Article 2: Key Concepts and Vocabulary

Power and energy

Energy is a fundamental physical quantity that comes in many different forms, and the quantity of energy does not change as it is transformed from one form to another. In a magnetic fusion reactor, there are many forms of energy. Electric currents flowing through coils of conducting wires create magnetic energy in the form of magnetic fields that confine the region where fusion occurs. During a fusion event, injected fuel reacts and releases nuclear energy that is then transformed into kinetic energy of the fusion products. These fusion products slow down through collisions with the surrounding material, transforming their kinetic energy into thermal energy. Some of the thermal energy sustains the plasma temperature, and some is converted into electricity. Finally, some of the electricity is used within the power plant to power magnets and other auxiliary systems, but most of the electricity is sent on transmission lines to provide consumers with power for refrigerators, lights, computers, and many other devices.

Although amounts of energy are expressed in many different units, depending on the country and the context, the scientific community uses a unified system of joules for macroscopic energy and electron volts for energy at the scale of atoms and nuclei. Associated with the joule is a rate of energy consumption, one joule per second, which is called the watt. Two multiples of the watt are widely used: the kilowatt (1,000 watts) and the megawatt (one million watts). Most nuclear fission power plants today have the capacity to produce electricity at a rate of about 1,000 megawatts, and fusion plants are currently expected to have a similar capacity.

At the microscopic level, the reference unit energy, the electron volt (eV), is approximately six quintillion (six billion billion, or six followed by 18 zeros) times smaller than the joule. One million electron volts, a common unit for nuclear science, is abbreviated MeV.

Atoms, nuclei, electrons, ions, plasma

Matter is made of nuclei and electrons. When matter is not very hot, it is structured as atoms, each of which has a tiny, positively charged, dense nucleus at its center. The nucleus is made of protons (p, positively charged) and neutrons (n, electrically neutral). Surrounding the nucleus are electrons, each carrying one negative electric charge. In an electrically neutral atom, the positive charge of the nucleus is balanced by the negative charges of electrons. When there is not perfect balance, the atom is called an ion; an ion can be positively or negatively charged.

At a very high temperature, such as that created in a fusion reactor, nearly all the electrons become free from their nuclei, and the result is a state of matter, called "plasma," where 1) nearly all matter is ions and electrons, and 2) overall, there is no (or very little) net electric charge. A plasma behaves fundamentally differently from a gas because in a plasma the particles attract or repel one another over a distance through electromagnetic forces, but in a gas the particles interact by colliding with each other. Plasmas are called the fourth state of matter, alongside solids, liquids, and gases. The field of plasma physics examines the behavior of plasmas, including the conditions under which they are stable or unstable. Our Sun is a plasma whose core is at a temperature of 15.6 million degrees Celsius. The temperatures in fusion research reactors are even higher.

Isotopes and radioactivity

The chemical behavior of an atom is determined by its electrons. For example, a neutral atom with 26 electrons (iron) will have a nucleus with 26 protons. The chemical behavior of an atom does not depend on how many neutrons are in the nucleus, and the nuclei of an element can have varying numbers of neutrons. Atoms with the same number of protons but different numbers of neutrons in their nuclei are called isotopes of one another. A widely used notation for isotopes provides the name of the atom and the total number of protons and neutrons. Iron-56, one of the isotopes of iron, has a total of 56 neutrons and protons; since the iron atom has 26 electrons balancing a total positive nuclear charge of 26, it has 26 protons and 30 neutrons. Iron-56 is also written as ^{56}Fe; Fe is the chemist's abbreviation for iron.

Isotopes can be either stable or radioactive. All stable isotopes are found on Earth, along with some radioactive isotopes. The stable isotopes in the Earth's crust occur in specific proportions. For example, ^{56}Fe happens to be the most common isotope of iron in the Earth's crust, accounting for 92 percent of the iron in the crust; the next most common is ^{54}Fe, accounting for six percent. As for

radioactive isotopes of iron, these can be created in nuclear reactions. For example, when the steel in a nuclear fission or fusion reactor is exposed to bombardment by energetic neutrons, some of the resulting isotopes are the iron isotopes, ^{55}Fe, ^{59}Fe, and ^{60}Fe.

Every radioactive isotope has a half-life, meaning that if a given amount of an isotope is present at a given moment, then – as a result of radioactive decay – half as much will be present after one half-life. The other half will have been transformed into another isotope, usually an isotope of another element. The half-life of ^{59}Fe, for example, is 45 days; after 45 days, half of it has become ^{59}Co, a stable (non-radioactive) isotope of cobalt, and half is still ^{59}Fe. After 90 days (two half-lives) three quarters has become ^{59}Co. The half-lives of ^{55}Fe, ^{59}Fe, and ^{60}Fe are 2.7 years, 45 days, and 2.6 million years, respectively. They are the radioactive isotopes of iron with the three longest half-lives.

Importantly for fusion, there are three isotopes of the hydrogen nucleus: the ordinary hydrogen nucleus (called the proton, written as either ^{1}H or p, consisting of one proton and no neutron); the deuterium nucleus (called the deuteron, written as either ^{2}H or D, consisting of one proton and one neutron); and the tritium nucleus (called the triton, written as either ^{3}H or T, and consisting of one proton and two neutrons). ^{1}H and ^{2}H are the two stable isotopes of hydrogen, and ordinary hydrogen is far more prevalent on Earth. Only one out of every 6,500 hydrogen atoms at the Earth's surface is deuterium. Tritium is radioactive, with a half-life of 12.3 years. Due to its short half-life almost no tritium exists naturally on Earth.

Nuclear reactions

Just as chemicals react to produce other chemicals in a chemical reaction, nuclei can react to produce other nuclei in a nuclear reaction. Many reactions in both cases also produce energy. For example, when gasoline burns, this is a chemical reaction that produces carbon dioxide and water and releases energy; energy is also released in the nuclear reactions discussed below. Nuclear reactions typically release roughly a million times more energy than chemical reactions.

For a nuclear fusion reaction to be possible, the total number of protons must be the same in the reactants and the products, and the equality must also hold true for the neutrons. We give two examples of energy-producing nuclear reactions important to fusion here:

Reaction 1: ^{2}H + ^{3}H → n + ^{4}He + 17.6 MeV. The reactants are a deuteron and a triton, with a total of two protons and three neutrons. The products are a neutron (n) and a "helium-4" nucleus. The helium-4 nucleus has two protons and two neutrons. (It has a special name, the "alpha" particle.) Thus, in all, the two products have two protons and three neutrons, just as the reactants do. Also, 17.6 million electron volts (MeV) are released, initially in the form of the kinetic energy of the two products. Of all the nuclear reactions, this "deuterium-tritium" or "D-T" reaction is the least difficult to produce in a hot plasma and accordingly is the focus of most of the work seeking to commercialize fusion energy. It will be discussed extensively in this distillate.

Reaction 2: n + ^{6}Li → ^{3}H + ^{4}He + 4.8 MeV. The lithium atom has three electrons, and this particular lithium nucleus, the lithium-6 nucleus, has three protons and three neutrons. Thus, there are a total of three protons and four neutrons in the reactants. There are also three protons and four neutrons in the products, which are tritium and the helium-4 nucleus. Reaction 2 plays a critical role in D-T fusion by creating tritium from lithium. Lithium is an abundant resource, but tritium, as noted above, is essentially absent from the Earth and yet is needed as a reactant for D-T fusion. Reactions 1 and 2 can be combined so that the neutron produced in Reaction 1 becomes a reactant for Reaction 2. Then the net result is that two ^{4}He nuclei are produced, and a deuterium nucleus and a lithium-6 nucleus are consumed. Tritium is destroyed in the first reaction but replenished in the second. The two reactions produce a total of 22.4 MeV.

Magnetic confinement of charged particles

A magnetic confinement fusion reactor features large and very strong magnets. The magnetic fields created by these magnets can be shaped into specific configurations that force all of the charged particles in the plasma to move within a specific region of the fusion reactor's vacuum vessel. One then says that the plasma is "confined."

At a fusion plant with conventional magnets, the power requirements for the magnets can become a significant fraction of the energy produced by the power plant. However, when currents run along wires that are made of a particular class of materials called "superconductors," no power is required to sustain the current and the magnetic fields. Magnets produced by current flowing in wires made from superconducting materials are called superconducting magnets. The world's largest and strongest superconducting magnets are being designed for use in fusion test facilities.

To date, no material has been found that is superconducting at room temperature, but some materials are superconducting at very low temperatures, only a few degrees above absolute zero

(zero Kelvin degrees, which is equivalent to -273.15 degrees Celsius and -459.67 degrees Fahrenheit). Thus, to enable superconducting magnets to be used, a large amount of cooling equipment must be installed at a fusion plant. However, even taking the cooling equipment into account, superconducting magnets require much less power than ordinary magnets.

In the most common configuration, a plasma is confined in a space resembling a donut, also called a torus. Figure 2.1 differentiates the two kinds of loops on a torus: toroidal and poloidal. In fusion research, one speaks of toroidal and poloidal magnetic fields.
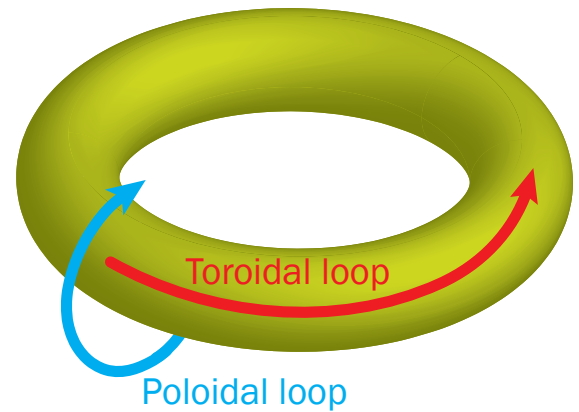
Figure 2.1: The two kinds of circular paths around a donut (torus) are identified.