Twisted Fusion: The Stellarator

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1. Introduction

Although I've written several posts on nuclear fission reactors, and even more that mentions them, I have only written a single posts on nuclear fusion reactors. This is described and linked below.

Distant Nuclear Fusion: *There are currently two experiments that are designed to reach "break-even" fusion within the next several years, but this means that the experiment will inject as much energy into the inner, or core process as comes out in the form of high energy neutrons. Forget any energy-conversion efficiencies outside of the core – no electric energy will come out of these initial facilities in spite of huge amounts going in.*

One of these two projects, the International Thermonuclear Experimental Reactor (ITER) is in Saint-Paul-lez-Durance, France. The other, the National Ignition Facility (NIF) is here in my home town of Livermore, California.

This post is a brief review of the former and a more thorough review of the latter, including its distant past and distant future.

https://energycentral.com/c/cp/distant-nuclear-fusion

In addition to the two designs described in the above previous post, there is a third much older design, the stellarator. Lately this pioneering design has received much more attention. It was abandoned many decades ago, primarily because the mathematics that describe the physics were just too complex to analyze using then-existing methods, and scientists moved on to a greatly simplified reactor, the tokamak. This is what the ITER Project mentioned above is.

However, recently more attention has been focused on the stellarator, and there is a major experiment in Germany that may prove to be the most viable path to a commercial nuclear fusion reactor.

This post is about the past, present and possible future of the stellarator.

2. The Past

A stellarator is a plasma device that relies primarily on external magnets to confine a plasma. Scientists researching magnetic confinement fusion aim to use stellarator devices as a vessel for nuclear fusion reactions. The name refers to the possibility of harnessing the power source of the stars, such as the Sun. It is one of the earliest fusion power devices...[1]

The stellarator was invented by American scientist Lyman Spitzer of Princeton University in 1951, and much of its early development was carried out by his team at what became the Princeton Plasma Physics Laboratory (PPPL). Lyman's Model A began operation in

[1] Wikipedia Article on the stellarator, https://en.wikipedia.org/wiki/Stellarator

1953 and demonstrated plasma confinement. Larger models followed, but these demonstrated poor performance, losing plasma at rates far worse than theoretical predictions. By the early 1960s, any hope of quickly producing a commercial machine faded, and attention turned to studying the fundamental theory of high-energy plasmas. By the mid-1960s, Spitzer was convinced that the stellarator was matching the Bohm diffusion rate, which suggested it would never be a practical fusion device.

The release of information on the USSR's tokamak design in 1968 indicated a leap in performance. After great debate within the US industry, PPPL converted the Model C Stellarator to the Symmetrical Tokamak (ST) as a way to confirm or deny these results. ST confirmed them, and large-scale work on the stellarator concept ended in the U.S. as the tokamak got most of the attention for the next two decades. Research on the design continued in Germany and Japan, where several new designs were built.

The tokamak ultimately proved to have similar problems to the stellarator, but for different reasons. Since the 1990s, the stellarator design has seen renewed interest. New methods of construction have increased the quality and power of the magnetic fields, improving performance. A number of new devices have been built to test these concepts. Major examples include Wendelstein 7-X in Germany, the Helically Symmetric Experiment (HSX) in the US, and the Large Helical Device in Japan.

3. The Present - Wendelstein 7-X

Is the search for fusion energy, long dominated by doughnut-shaped devices called tokamaks, about to undergo a shape shift? Just as ITER, the world's largest tokamak—and at tens of billions of dollars the most expensive—nears completion in the hills of southern France, a much smaller testbed with a twisty geometry will start throttling up to full power in Germany.[2]

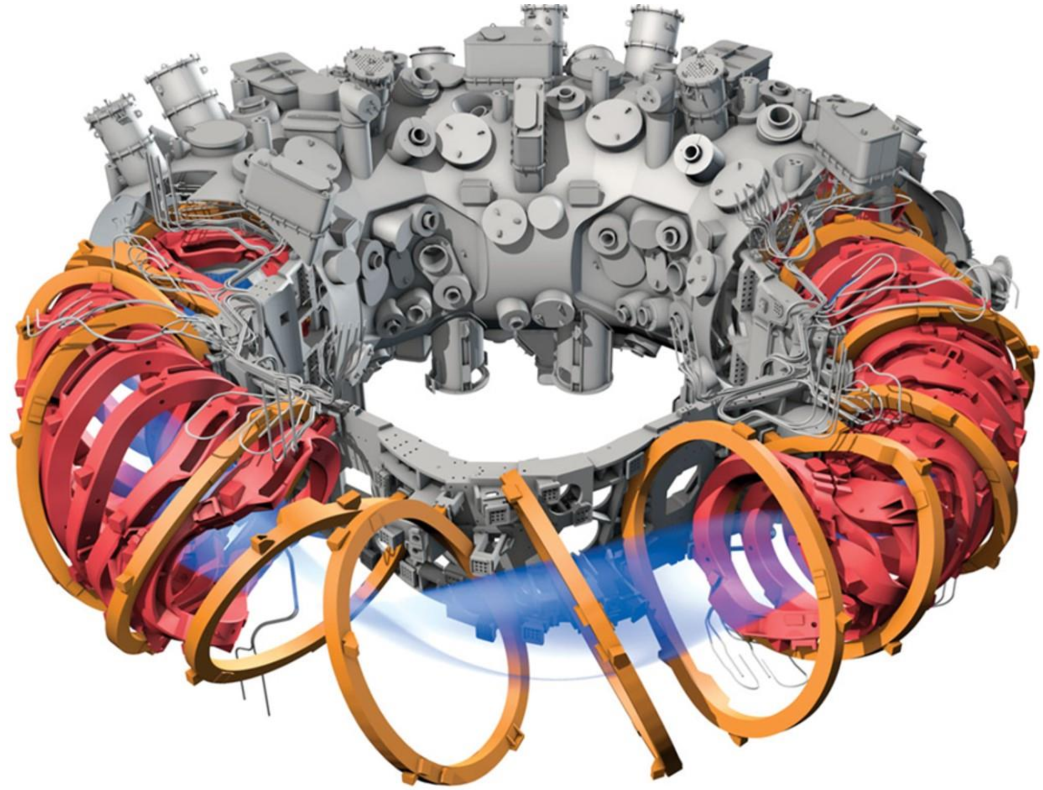
If the 16-meter-wide device, called a stellarator, can match or outperform similar-size tokamaks, it could cause fusion scientists to rethink the future of their field. stellarators have several key advantages, including a natural ability to keep the roiling superhot gases they contain stable enough to fuse nuclei and release energy. Even more crucial for a future fusion power plant, they can theoretically just run and run, whereas tokamaks must stop periodically to reset their magnet coils.

In runs of a few seconds, the €1 billion German machine, dubbed Wendelstein 7-X (W7-X (rough translation of Wendelstein is coil-piece), is already getting "tokamak-like performance," says plasma physicist David Gates, proving adept at preventing particles and heat from escaping the superhot gas. If W7-X can achieve long runs, "it will be clearly in the lead," he says. "That's where stellarators shine." Theorist Josefine Proll of the Eindhoven University of Technology is equally enthusiastic: "All of a sudden, stellarators are back in the game." The encouraging prospects are inspiring a clutch of startup companies, including one for which Gates is now leaving Princeton Plasma Physics Laboratory, to develop their own stellarators.

W7-X has been operating since 2015 at the Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany, but only at relatively low power levels and for short runs. Over the past 3 years, W7-X's creators stripped it down and replaced all the interior

[2] Daniel Clery, Science, "Twisty device explores alternative path to fusion," Sep 7, 2022, https://www.science.org/content/article/twisty-device-explores-alternative-path-fusion , Note that access to this article may be limited.

walls and fittings with water-cooled versions, opening the way to much longer, hotter runs. At a W7-X board meeting last week, the team reported that the revamped plasma vessel has no leaks and is ready to go. It is expected to restart later this month, on its way to showing whether it can truly get plasma to conditions that, in a future device, would ignite fusion.



Wendelstein 7-X's complex geometry was a nightmare to build but, when fired up, worked from the start.

Both stellarators and tokamaks create magnetic cages for gas at more than 100 million degrees Celsius, so hot it would melt any metal container. Heating is provided by microwaves or high energy particle beams. The outlandish temperatures produce a plasma—a roiling mix of separated nuclei and electrons—and cause the nuclei to slam together with such force that they fuse, releasing energy. A fusion power plant would be fueled with a mix of the hydrogen isotopes deuterium and tritium, which react most readily. Research machines like W7-X that aren't trying to generate energy avoid radioactive tritium and stick to safer, more plentiful hydrogen or deuterium.

Author's comment: Deuterium is the second Isotope of hydrogen and has a proton and neutron in its nucleus. It exists in any natural water source with an abundance of about 1.5%, and is relatively easy to produce. Tritium is the third isotope of hydrogen, has two neutrons and a proton in its nucleus and is moderately radioactive. In addition to being radioactive, tritium has two other problems that make its use in an experimental stellarator problematic: it is extremely rare, and it has a half-life of 12.32 ± 0.02 years.

A working, power producing fission reactor will use fuel that is a mixture of deuterium and tritium as pointed out above. Because tritium is so rare, the reactor would probably need to breed its own tritium (see below).

Tritium is most often produced in nuclear reactors by neutron activation of lithium-6. The release and diffusion of tritium and helium produced by the fission of lithium can take place within ceramics referred to as breeder ceramics. The production of tritium from lithium-6 in such breeder ceramics is possible with neutrons of any energy, and is an exothermic reaction yielding 4.8 MeV. In comparison, the fusion of deuterium with tritium releases about 17.6 MeV of energy. For applications in proposed fusion energy reactors, such as ITER, pebbles consisting of lithium bearing ceramics including Li_2TiO_3 and Li_4SiO_4, are being developed for tritium breeding within a helium-cooled pebble bed, also known as a breeder blanket. [3]

To make their plasma-confining magnetic fields, tokamaks and stellarators employ electro-magnetic coils looping around the vessel and through the central hole. But such a field is stronger nearer the hole than the outer edge, causing plasma to drift to the reactor's wall.[2]

Tokamaks tame the drift by making the plasma flow around the ring. That streaming generates another magnetic field, twisting the ionized gas like a candy cane and steadying it. Stellarators use weirdly shaped magnetic coils instead of streaming plasma to produce the twist. The tokamak scheme has long proved the more successful at holding plasma in place, but once plasma physicists had supercomputers powerful enough, they could tweak the complex geometries of stellarator magnets to improve confinement, a process called optimization.

W7-X is the first large, optimized stellarator and contains 50 bizarrely twisted superconducting coils, each weighing 6 tons. Its construction, begun in the mid-1990s, was tortuous, completed 10 years late and costing almost twice the €550 million originally budgeted.

Despite the wait, researchers haven't been disappointed. "The machine worked immediately," says W7-X director Thomas Klinger. "It's a very easy-going machine. [It] just did what we told it to do." This contrasts with tokamaks, which are prone to "instabilities"—the plasma bulging or wobbling in unpredictable ways—or more violent "disruptions," often linked to interrupted plasma flow. Because stellarators don't rely on plasma current, that "removes a whole branch" of instabilities, says IPP theorist Sophia Henneberg.

In early stellarators, the geometry of the magnetic field caused some slower moving particles to follow banana-shaped orbits until they collided with other particles and got knocked out of the plasma, leaching out energy. W7-X's ability to suppress that effect means its "optimization worked as it was supposed to," Gates says.

With this Achilles heel removed, W7-X mostly loses heat through other forms of turbulence—little eddies that push particles toward the wall. Simulating turbulence takes serious computing power, and theorists have only recently got a handle on it. W7-X's upcoming campaign should validate the simulations and test ways to combat turbulence.

The campaign should also showcase a stellarator's ability to run continuously, in contrast to the pulsed operation of a tokamak. W7-X has already operated for runs of 100 seconds—long by tokamak standards—but at relatively low power. Not only were its components uncooled, but the device's microwave and particle heating systems could only deliver 11.5 megawatts of power. The upgrade will boost the heating power by 60%.

[3] Wikipedia article on Tritium. https://en.wikipedia.org/wiki/Tritium

Running W7-X at high temperature, high plasma density, and for long runs will be the real test of stellarators' potential for producing fusion power. An initial aim, Klinger says, is to get the ion temperature up to 50 million degrees Celsius for 100 seconds. That would put W7-X "among the leading machines in the world," he says. Then, the team will push it for longer, up to 30 minutes. "We'll go step by step, exploring uncharted territory," he says.

W7-X's achievements have prompted venture capitalists to back several startups developing commercial power-producing stellarators. First priority for the startups: Find a simpler way to make the magnets.

Princeton Stellarators, founded this year by Gates and colleagues, has secured $3 million and is aiming to build a demonstration reactor that will forgo the twisted magnet coils of W7-X. Instead, it will rely on a mosaic of about 1000 tiny square coils made of high-temperature superconductor (HTS) on the outside surface of the plasma vessel. By varying the magnetic field produced by each coil, operators will be able to change the shape of the applied field at will. "It takes complexity out of the coils and puts it in the control system," Gates says. The firm hopes to initially develop a reactor that will fuse just cheap, abundant deuterium, to generate not power, but neutrons for manufacturing radioisotopes. If successful, the firm will then aim for a power-producing reactor.

Renaissance Fusion, based in Grenoble, France, has raised €16 million and plans to coat segments of the plasma vessel in a multilayered HTS, forming a uniform coating. Then, using a laser, engineers will burn off tracks within the superconductor to etch a twisting pattern of magnet coils. They aim to make a meter-long test segment over the next 2 years and a full prototype by 2027.

A third firm, Type One Energy in Madison, Wisconsin, received U.S. Department of Energy funding to develop HTS cables with enough bend to be used in stellarator magnets. The company would sculpt pieces of metal with computer-controlled etching machines, carving twisting channels into which the cable is wound to turn it into a coil. "Advanced manufacturing technology opens the door for the stellarator," says co-founder David Anderson of the University of Wisconsin, Madison.

Anderson says the next phase of W7-X's operation will accelerate the boom in stellarator efforts. "With half-hour discharges, you're essentially steady-state," he says. "This is a big deal."

4. The Future - Princeton Stellarators?

As seen above, there are many firms attempting to make fusion energy reactors. The really good news is that there are many paths forward. I'm guessing that with their really deep roots in this design, Princeton Stellarators, Inc. has a better chance than most to be successful in this quest. In addition to the text in the prior section, go through the link below for more information.

https://www.princetonstellarators.energy/tech