Possibilities of Nuclear Fusion Based on the Functionality of Superconductors

Siming Fu
Poly Prep Country Day School, NY 11228, US.

Abstract: This article will explain the possibilities of nuclear fusion based on the functionality of superconductors. It discusses the world energy demand as a whole and compares other energy sources with nuclear fusion power. It then introduces the superconductor by explaining the conductivity first and then how superconductors work. Next, it discusses the feasible application of superconductors in fusion reactors, as well as the future and challenges surrounding the topic.

Keywords: Nuclear Fusion; Plasma; Magnetic Confinement; Superconductor; Electrons; BCS Theory; Cooper Pair

Introduction

In the world that updates itself every single day, its energy consumption is an inevitable question. Fossil fuels, including coals, oil, and gas, have been playing a great role in the global energy system. The energy demand for over 7 billion people on the earth is astronomical. Moreover, as the world continues to grow, not only the population is contributing to the growth, but also the technology that advances quickly requires more and more electricity to power them. The transportations that is becoming more connected worldwide is also demanding for even more.

Fossil fuels now provide about 80 percent of the energy in the world while the rest comes from nuclear, biochemical, and other renewable sources. Even though solar power has increased by 50 percent, providing about 24 Gigawatts of energy, is not even one of one million of the expected energy demand in 2040: 47,000,000 gigawatts; whereas wind power only provides 53 gigawatts of power in 2017. Even at the ideal scenario where the efficiency of renewable energy sources is at the best, these sources can only account for 40 percent of the total energy demand expected in 2040: 7.6 million gigawatts renewable power and 19 million gigawatts of electricity power out of 47 million gigawatts of total increased power demand in 2040.

Fossil fuels provide us with extensive power, but it comes with a cost: burning fossil fuels produce carbon dioxide, the largest driver of global climate change, and contributes to air pollution, which is estimated to be linked to millions of premature deaths each year. Furthermore, fossil fuels are not unlimited on the Earth; therefore, the world needs clean and renewable energy sources.

The energy consumption of US in 2021 is 92.97 exajoule, which is 25,825,000 gigawatts hour. If people were to use solar energy to completely replace fossil fuels, assuming that these solar panels work under the most ideal conditions with the best energy output in the market, which is about 0.35kWh each solar panel per day, people would need 202,152,641,879 solar panels in the country in order to provide the average energy use in the US - 70753424657.5 kWh per day. The average solar panel size is about 1.6 square meters, which means that these panels would take up 323444 square kilometers of area in the country. There is no way for people to completely replace fossil fuels not only because other energy sources do not keep up with the demand, but also because the demand for fossil fuels in many areas would continue to increase exponentially. Let along other renewable energy sources: wind mills sometimes cannot even produce any energy in several days.

Therefore, the only possible solution to these energy issues is Nuclear Fusion power. Fusion has been imagined by scientists for decades because it promises unlimited, safe, and carbon-free energy. The fusion energy is more than a million times denser than fossil fuels.

In the fission process, a neutron blasted into an Uranium-235 atom and split into smaller fragments, and these new particles will hit other atoms to generate a chain reaction - eventually releasing heat energy during the process of breaking down. However, this kind of nuclear power uses very scarce sources in the world, long-live radioactive uranium and plutonium particles, and it causes very dangerous nuclear pollution that can contaminate our planet for decades if not controlled appropriately.

The fundamental mechanic of fusion is combining two tiny atoms into one under extremely high temperature and pressure and releases enormous amounts of energy. The fusion process can obtain 4 times the energy output than the fission process. The hydrogen isotopes, Deuterium and Tritium, in the fusion process are very stable and the radioactivity does not last very long, which is also a lot more abundant and cheaper than the fission fuels. The fusion process is exactly what is happening inside the Sun. 0.1 g of Deuterium plus 0.3 g of Lithium in the fusion process can generate enough electricity for an average American for a full year. Moreover, fusion reactors are much smaller than nuclear fission plants, which would also cost much less to build enough fusion reactors to power the whole country in the ideal situation.

In a fusion reactor, hydrogen isotopes must be heated to extreme temperature (50 million degrees Celsius), kept under stable intense pressure, therefore confine the nuclei long enough for it to fuse. When the hydrogen is heated to such a temperature, it transforms from gas into plasma in which the negatively charged electrons are separated from the positively charged nuclei.

However, the main challenge for the fusion reactor is to achieve a rate of heat generated by the fusion plasma which exceeds the rate of energy used to control the plasma. Therefore, the possible solution to this is Magnetic confinement which uses a magnetic field to control the extremely hot plasma. Nonetheless, even the most strong magnets cannot provide such a strong magnetic field to control the plasma; therefore, this is where a superconductor comes in.

Superconductor

Before trying to understand what a superconductor is, it is important to understand the concept of conductivity. There are three types of materials categorized by conductivities: conductors, insulators, and semiconductors. In conductors, mostly metals like copper, aluminum, and graphite, their molecular structures explain why they conduct electricity. For example, in a copper atom, it has its neutrons and protons forming the nucleus, and has several orbits of orbiting electrons. The different orbits of electrons are grouped into energy levels, shells. The outermost shell is called the valence shell, which represents a band of energy levels (the most energy it has), so it is also called the valence band and electrons are confined to this band. When the valence electrons receive enough energy from an external source, they are able to go to the conduction band, where electrons can move freely in the material.

The amount of energy an electron needs to jump from the valence band to the conduction band is called the band gap. The gap between the valence band and the conduction band in conductors is zero and sometimes overlapped; therefore, the electrons in conductors are free to move from valence band to the conduction band, which is the reason for its conductivity. Whereas in an insulator, the band gap is too large so the electrons are not able to escape the valence band. In a semiconductor, the gap is relatively small so when it receives some energy, it is able to conduct electricity.

Therefore, in copper, electrons are free to move inside the metal, and because there are no external forces, they move in ways similar to the ways water molecules move in a static lake. When a battery's ends are connected by a copper wire, the voltage difference of the battery causes the electrons in the copper wire to move from the low voltage side towards the higher voltage side, just like the water moving in a river flooding from the top of the hill towards the bottom. However, electrons have their original velocity towards different directions, so they will constantly bump into atoms. The atoms inside the copper wire are the obstacles to the electron motion, which creates resistance. The resistance created by the copper atoms are called the electrical resistance, a defining property of a metal.

When a voltage is applied to a conductor, because of its electrical resistance, when electrons collide with atoms, they slow the current down and produce heat energy that is dissipated. The lower the electrical resistance a conductor has, the better conductor it is because it is more energy efficient by losing less energy in the process.

Nevertheless, superconductivity was discovered in 1911 by Dutch scientist Heike Kammerlingh Onnes, who used liquefied helium to cool metals to near absolute zero (0 kelvin / −273.15 °C). When metals were cooled to this extent, their electrical resistance dropped to zero suddenly. Current can move without any resistance in the extremely cooled metal. Therefore, he named it such a state of material superconductivity.

In normal conductors, when electrons move through its network of atoms, they create heat and light like in a light bulb. The higher the temperature it is, the more resistance it has because high temperature results in more intense particle movements and electrons are more likely to collide and move less freely. When the temperature is cooled down to a certain point, critical temperature, the resistance in the conductors becomes absolutely none at all. The simple explanation of lowering the temperature would result in very little particle movement inside the material therefore creating nearly zero resistance would not work in superconductors because the resistance is none instead of nearly none.

The later discovered theories by physicists John Bardeen, Leon Cooper, and John Schrieffer in 1957, called the BCS Theory, explained the superconductivity. The theory explains the superconductivity at a quantum level. When a conductor is close to absolute zero temperature, the atoms' thermal movement is negligible. When a voltage is applied, electrons will start moving in the lattice of atoms in the material. Since the conductor's atoms have their electrons freely move in the conduction, they are positively charged because of the nucleus, and therefore the negatively charged moving electrons will attract the atoms in the lattice, causing distortion in the lattice. This distortion makes the lattice slightly more positively charged, which attracts the next electron moving into the lattice. The two electrons will not repel each other because the disturbance caused by different charges in electrons and the lattice happen in a very large scale in the material; therefore, these two electrons start moving together and bind to Cooper Pair. The Cooper Pair is extremely weak so any thermal movement can break it, which is the reason why superconductivity only happens at an extremely low temperature.

A normal atom formed by neutrons, protons, and electrons are called a fermion, and particles such as photons are called bosons. Fermion does not allow more than two particles to be in the same energy state, which is why atoms have different orbits of electrons that have different energy levels. Whereas bosons can have all the particles in the same energy state, so if an atom were a boson, it can have all the electrons orbiting in the lowest energy state and no chemical reaction can happen in this situation. In superconductors, the Cooper Pair electrons start to behave like a boson even though they are still fermions, so many pairs can behave like bosons having all the particles at the lowest energy level. The larger group of Cooper Pairs become very stable and the interactions with the lattice can prevent any collision with the lattice. Another way to understand this is that these electrons are now all in the ground state of energy, so there is no energy to dissipate during the movement, which means that there has to be no resistance.

In the state of superconductivity, it can be used for many applications, and Fusion is one of them.

Superconductors Applications

Ever since scientists started exploring fusion in the 1960s, people have never succeeded in making the reactor work in a way that generates more energy than the energy they put in to stabilize the extremely pressured and heated plasma. The goal for a fusion reactor at this point is to achieve a Q, the ratio of fusion energy output to the energy input to maintain the plasm, that is greater than 1. So far the record is a Q of 0.67. Practically, accounting for the costs of converting thermal energy into electricity and other factors, the Q will need to be between 10 - 25 in order for it to be implemented for commercial use.

The type of fusion reactor that adopted the magnetic confinement method is called Tokamak. Tokamak is a doughnut shaped device surrounded by powerful electromagnets to contain the plasma inside the device. Conventionally, such as the ITER tokamak reactor, uses low-temperature superconductors, which have critical temperatures below 30 Kelvin, as the electromagnets to generate the high magnetic field. However, the current that can run through such a superconductor is limited in high magnetic fields, which in turn confines its strength of magnetic field it can generate.

Therefore, MIT and the CommonWealth Fusion Systems have designed a more powerful magnet using the high-temperature superconductor (HTS) with critical temperature above 30 Kelvin, which can allow a more powerful magnetic field to pass through. Using the HTS, MIT and CFS are able to use it to produce fields of 20 T in the reactor, whereas the ITER reactor can only have 5 T. The HTS also turns out to be more energy efficient because it can be shrunk to a much smaller size, roughly 2 percent the size of ITER. The team has hoped to fully assemble the prototype in 2025 in order to test out if all the theories would work out in this fusion reactor. Whether they achieve their goal or not, it will be a promise to the future of clean energy sources, proving that it will not be constantly "in the future".

Challenges and Outlook

Although the HTS application in the fusion reactor seems very promising, people still face many challenges in terms of the material and the construction of it. The SPARC reactor is significantly smaller than the ITER reactor, so the energy density of plasma inside is also a lot denser. The plasma is similar to the solar flares, which would damage the reactor interior very easily if the magnetic field surrounding it is not powerful enough.

Furthermore, the building of the electron wires made of HTS also poses a challenge to the researchers. They have to be able to turn the superconductor tapes, which is a thin strip of conductor, into coils that can generate the magnetic field. These tapes are usually made of Rare-earth barium copper oxide, which is a lot more expensive and rarer than copper wires; in the test magnet used in the fusion reactor it consists of 267 km of tape.

Even though the tests have demonstrated a lot higher energy output, the SPRAC is only predicted to have a Q greater than 2. It is indeed an exciting increase from what we have achieved already, but it is still very far away from the 10 - 25 Q mark in order to put it into commercial use. The construction of these reactors in large scales is also a challenge even if they have achieved the ideal net energy output.

Nonetheless, all these advancements are very astonishing innovations and will make us a step closer to the unlimited clean energy.

References

[1] EDinformatics. (2019). Why do metals conduct heat and electricity so well? What metals conduct the best? Retrieved from : https://www.edinformatics.com/math_science/why_metals_ conduct.htm.

[2] Dull, R., High, L., & Largo, S. (n.d.). A Teachers Guide to Superconductivity for High School Students. Retrieved from https://sites.evergreen.edu/psam1819/wp-content/uploads/sites/388/2019/02/A-Teachers-Guide-to-Superconductivity-for-High-School-Students-NSCHSS.pdf.

[3] Superconductivity. (n.d.). Retrieved from: https://www. open.edu/ openlearn/ science-maths-technology/engineering-technology/ superconductivity/content-section-1.

[4] Exploring the Realm of Conductivity–Young Scientists Journal. (n.d.). Retrieved from https://ysjournal.com/physics/exploring-the-realm-of-conductivity/.

[5] Higgsino Physics. (2018). The Physics of Superconductors [YouTube Video]. In Youtube. https://www.youtube.com/watch?v=h6FYs_AUCsQ.

[6] Chemistry Solid States part 22 (Electrical properties: conductor) CBSE class 12 XII. (n.d.). Retrieved October 23, 2022, from www.youtube.com website: https://www.youtube. com/ watch?v= 3MHdcrWEAoc.

[7] How does Superconductivity work at the Quantum level? (n.d.). Retrieved from www.youtube.com website: https://www.youtube.com/watch?v=vruYFOlM1-Q.

[8] A commercial path to fusion. (2019,August5). Retrieved from Physics World website: https://physicsworld.com/a/a-commercial-path-to-fusion/.

[9] Maya Posch, Commonwealth Fusion's 20 Tesla Magnet: A Bright SPARC Towards Fusion's Future. Retrieved October 23, 2022, from Hackaday website: https://hackaday. com/2021/09/27/ commonwealth-fusions-20-tesla-magnet-a-bright-sparc-towards-fusions-future/#more-497009.

[10] Exploring Why This Nuclear Fusion Breakthrough Matters. (n.d.). Retrieved from www. youtube.com website: https://www.youtube.com/watch?v=-KEwkWjADEA.

[11] Developing novel superconducting magnets for fusion energy. (n.d.). Retrieved October 23, 2022, from www.youtube.com website: https://www.youtube.com/watch?v=VHl02g5DUAU

Environmental and Energy Study Institute. (2021).

[12] Fossil Fuels | EESI. Retrieved from www.eesi.org website: https://www.eesi.org/topics/fossil-fuels/description#:~:text=Fossil%20fuels%E2%80%94 including%20coal%2C%20oil.

[13] Ritchie, H., & Roser, M. (2017). Fossil Fuels. Our World in Data. Retrieved from https://ourworldindata.org/fossil-fuels#.

[14] Statista. (2020, June). Leading countries for primary energy consumption 2018. Retrieved from Statista website: https://www.statista.com/statistics/263455/primary-energy-consumption-of-selected-countries/.

[15] How Much Energy Does A Solar Panel Produce? | EnergySage. (2022, April 1). Retrieved from EnergySage Blog website:https://news.energysage.com/what-is-the-power-output-of-a- solar-panel/#:~:text=How%20much%20energy%20do%20solar.

[16] Sánchez, J. (2014). Nuclear fusion as a massive, clean, and inexhaustible energy source for the second half of the century: brief history, status, and perspective. Energy Science & Engineering, 2(4), 165–176.

[17] World Nuclear Association. (2021, August). Nuclear Fusion : WNA - World Nuclear Association. Retrieved from world-nuclear.org website: https:// world-nuclear. org/information- library/current- and-future-generation/nuclear-fusion-power.aspx.

[18] ReBCO High Temperature Superconducting Tape. (n.d.). Retrieved October 23,2022, from www. fusionenergybase.com website: https://www.fusionenergybase. com/concept/ rebco-high -temperature-superconducting-tape.

[19] Band Gap and Semiconductor Current Carriers | Intermediate Electronics [YouTube Video]. (2018). Retrieved from https://www.youtube.com/watch?v=N8MuD_xu6L4.