The Hows and Whys of Fusion Energy

Plasma based fusion is one of the novel ways for generating clean energy. Despite not being technically renewable, fusion byproducts are much cleaner than nonrenewable sources such as coal, oil, and natural gas. Even fission reactors, which are virtually renewable in their efficiency[1] there is still the buildup of radioactive waste which needs to be stored safely deep underground. Plasma fusion mimics the process that the sun uses to warm the Earth with solar radiation. However, there are some important distinctions between how the sun undergoes fusion and how physicists and engineers can recreate it. The sun has the benefit of harboring enough mass, that gravity does all the compression needed to generate fusion conditions. On Earth, those pressures are not feasible, so instead we circumvent the pressure requirements by increasing the temperature of the plasma. Furthermore, incredibly strong electromagnetic fields are used to trap and compress the plasma since anything that could physically pressurize it would be incinerated at the extremely high operating temperatures.

Another aspect of fusion that we can manipulate is the type and ratio of chemical species being (hopefully!) fused. The Lawson Criterion is the technical description of what temperatures and pressures allow for 'ignition' of these fuels. These species include deuterium (a slightly heavier isotope of hydrogen with a proton *and* neutron in its nucleus), tritium (a radioactive isotope of hydrogen with one proton and two neutrons), and helium-3 (two protons and one neutron in its nucleus). The sun fuses whatever elements are available, but fusion reactors can be modified to utilize the most efficient combination of hydrogen and helium isotopes. This is deuterium-tritium for the DIII-D, JET, and ITER sites, but some deuterium-deuterium tests are being done on DIII-D.

Because the principles of fusion involve nuclear physics, fluid mechanics, and electro/magnetodynamics, there is an inordinate number of simulations that go into the production of different fusion reactors. Starting with the layout, many reactors fall under the category of "tokamak" which is torus shaped. These contain two sets of coils generating magnetic fields to trap and compress the plasma. If you think of the torus as a jelly filled donut, the two groups of magnetic fields are directed circularly through the jelly (toroidally) and around the outside but wrapping through the donut hole. Since the conditions inside the tokamaks are so extreme, most sensors can only measure properties of the plasma near the outer edge of the reactor. Thus, numerical simulations need to be in constant use throughout the design and production phases of creating these.

The challenges of fusion continue past the design and production, unfortunately. Because the fusion reaction releases high energy neutrons, (which are unaffected by the electromagnetic fields) these damage the interior walls of the reactor through radiation embrittlement. There is also the challenge of injecting new fuel into the reactor since the plasma is constantly expanding. Some of these problems are solved by the introduction of novel techniques such as using lithium as the thermal insulation for the interior walls. It acts as coolant being cycled but can also decay into useful fusion products when it reacts with free neutrons. Stellarators are another architectural design that hopes to compress the plasma more by adding helical coils as well. The computational and engineering techniques being used in fusion reactors are on the cutting edge, and the hope is to achieve reliable and efficient energy through this method in coming decades.

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[1] Fissile material is incredibly energy dense and even using purely fission reactors, we would not run out of fissile material for many centuries when accounting for uranium and thorium.