Direct Energy Conversion in Fusion Reactors

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Direct energy conversion[1] may play a major role in the development of a high-efficiency fusion reactor, here defined as a fusion reactor that converts fusion energy to electricity at an efficiency significantly greater than modern thermal-cycle efficiencies. Thermal efficiencies are now about 40 percent; 70 percent would be a high but achievable goal for a fusion reactor. Successful development of direct energy conversion contribute could materially contribute not only to making fusion an abundant energy source but also to making it an environmentally outstanding energy source.

Four factors contribute to the efficiency of a fusion reactor:

1. Good plasma confinement in the sense of low recirculation power; i.e. $n\tau >> n\tau$ Lawson, where where n is the plasma density, and τ is the mean ion lifetime
2. A fuel cycle that primarily results in charged reaction products instead of in neutrons.
3. An operating cycle and a containment device that minimize radiation by the plasma.
4. A direct converter that can efficiently convert to electricity the energy released in the form of charged reaction products.

Direct energy conversion thus offers both near- and long-term advantages. In near-term fusion reactors, it would improve the power balance by efficiently and cheaply recirculating power. For the long term, it would raise plant efficiency because fuel cycles that primarily result in charged fusion products can be used: i.e.,

$$\mathrm{D + D \rightarrow T + p + 4.04\ MeV}$$
$$\mathrm{D + D \rightarrow {}^3He + n + 3.27\ MeV}$$
$$\mathrm{D + D \rightarrow {}^4He + n + 17.58\ MeV}$$
$$\mathrm{D + D \rightarrow {}^4He + p + 18.34\ MeV}$$

$$\mathrm{6D \rightarrow 2\,{}^4He + 2p + 43.23\ MeV}$$

Two classes of direct energy converters are being studied: electrostatic and magnetic. The electrostatic converter is essentially a linear accelerator run backwards. That is fast ions from the fusion plasma enter the "exit" of the accelerator and decelerated and finally collected. By this process, the kinetic energy of the ions is directly converted to electric potential energy. The magnetic direct energy converters are analogous to the internal-combustion engine. As the hot plasma expands against a moving magnetic field front in a manner similar to that in which hot gases expand against a moving piston, part of the energy of the internal plasma is inductively converted to an electric magnet (pickup) coil.

Electrostatic Direct Energy Conversion

As illustrated in Figure 1, five processes[2] are involved in the electrostatic direct conversion of the plasma energy that leaks out of a mirror fusion reactor *(It may be possible to convert the plasma energy directly, leaving a toroidal reactor via a diverter; however, a detailed technique has not yet been worked out.)*:

1. **Selective Leakage:** By means of magnetic and electrostatic, the ions and electron are made to leak selectively through limited regions of the plasma boundary.
2. **Expansion:** The plasma stream is guided and expanded in volume by a decreasing magnetic field that reduces the power density and converts rotational energy to directional energy.
3. **Electron Separation:** The electrons are separated from the plasma steam and collected on an electron collector grid, an electrode that forms the negative terminal of the power source of the direct energy converter.

4. **Deceleration:** The ions are decelerated by retarding electric fields; kinetic energy is thereby converted to potential energy.
5. **Collection:** The decelerated ions are collected on high-voltage electrodes that form the positive terminal of the power source of the direct energy converter.

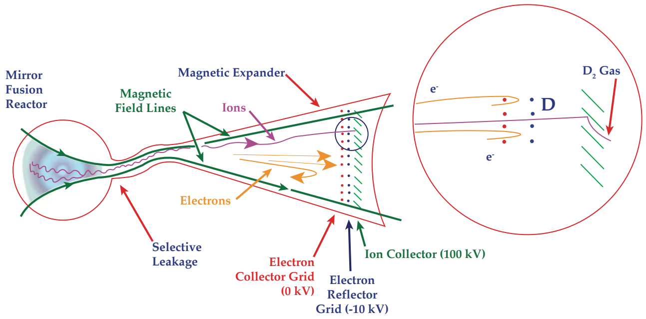

Figure 1 — One stage direct energy converter with a conically-shaped magnetic expander.

Ions, as shown in Figure 2, have a wide energy distribution.[3] Therefore, because it has only one collector electrode at only one potential, the direct energy converter shown in Figure 1 is limited in efficiency to about 50 percent.[4] Higher efficiencies can be obtained by providing many collectors at different potentials so that the ions of different energies can be collected on electrodes where potentials (measured in volts) are near the initial energies of the ions (measured in electron volts). In the multistage (22-stage) collector[2] shown in Figure 3, the plasma stream is followed into a slab beam by a fan-shaped magnetic expander. A carefully controlled laboratory test of this multistage converter gave a measured efficiency of 86.5 ± 1.5 percent. This value compares well with a computer-simulation calculation of 88.5 ± 1.5 percent.[4]

These same principles are being used in several other applications. For example, NASA has developed a practical, multistage, direct energy converter to recover the energy of an electron beam as it leaves a traveling microwave tube.[5]

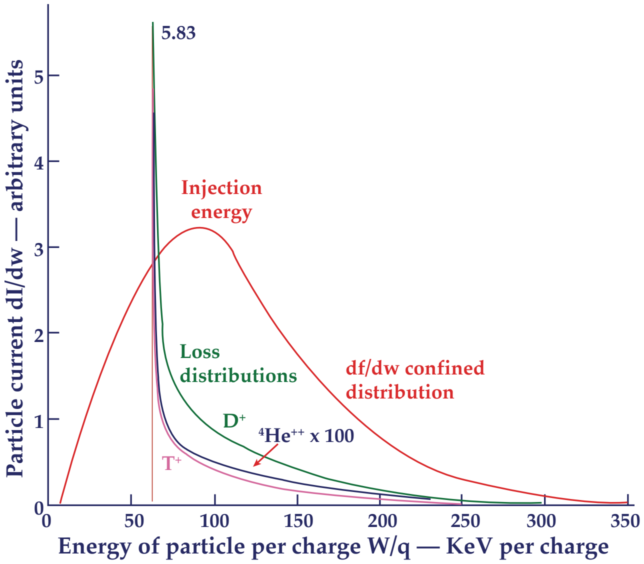

Figure 2 — Energy distribution of the ions leaking out of a mirror fusion reactor.

Also, the concept illustrated in Figure 4 is being developed[4] for mirror fusion reactors that are fueled and heated by the injection of energetic (100- to 200-keV) neutral deuterium and tritium beams. These neutral beams are formed by first accelerating either D^+ and T^+ or D^- and T^- ions to the desired energy, and then using a gas cell to convert a fraction of these ions to neutral atoms. To produce the neutral beam efficiently, it is highly desirable to directly convert the energy of those ions not converted to neutrals.

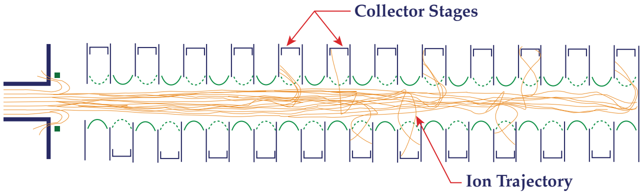

Figure 3 — Twenty-two stage direct converter, with ion trajectories inside the focusing and collecting system.

Electrostatic direct energy converters designed for fusion reactors will encounter various effects that must be considered in their design. For example:

1. The efficiency of the converter may be limited because of space charge in the collector regions, secondary electron-leakage currents arising from ion impact and the resulting x-rays, voltage holding and sparking damage, and charge exchange and ionization of background gas.
2. The lifetime and operation must allow for blistering and spalling of collector surfaces because of He^{++} bombardment, sputtering, tritium recovery, and cooling of the electrodes and possible recovery of this energy in a thermal bottoming cycle. To be practical, a direct converter

must operate for about 10,000 hours between maintenance cycles.

Magnetic Compression-Expansion Direct Energy Conversion

As illustrated in Figure 5, four steps are involved in the magnetic compression-expansion cycle for direct energy conversion:

1. **Compression:** A column of plasma is compressed by a magnetic field that acts like a piston.
2. **Burn:** The compression heats the plasma to the thermonuclear ignition temperature.
3. **Expansion and Energy Removal:** The thermonuclear bum (fusion reactions) increases the plasma pressure and pushes the magnetic field outward.
4. **Refueling:** After expansion, the old, partially burned fuel, D+ and T+, and ash 4 He^{++} for example, are flushed out; new fuel in the form of gas is introduced and ionized; and the cycle is thus completed.

The magnetic compression-expansion concept is being developed by the Los Alamos Scientific Laboratory for the toroidal theta-pinch reactor[6] and has also been suggested for an ATC-type tokamak reactor being developed at the Princeton Plasma Physics Laboratory.[7]

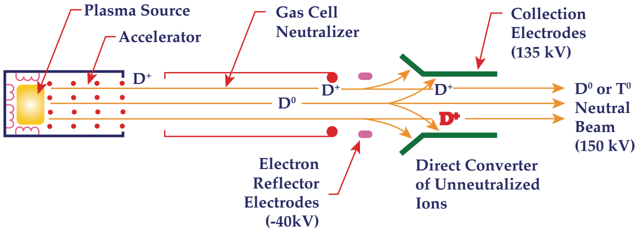

Figure 4 — Neutral beam injector system with “in-line” beam direct energy converter

Although experimental verification of the compression-expansion cycle has not been reported, successful compression heating in several different devices has demonstrated that the principle is sound.

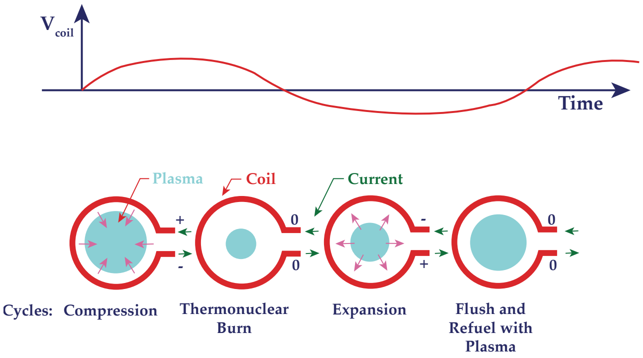

Figure 5 — Magnetic direct energy converter, with the compression, bum, expansion, and refueling parts of the cycle shown.

Application of the magnetic compression-expansion cycle to reactors involves several considerations:

1. Because large expansion ratios are needed for high efficiencies, a relatively large vessel is required.
2. The rapid current changes place stringent requirements on superconducting magnets for the pickup coils.
3. Joule heat losses, switching losses, and storage of the large power pulses required are critical aspects.
4. To attain reasonable average-power levels, burn times must be maximized, and cooling and refueling times minimized.
5. As with the electrostatic converter, this direct energy converter must also operate about 10,000 hours between maintenance cycles.

Publishing History

First published as a chapter in Energy Technology Handbook, McGraw Hill, 1977, pp. 5-150 to 5-154.

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