isotopes, to produce helium and a neutron, which has a lot of energy. This is not a chain reaction like fission, which eliminates the possibility of runaway accidents faced by fission reactors. In fusion, if the system fails due to natural forces, the reaction instantly stops. Fusion, unlike fission, does not produce plutonium, whose radiation makes areas uninhabitable in the case of an accident. If more nuclear fission plants were established to meet global energy demand, it would mean transporting and storing megatons of nuclear waste, and there is a lot of pushback in communities about accepting the waste. This is not the case with fusion. Also, the uranium used as fuel for nuclear fission is a precursor to material used in atomic bombs, which also creates some fear and risk in terms of securing supply chains.

Cowley: In terms of benefits, fusion is one of the very few truly sustainable energy sources, along with renewable resources, like solar and wind. It has the advantage over many technologies, even over renewables, because fusion reactors can be switched on and off, and the fuel (hydrogen isotopes, typically tritium and deuterium) is abundant. One of the advantages of fusion is that it is safe and can be sited next to population centers. It is important to be able to locate fusion plants next to megacities to minimize the amount of energy that needs to be transmitted down the grid, and to minimize the size of the transmission and distribution infrastructure that needs to be built.

PPPL is involved in designing, building, and assembling parts of ITER, and you have traveled to the site to support the project. What is the fusion community looking to accomplish with ITER, and what are the challenges of the experiment?

Teams have been active all summer at the very bottom of the Tokamak pit, in preparation for the installation of the cryostat base. On top of the concrete crown, at the point of intersection with each of its 18 radial walls, contractors are installing a set of 18 metal bearings. July 2019. (ITER)

Kolemen: The biggest challenge is that we have not produced net energy, a reaction that produces more energy than is needed to create the reaction. We have almost produced net energy. Making ITER work is the number one priority for us – it is the most expensive science experiment that humanity has ever tried, on the order of $20 billion.

Cowley: One thing to note is that we have done fusion before. We made the extraordinary conditions necessary at the core of the experiment, 200 or 300 million degrees Fahrenheit, and sustained the condition. In the 1990s, we made 10 megawatts of fusion power at Princeton in a device called the Tokamak Fusion Test Reactor (TFTR), but we needed to add outside energy to keep heating the plasma to make that happen. What ITER is going to do is achieve what we call a fusion burn, where the fusion is sustaining itself. We have never gotten to that state, and it will be a historic experiment. It is fundamentally exactly what a star, like our sun, is doing. Using a camp fire analogy, the TFTR experiment was similar to using a wet log to fuel a fire. You still get some heat from the wood, but it is not self-sustained. ITER is like a fire with nice dry wood where you light it take the match away, and it continues to burn. The heat that the fire makes allows you to put another log on the fire, and another log after that, and keep burning wood.

How might fusion play a role in global decarbonization?

Cowley: We have an opportunity to decarbonize our energy systems by using what I would call transitional technologies. We could decarbonize with a combination of renewables, capturing and storing the carbon associated with burning fossil fuels, and conventional nuclear power. The combination of those will allow you to decarbonize in a couple of decades, maybe three decades. But, at least two of those technologies, fission and carbon capture and storage, cannot be done forever. There is only a certain amount of carbon capture and storage you can do geologically, and there's only a certain amount of fission you can do without going to advanced nuclear cycles, which nobody wants to do because of proliferation risks. At some point fusion will be needed. There will be many energy options, but we will need a system like the one that fusion can provide, a system that will work when the sun does not shine and the wind does not blow. It will need to work for weeks on end and provide the base load of our energy system. We are going to need that, and we are going to need it in this century.

We should not wait for fusion to decarbonize our energy systems, and we should use all the transitional elements that we can. That's going to be hard enough in and of itself, but the long-term goal is to develop a system that is sustainable over millions of years. The interesting thing about fusion is that it is not a limited resource. There is enough fuel really to power the planet for its entire existence. The trick here is to know how to do it on a commercial scale, and once we have that knowledge, we will always have it. It's a bit like flying. Humans tried to fly all of recorded history. We had Greeks jumping off cliffs. It wasn't until the beginning of the 20th century that really it was mastered, but after it was mastered it expanded everywhere. Everybody started to fly.

Kolemen: If we learned anything in the last two decades in the energy sector, it is that predicting our energy future is very difficult. Solar power, which was not thought of as a viable option, dramatically came down in price. So, the most reasonable approach to decarbonization is an "all the above" strategy, where all possible options are funded unless the option is shown to be unfeasible. Fusion reactors are not currently ready to solve the climate emergency in the next decade. However, with focused research and investment, we can make an impact on fossil-fuel replacement by the end of the century.

How can society drive innovation and the deployment of fusion?

Kolemen: While building ITER and making it work, we must visit alternatives, such as producing smaller test reactors where we can try new ideas. Also, bringing in the industry and contracting companies to build the components we need is another priority. Historically, the fusion community has focused on the science of fusion. But how you build an industry to make all the components is a big challenge. You cannot build hundreds of companies to produce the parts for the reactors overnight; it takes decades. The engineering side is critical because we need to develop new materials to withstand high heat fluxes and neutron environments, systems for heat removal and plasma confinement, and ones that can perform not just for days but for years. These three pieces – making ITER successful, exploring alternative ways to do fusion, and bringing in industry – will help make the timeframe for commercial fusion reactors viable.

Cowley: The thing that drives down the cost over time is how many reactors you make. If you make lots of something, even if it is a really impressive, complex technology, like a modern car, you can really drive the cost down. It's amazing how cheap cars are for the amount of technology that is in them, but car manufacturers make thousands of a model, and they drive down the costs by incremental innovation until they have something really good. Part of the problem with the nuclear industry is that only a few reactors are built per year, and so the industry never gets those costs savings due to iterative learning.

I also worry that we don't always seek the innovation that we need. We know ways to make fusion happen, and sometimes the risk-reward profile in research makes you stay stick with what you know. If your true answer lies a long way from where you have been looking, you may not reach it. But the students right now at the laboratory and on campus will lead us down pathways unexplored by my generation. We are trying to work with the various new private fusion companies to help foster and grow those new ideas. We are a big, government lab with lots of expertise that can help some of these startup companies develop new processes and measure their performance, and ultimately support and spur innovation.

More resources:
Andlinger Center's Energy Technology Distillate: Fusion Energy via Magnetic Confinement
Faculty spotlight on Egemen Kolemen
Story on Kolemen's data-driven research
10 facts about fusion via magnetic confinement
PPPL's Science on Saturday lecture series

Fusion in the news:
Joint DOE program for public-private partnership
Public-private INFUSE projects to speed fusion development housed at PPPL
This U.K. startup is trying to change how we get energy
The new nuclear: How a $600 million fusion energy unicorn plans to beat solar)
The dream of clean energy at a very high price