Ways To Improve The Energy Extraction From Nuclear Fusion

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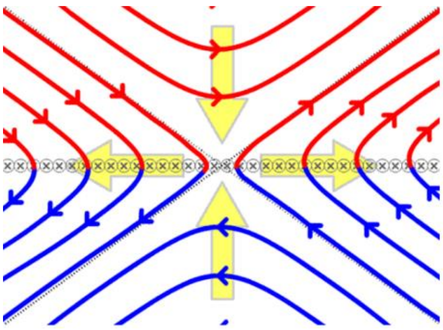
Abstract—The hunt for a clean, limitless energy source is ongoing. One of the solutions might be nuclear fusion. It happens at the Sun, which releases heat and light energy as well as changes the magnetic flux and produces new molecules. Deuterium and tritium are used to create small-scale nuclear fusion in a lab at 100 million Kelvin and 3 to 10 atmospheric pressure, producing helium, fast-moving neutrons, and energy. $E=mc^2$ will convert the mass loss to energy. The two main energy outputs are changes in magnetic flux and heat energy. Helium and the neutron's kinetic energy are two more examples. Lithium blankets and cooling systems can capture the energy of these moving particles. The shift in the magnetic flux around the fusion chamber induces an electromotive force (e.m.f.) in the inductor coil that surrounds it. Solar cells will capture the insignificant light energy.

The Sun is a plasma ball that spins and produces its own magnetic field. In this manner, the solar wind is created. Similar to this, in nuclear fusion the expansion of the explosion products causes a strong circumferential shock and a powerful thermal wave to occur within microseconds. "Heat" gives energy causing vibrations and rotations of atoms and molecules, and directly excites the contained electrons kicking them up into higher shells. With sufficient energy, the electron leaves the atom entirely and the atom becomes ionised. Ionized patch movement generates current, which in turn induces electric and magnetic fields according to the Biot-Savart Law. When a powerful electric current flows through plasma sheets, plasmaid instability occurs with larger islands break up into smaller ones. The initial linear phase will proceed to an explosive phase, causing a magnetic reconnection. The resulting magnetic flux radiates out from the site of fusion.



Ignition by an inertial confinement laser leads to nuclear fusion, with energy output 50% more than the energy input. The heat generated in the thermite reaction can increase the environment's temperature and pressure, making the fusion more easily to occur. The most powerful Japanese LFEX laser can replace the large number of lasers currently used. If an coil is placed around the reaction chamber, an induced and opposing electromotive force (e.m.f.) will be generated according to Faraday's Law and Lenz Law. The underlying principle is that a change in magnetic flux occurs during nuclear fusion. Amumetal (80% nickel-iron alloy) magnetic shield is utilized to separate the two coils, one above and one below the nuclear fusion site because the direction of magnetic flux is up above the fusion site and down below the fusion site. Without such arrangement, the two e.m.f.s will cancel each other.

The pulsed heating in Helion fusion reactor compresses the plasma to extremely high temperatures and densities. With a shift in the magnetic field, the plasma at both ends is accelerated and collides. An opposing e.m.f can be produced by the two inductor coils that enclose the fusion chamber's two sides. The orientation of the induced e.m.f. in the left half and the right half is opposed to one another, due to the radial outward magnetic flux. This justifies the usage of two coils separated by an Amumetal magnetic shield. The two induced e.m.f.s can be used to heat up the plasma, further boosting efficiency by self perpetuation—fusion reaction generates induced e.m.f.s that enhance the fusion reaction.

Depending on the reaction chamber's surface temperature, the heat generated during nuclear fusion can be transferred by heavy water, air, carbon dioxide, helium, liquid sodium, a sodium-potassium alloy, or polychlorinated biphenyls (PCBs). The heat dissipating system receives the heat to generate steam, which in turn pushes the turbine to generate electricity.

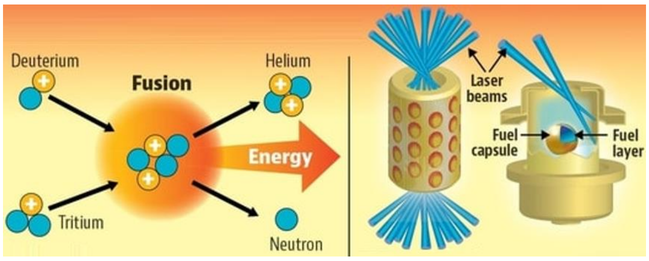
For in-built coil surrounding the fusion chamber, we can add an outside coil. The space between the coils is filled up with soft iron to increase the efficacy of the inductor coil. For areas without in-built coil, an iron core with a central hole to fit the fusion chamber with an outside coil is employed. The coil material is niobium/titanium or niobium/tin wrapped in copper. The energy output form the coils will increase as there is no resistance in critical temperature (achieved by liquid helium). This method has been employed in supermagnet of magnetic resonance imaging (MRI) machine.

A rectifier can convert the frequency of a 1 cycle per minute alternating current (AC) output into direct current (DC). Then a power converter is used to convert to the desired 50 Hz AC output. Because the pulse voltage in nuclear fusion can reach up to 10 to 500 megawatts, variable frequency drives or cycloconverters may not function well.

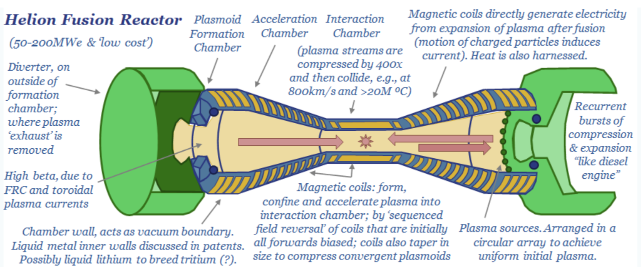
Keywords—Inertial confinement laser-driven fusion, Thermite reaction**,** Japanese LFEX laser, induced electromotive force, Faraday's Law, Lenz Law, Helion fusion reactor, solenoid with soft iron core, magnetic shield Amumetal (80% Nickel-Iron alloy), transformer oil (polychlorinated biphenyls), Variable Frequency Drive, Cycloconverter, DC to AC power inverter, superconducting inductor coil (niobium/titanium or niobium/tin surrounded by copper) in liquid helium

I. INTRODUCTION (*Heading 1*)

Nuclear fusion is possible in plasma—the hot, charged state of free electrons and atomic nuclei. By utilizing an external magnet to contain the hot plasma, nuclear fusion occurs in DIII-D tokamak and W7-X stellarator. In the inertial confinement laser-driven fusion engine,192 lasers direct into a gold cylinder with an inner capsule containing deuterium and tritium to generate a positive fusion energy gain factor of 1.5. Given that the energy released during fusion ignition heats the fuel mass more quickly than it cools, nuclear fusion is self-sustaining.

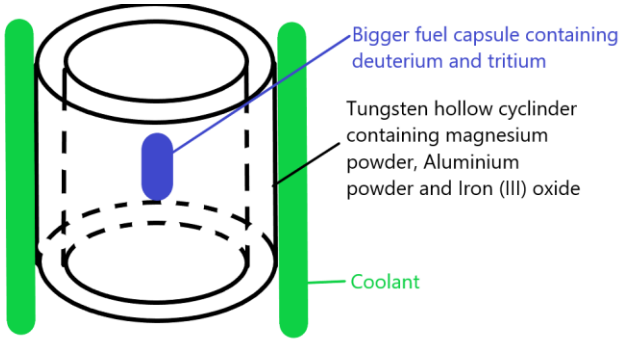


Helion Energy, Inc. generates electricity from nuclear fusion directly, using magneto-inertial fusion technology. The principle is based on tests done with the Inductive Plasmoid Accelerator (IPA) between 2005 and 2012.



II. NUCLEAR FUSION IGNITION IN LAWRENCE LIVERMORE NATIONAL LABORATORY AT THE NATIONAL IGNITION FACILITY FIRST GENERATES ENERGY OUTPUT MORE THAN THE LASER ENERGY INPUT, BUT THE RESULT CAN BE MUCH BETTER BY THE FOLLOWING MODIFICATION.

A. *Use thermite reaction to raise the fusion chamber's temperature and pressure*



The gold cylinder is replaced by a hollow tungsten cylinder filled with a mixture of magnesium, aluminum, and iron III oxide powder. Magnesium powder is burnt by a remote-control automated ignitor. The temperature rises to 400°C and thermite replacement reaction starts and raising the cylinder temperature further to more than 2000°C until all of the reactants have been consumed. The molten iron metal (melting point 1535°C, density 7.874g/cm^3) and aluminium (III) oxide (melting point 2072°C, density 3.987g/cm^3) will be produced from the reaction $Fe_2O_3(s) + 2Al(s) \rightarrow Al_2O_3(s) + 2Fe(s)$ and will be separated due to the difference in densities, with the molten iron at the bottom and molten aluminium (III) oxide at top. The fuel capsule's deuterium and tritium atoms' kinetic energies will rise with temperature. If the capsule volume is held constant, the pressure of the fusion mixture rises according to the Gay-Lussac's law.

To withstand 2000-3000°C and to have high thermal conductivity , the hohlraum should be made of tungsten (melting point: 3422°C, thermal conductivity175 W/(mK)). Although tantalum and hafnium carbides withstand 4,000°C, they are poor heat conductors.

B. *Employ Japanese Laser for Fast Ignition Experiments (LFEX laser)*

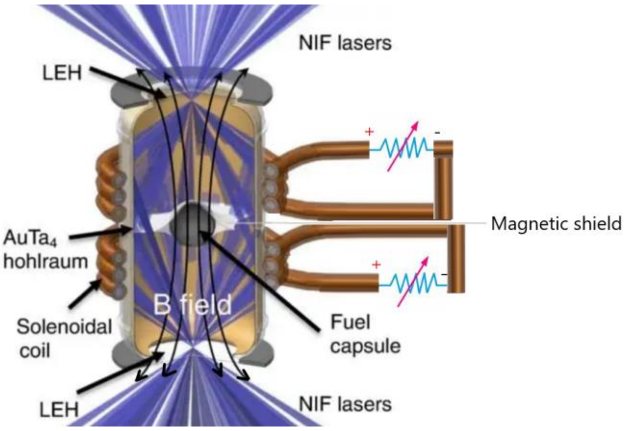
For one trillionth of a second, the petawatt laser "LFEX" is amplified to 2,000 trillion times its original power. 4-beam amplifier system and the high performance dielectric multilayer diffraction grating are used to provide a high power output. Thus the number of lasers can be reduced. The underlying principle is that a photon strikes a mirror with another mirror in front of it. The photon oscillates back and forth between mirrors. Each time electrical energy is imposed on the laser, pushing the photon faster and harder. Suddenly, the mirror is unexpectedly knocked down and a high strength laser is released.

C. *Self-sustaining nuclear fusion allows more reactants to add*

If the energy generated when atoms fuse provides the energy required to fuse further accessible atoms, the nuclear reaction will continue until all reactants are used up. Finding a source of reactants is a problem. Deuterium makes up one part in 5000 of the hydrogen in seawater and is isolated from heavy water using the Girdler sulfide process, distillation, or others. Nowadays, commercial and research nuclear reactors, weapons manufacturing facilities leak tritium into the subsurface soil and ground water or emit it as steam. The production of tritium from lithium-6 through neutron bombardment appears most promising. Tritium can also be created by irradiating burnable absorber rods that contain tritium in nuclear reactors.

D. The coil around the hohlraum will experience an induced electromotive force (e.m.f.)

The energy yield is improved by using a hollow soft iron cylinder between the hohlraum and a liquid helium-filled superconducting inductor coil made of niobium/titanium or niobium/tin surrounding by copper.



The inductor coils try to resist changes imposed on them by the electric current flowing through it. A magnetic field forms within the coil due to electric current passage. Based on the change in the magnetic, an e.m.f. is induced in the coils—electromagnetic induction, according to the Faraday's law of induction. Inductance is given by $L = N^2\mu A/l$, where μ = permeability (Wb/Am)= relative permeability, dimensionless μ_r x permeability of free space μ_0, N = coil's number of turns, A = coil's cross sectional area, l = Length of coil (m).

Superconductors with great carrier mobility exhibit kinetic inductance. At very low temperatures (below 20K), superconducting materials have no resistance. In MRI, coils of niobium/titanium or niobium/tin alloys encircled by copper have been employed. When cooled to 10K by liquid helium, these alloys become superconducting without resistance to current flow.

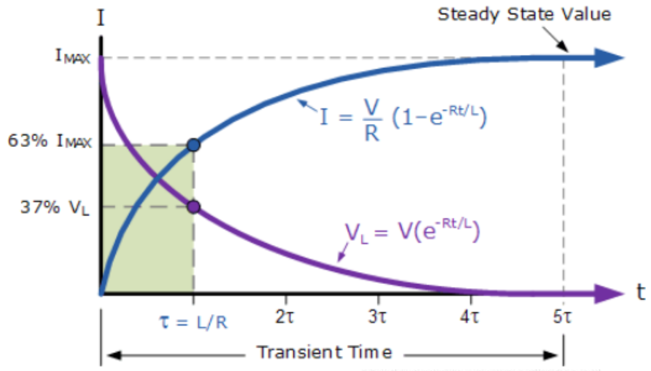
High-temperature superconductors function above boiling point of liquid nitrogen (above 77K) like yttrium barium copper oxide that superconducts at 93K). Room-temperature superconductors works above 0°C and in high pressure. Yttrium-palladium-hydron material superconducts at 262K and 187GPa, where palladium facilitate the migration of hydrogen in the substance.

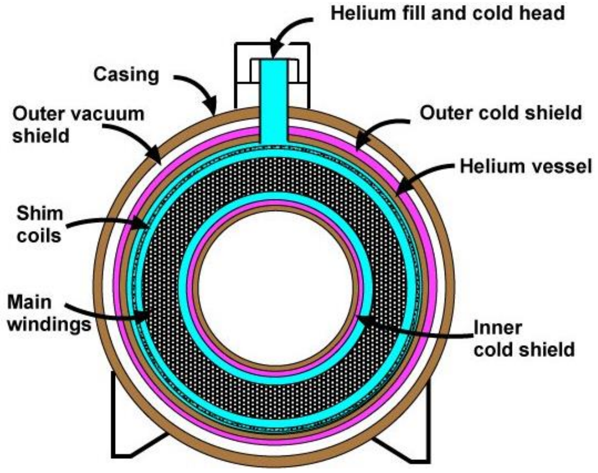
The magnetic flux (LI = inductance times current) will be conserved and current will run indefinitely if there is no resistance in the coil. After a period of time time constant (τ=L/R), the voltage drops to 37% of the maximum value in a series inductor-resistor (L-R) circuit. The resistance R abruptly decreases to zero in a superconducting coil at critical temperature, causing the time constant to approach infinity. The current will stay the same and electricity will continue to be produced.

By employing a rheostat, the power P can be dissipated in a given time period.

$$P = i^2 R + Li\frac{di}{dt}$$

where the first I^2R term denotes the energy that the resistor loses as heat and the second term denotes the energy that the inductor absorbs as magnetic energy.





where V is in Volts, R is in Ohms, L is in Henries, T is in seconds, e = 2.71828.

III. In Helion reactor, the plasma fuel is compressed to extremely high temperatures and densities using a pulsed heating process

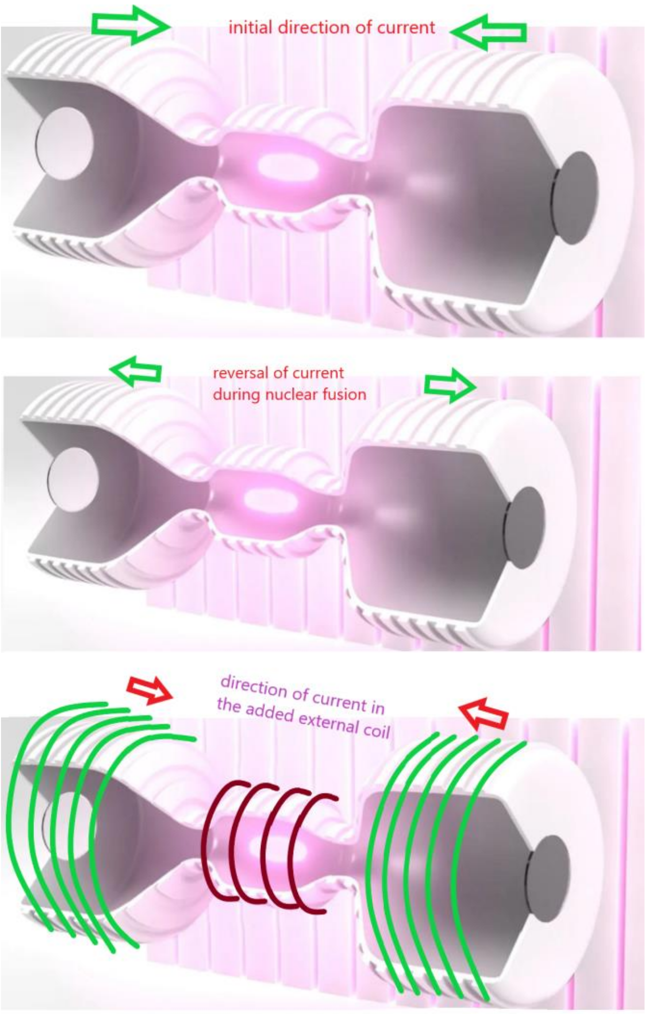
Initially, magnetic energy is used to heat up and contain the plasma in the reactor. At the moment of nuclear fusion, the plasma expands and pushes back the magnetic field. Current is generated with the change in magnetic field according to the Faraday's law. At the point of collision, the magnetic flux lines will radiate out circumferentially. Yet, only the horizontal component of the magnetic flux lines within the coil is used to induce current. Extreme heat will be produced during the nuclear collision and fusion, that can be transferred by coolants coupled with steam generator and turbine to generate electricity.

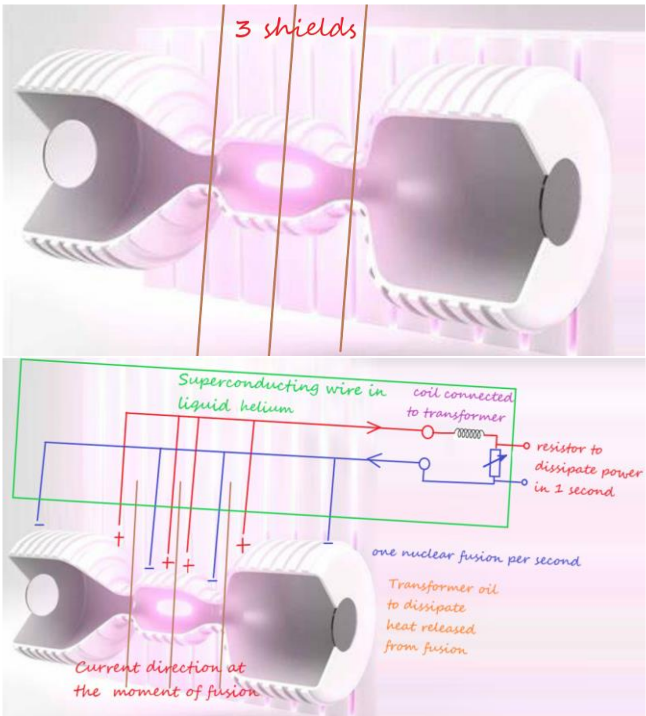
A. Employ two coils to enclose the collision chamber's left and right halves, with a magnetic shield between them

The left and right halves of the collision chamber will have different magnetic flux direction because the magnetic flux emanates from the nuclear fusion point. There won't be any induced current if we utilize a single coil rather than two separate coils.

Soft iron core

If we put a soft iron hollow cylinder between the interaction chamber and the magnetic coil, the magnetic field's strength increases dramatically. It is because current induces magnetization into the iron cylinder where iron atoms line up to strengthen the magnetic field. Because the central airspace has lower magnetic permeability than iron, this hollow iron cylinder is less effective than iron core. By adopting a larger cross-sectional area, more coil turns, coil width and pitch between the adjacent coils, the inductance will increase.



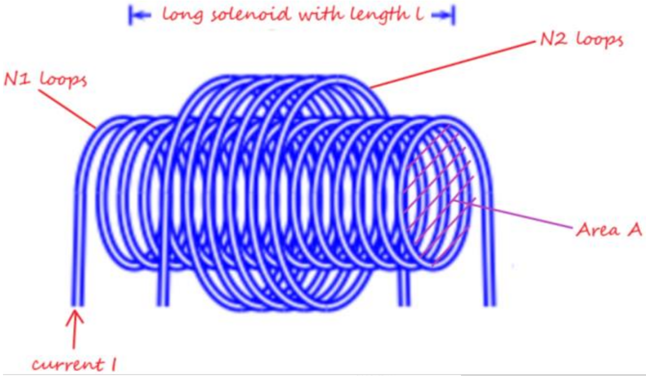


Magnetic flux in the collision chamber radiate outward from the nuclear fusion point. Hence, the induced e.m.f. in the left and right halves of the coil will be in the opposite direction. The center coil ought to be split into two parts and separated by a magnetic shield, otherwise current will cancel out each other. Three separate coils with three magnetic shields are utilized. 80% Nickel-Iron alloy (Amumetal) has high magnetic permeability (µ Max 400,000) and lowest saturation value (8000 Gauss). Permeability dictates how well a given shield can trap magnetic flux. Based on the shield's thickness and the strength of the magnetic field, saturation establishes the highest flux density that a particular shield may contain. Amumetal is created specifically for magnetic shielding purposes by providing a low reluctance channel.

B. Use mutual inductance to induce current in the added outside coil

Initially two currents with opposite direction passing through the in-built left and right coils to push the hot plasma towards each other. At the moment of collision, the magnetic flux is pushed back and the two currents reverse in direction.

If an additional external left and right coils is added, the induced current (by mutual inductance) will create magnetic fluxes trying to push the 2-side plasma to collide each other at centre. As the original coil and the additional external coil have the same direction of current, the induced current in the latter can help to accelerate the plasma.



Magnetic field within a coil $B = \frac{\mu N_1 I}{\ell}$

Magnetic flux $\Phi = B A = \frac{\mu N_1 I A}{\ell}$ (B: Magnetic field; A: Area perpendicular to magnetic field B)

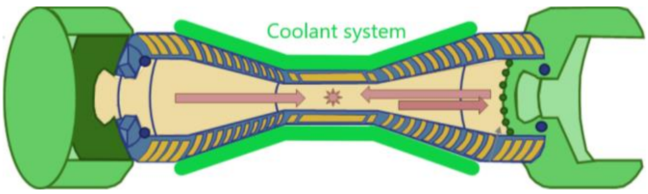
Mutual inductance $M = \frac{N_2 \Phi_{21}}{I} = \frac{\mu N_1 N_2 A}{\ell}$

Induced e.m.f. at added coil $\epsilon = -M\frac{\Delta I}{\Delta t}$

μ is the magnetic permeability of the space in between the coil. Air has permeability of 1.26 x 10^{-6} T•m^2/A, and iron has permeability of 0.25 T•m^2/A. In comparison to air, adding a hollow iron cylinder will produce a magnetic field that is nearly one million times stronger.

C. What coolant is used depends on the surface temperature of reaction chamber?

When two or more atoms combine to form one larger atom with mass lost, tremendous heat energy is released and overheats the superconducting coil. The coil resistance will rise, reducing the induced current. So the heat must be removed from the system by coolant, then to steam generator. The steam generated will push the turbine to generate electricity.



For temperature higher than 380°C, heavy water, oxygen, carbon dioxide, helium, liquid sodium, and a sodium-potassium alloy, are used. Helium is a desirable coolant for fusion power plant due to its chemical inertness, compatibility with other reactor materials, low neutron cross section, and high temperature capability to allow high thermodynamic efficiencies. Cooling water that circulates in the vessel walls of ITER will absorb the heat and ultimately release heat through cooling towers. Molten lithium-lead, or lithium-containing salt work by coupling to Rankine cycle or Brayton (gas turbine) cycle. The high energy neutrons released during fusion will collide with the lithium blankets where the kinetic energy is captured.

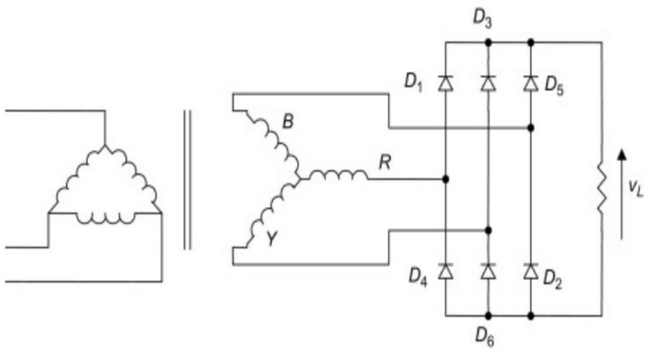
For temperature less than 170–380°C, polychlorinated biphenyls (PCB) transformer oil can be used due to its high electrical constant By transmitting the heat to the steam generator, which subsequently drives the turbine to produce power. The chemical formula is $C_{12}H_{10-n}Cl_n$ where n is between 1 and 10. PCBs appears light yellow to transparent oils or resins. They are heavier than air and do not crystallize in low temperature. Furthermore, they have strong thermal conductivity but low electrical conductivity. Moreover, they are fire resistant due to its high flash points (170-380°C) and their vapours are not explosive. However, they are highly persistent and can build up in food chains.

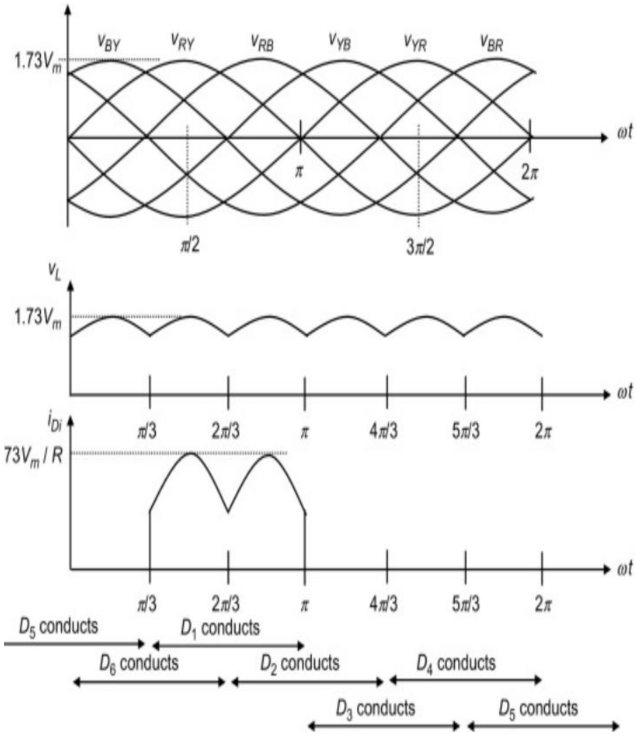
D. Rectifier and power inverter convert the induced e.m.f. to 50Hz output.

Although the pulsed induced current is high, the output voltage can be controlled by connecting to a rheostat in series. The product of high current and low resistance leads to a desired voltage outputaccording to the Ohm's Law (V=IR). 7th generation Polaris generates one pulse per **miniute**. It needs to convert to a 50 Hz alternate current (AC) output for home use.

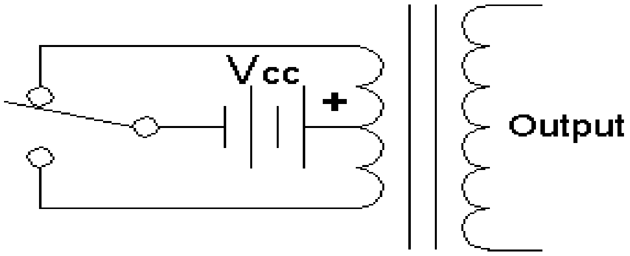
The induced e.m.f. is varied due to the pulse-like character of nuclear fusion and the impact of the employed superconducting coil. A 3-phase voltage should be the result of the induced e.m.f. caused by the shift in the B-field. The applied current (+ve) before fusion is what causes the first phase. When nuclear fusion occurs, the second phase has an opposing current flow (-ve). The third phase follows nuclear fusion but comes before the following fusion (+ve), with current flowing in the same direction as the first applied current. Nuclear fusion can produce pulse voltages of up to 10 to 500 megawatts, which can damage the electronic parts. As a result, transformer-coupled 2SC5200 high-power NPN transistor, cycloconverter, and variable frequency drive will not function.

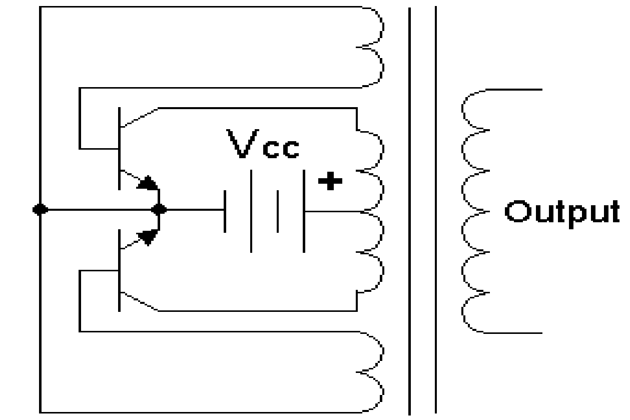
Three-phase bridge rectifiers are commonly used for high-power applications because they have the highest possible transformer utilization factor for a three-phase system. The circuit of a three-phase bridge rectifier is shown below.



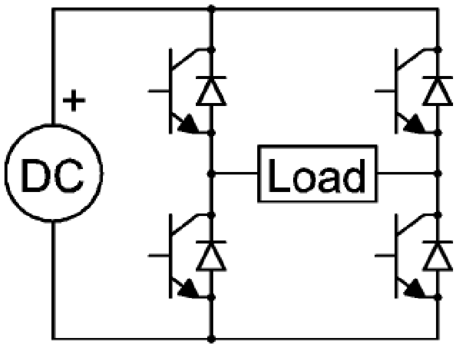


Power inverters convert high voltage direct current (DC) over long distances to alternating current (AC). An H bridge inverter circuit OR an electromechanical switch with automatic comparable auto-switching capability can be used for this purpose. The outcome will be a component of a sine wave with various harmonics.

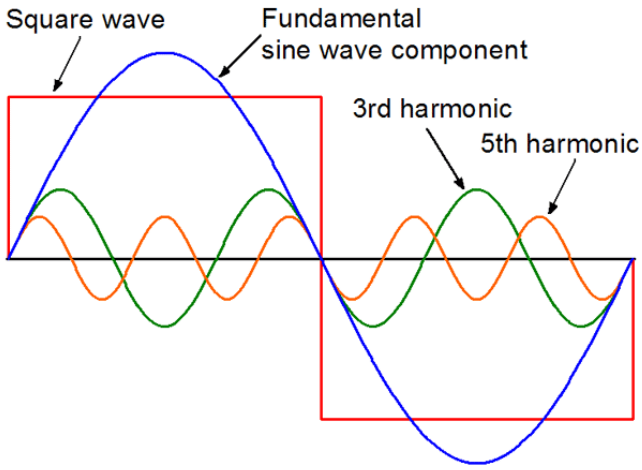




Replace the mechanical switch with an electromechanical switch and an automatic comparable auto-switching device using two transistors and a split winding auto-transformer.



Antiparallel diodes and transistor switches are used in the H bridge inverter circuit.



The total harmonic distortion (THD), which is equal to the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage, can be calculated using Fourier analysis:

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

IV. Conclusion

If we are unable to acquire the anticipated energy production, it must be lost somewhere by Law of Conservation of Energy. In addition to heat released, nuclear fusion also causes change in magnetic flux and release of fast-moving neutron and helium particles. This energy is pure, pollution-free, and supports sustainability. For ignition method, thermite's chemical displacement reaction can increase the pressure and temperature, that in turn speed up the fusion reaction. For Helion's reactor, coil outside coil can trap the magnetic energy through mutual inductance. Due to the opposite direction of the magnetic field centering the site of fusion, magnetic shield is employed to obtain maximum yield of induced current. Coils with soft iron hollow cylinder can further enhance the magnetic permeability and induce more e.m.f. Superconducting material, just like that in MRI machine, reduces the energy loss due to zero resistance at critical temperature.

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