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Nuclear fusion: Status report and future prospects

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HIGHLIGHTS

- Renewable energy sources need to be complemented by clean and environmentally friendly backup energy sources.
- Controlled nuclear fusion has the potential to be a major player in future energy systems.
- Magnetic fusion research is entering a new research phase with the construction of ITER, that, once in operation, will be the largest magnetic fusion device in the world.

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ABSTRACT

The paper gives an overview of fusion research in the world. The prospects for fusion as an energy source for the future are reviewed. Environmental compatibility, safety and resources are discussed.

1. Introduction

Perhaps the greatest challenge facing our modern world is to develop the necessary technology for an affordable, clean and sustainable energy production. Currently more than 85% of the primary energy production in the world is originating from fossil fuels. The disadvantages are well known: risk of irreversible changes to the climate system, limited reserves, dependency in supply. The number of conceivable non-fossil candidates that could replace the current massive use of fossil fuels is very limited: renewables, nuclear fission and fusion. Fusion is the least developed of the three, but has particularly valuable environmental and safety advantages and has virtually inexhaustible resources. It could prove very important as a backup energy source to cope with the variability of renewable energy sources, thus able to cover long cloudy and/or wind still periods. This paper discusses the current status of worldwide fusion research, resources, safety, environmental and economic aspects of fusion energy.

Fusion research is a worldwide effort. There are currently about 100 fusion research labs scattered in nearly all continents. The EU, Japan, the Russian Federation and the USA undertake a large research effort, with fast growing contributions from China India and South Korea. Other countries like e.g. Brazil and Australia are participating as well with substantial investments.

2. Nuclear fusion: principles

Replicating the fusion reaction in the sun would be a first possible approach to realise fusion on earth. However, the p-p reaction in the sun essentially converts 4 protons into a Helium-4 (^4He) nucleus containing 2 neutrons. This reaction requires thus the conversion of protons into neutrons, via inverse beta decay with a very low probability and therefore not suited for an economical process on earth. A much more 'simple' solution is offered using hydrogen isotopes, already containing the necessary numbers of neutrons and protons from the start, thus resulting in a reaction where essentially a rearrangement of the nuclides takes place, with a 10^{24} times higher reaction rate than the p-p process in the sun. From all possible reactions involving H isotopes, the least difficult fusion reaction is the one between the hydrogen

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isotopes deuterium (D) and tritium (T):

$$\mathrm{D}+\mathrm{T}\rightarrow{}^{4}\mathrm{He}\ (3\cdot 5\ \mathrm{MeV})+\mathrm{n}\ (14\cdot 1\ \mathrm{MeV})$$

To produce sufficient fusion reactions, the core temperature of a D-T plasma has to be about 150–200 million C. This is about 10–15 times larger than the temperature in the centre of our sun, estimated to be about 15 million C.

The reaction products are a 3.5 MeV helium nucleus (alpha particle) and a 14.1 MeV neutron, i.e. in total about 17.6 MeV is released per fusion reaction. This could be converted into heat in a blanket and then into electricity using conventional technology (Carnot cycle). The huge energy release from the fusion reaction also results in a minimal fuel consumption: the deuterium contained in 1 l of sea water (about 30 mg) and used in D-T reactions will produce as much energy as burning 250 l of gasoline.

Other fusion reactions of interest are:

$$\mathrm{D}+\mathrm{D}\rightarrow{}^{3}\mathrm{He}\ (0\cdot 82\ \mathrm{MeV})+\mathrm{n}\ (2\cdot 45\ \mathrm{MeV})$$

$$\mathrm{D}+\mathrm{D}\rightarrow\mathrm{T}\ (1\cdot 01\ \mathrm{MeV})+\mathrm{H}\ (3\cdot 02\ \mathrm{MeV})$$

$$\mathrm{D}+{}^{3}\mathrm{He}\rightarrow{}^{4}\mathrm{He}\ (3\cdot 6\ \mathrm{MeV})+\mathrm{H}\ (14\cdot 7\ \mathrm{MeV})$$

They are more difficult to realise, as they need even higher temperatures, but the lower neutron energy or even absence of neutrons is important benefit.

3. Status of fusion research: magnetic and inertial fusion

From the above, it is clear that the first two major challenges in fusion research are: (i) heating the fuel to several tens of million degrees, which is several times hotter than in the centre of the sun, and (ii) confining the hot fuel in some kind of ‘bottle’. This cannot be a material ‘bottle’ as the highest know melting point is around 3000 C. Thus the ‘bottle’ must be necessarily ‘immaterial’. The solution of these two seemingly impossible requirements necessitates evidently solutions that are radically different from all we know in daily life. There exist presently two approaches: inertial and magnetic fusion (Chen, 2011). Magnetic fusion makes use of magnetic fields. Strong magnetic fields are used to keep the hot particles away from the walls of the confinement device. This is possible because of the property of charged particles to follow a helical path around magnetic field lines caused by the Lorentz force and possible movements perpendicular to the field are thereby highly restricted. This line of research into controlled fusion is being funded in a large number of countries around the globe.

In inertial fusion a small pellet (containing a 50/50 mix of D and T) is compressed using lasers or particle beams and the fuel reacts in the very short time before the pellet is blown apart.

Two main classes of toroidal devices are in use in magnetic fusion research: tokamaks and stellarators. In a tokamak, a set of coils placed around the doughnut-shaped plasma chamber produces the main toroidal magnetic field (Fig. 1). The conducting plasma ring itself serves as the sole secondary winding of an enormous transformer. A current pulse in the primary winding induces a large current in the secondary, i.e. in the plasma ring itself. This induced plasma current generates a poloidal magnetic field. The combination of this poloidal field with the main toroidal field results in a helical magnetic field. The magnetic structure thus generated consists of an infinite set of nested toroidal magnetic surfaces, each with a slightly different twist, reducing further the leakage of particles and heat from the plasma. These surfaces fit into each other just like the puppets in a Russian doll. On each of these surfaces, the plasma pressure is constant and each field line lies on one such surface. The tokamak is a pulsed device, since the transformer that induces the plasma current needs a steadily increasing current. For practical applications, continuous operation of such a device would clearly be a great advantage and it is an object of present research.

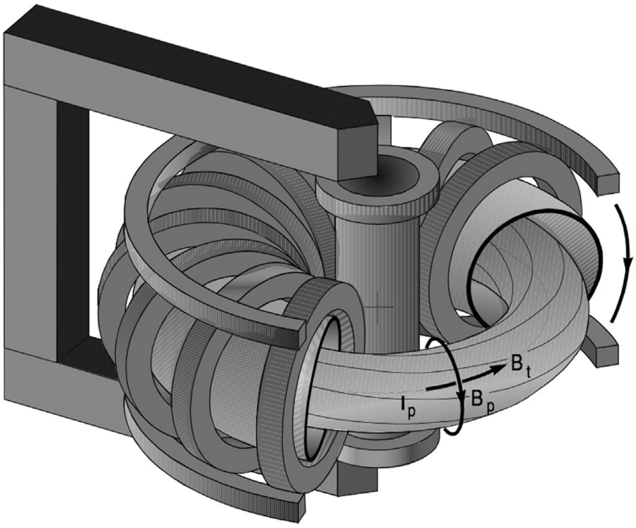

Fig. 1. Schematic representation of a tokamak. The main components are: (i) transformer (yokes and primary windings around the central column) to induce the plasma current; (ii) set of coils around the plasma vessel for the toroidal magnetic field; (iii) planar coils for the vertical field. The poloidal field associated with the plasma current adds to the toroidal field resulting in a helical field, needed for stability. The vertical field is needed to cope with hoop forces originating from the plasma current and the stored energy in the plasma.

One way to obtain continuous operation of a fusion device is to avoid the need for the (pulsed) plasma current. The stellarator exploits this idea by relying on currents external to the plasma. Extra helical coils around the toroidal plasma provide the necessary additional twist to the toroidal magnetic field generated by the main field coils. These helical windings around the plasma ring, however, complicate the construction of a stellarator. In addition, their presence renders the accessibility to the device more difficult than in the case of the tokamak. This is why the latest generation of stellarators is based on a new concept: a set of specially shaped coils (Fig. 2) generates the necessary twisted magnetic field configuration directly and eliminates the need for the extra helical coils. Owing to advanced research and calculational efforts, encouraging results are now obtained with stellarators of the current generation. Their performance, however, lags one or two generations behind that of the tokamak. Only research on larger stellarators will show whether these devices

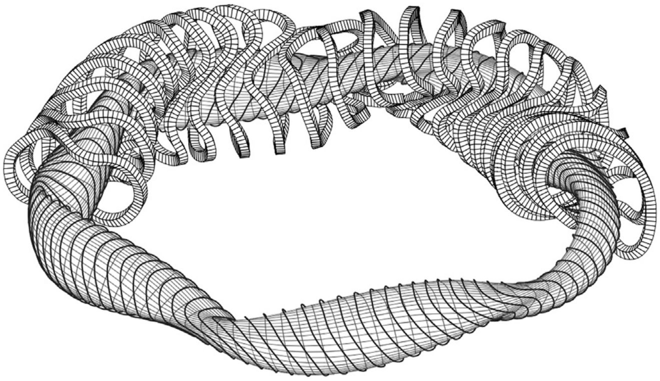

Fig. 2. The complex coil system used in a modern optimized stellarator like W7-X. The twisted plasma shape is also shown.

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