Preface

Since the late 1940s, researchers have used magnetic fields to confine hot, turbulent mixtures of ions and free electrons called plasmas so they can be heated to temperatures of 100–300 million kelvins (180–540 million degrees Fahrenheit). Under those conditions, positively charged deuterium nuclei (containing one neutron and one proton) and tritium nuclei (two neutrons and one proton) can overcome the repulsive electrostatic force that keeps them apart and "fuse" into a new, heavier helium nucleus with two neutrons and two protons. The helium nucleus has a slightly smaller mass than the sum of the masses of the two hydrogen nuclei, and the difference in mass is released as kinetic energy according to Albert Einstein's famous formula $E = mc^2$. The energy is converted to heat as the helium nucleus, also called an alpha particle, and the extra neutrons interact with the material around them.

Magnetic confinement fusion is an approach to generating fusion power that uses magnetic fields (which is a magnetic influence of electric currents and magnetic materials) to confine the hot fusion fuel in the form of a plasma. Magnetic confinement is one of two major branches of fusion energy research, the other being inertial confinement fusion. The magnetic approach is more highly developed and is usually considered more promising for energy production. Construction of a 500-MW heat-generating fusion plant using tokamak magnetic confinement geometry, the ITER, began in France in 2007.

Fusion reactions combine light atomic nuclei such as hydrogen to form heavier ones such as helium. In order to overcome the electrostatic repulsion between them, the nuclei must have a temperature of several tens of millions of degrees, under which conditions they no longer form neutral atoms but exist in the plasma state. In addition, sufficient density and energy confinement are required, as specified by the Lawson criterion.

Magnetic confinement fusion attempts to create the conditions needed for fusion energy production by using the electrical conductivity of the plasma to contain it with magnetic fields. The basic concept can be thought of in a fluid picture as a balance between magnetic pressure and plasma pressure or in terms of individual particles spiraling along magnetic field lines.

The pressure achievable is usually on the order of one bar with a confinement time up to a few seconds. In contrast, inertial confinement has a much higher pressure but a much lower confinement time. Most magnetic confinement schemes also have the advantage of being more or less steady state, as opposed to the inherently pulsed operation of inertial confinement.

The simplest magnetic configuration is a solenoid, a long cylinder wound with magnetic coils producing a field with the lines of force running parallel to the axis of the cylinder. Such a field would hinder ions and electrons from being lost radially, but not from being lost from the ends of the solenoid.

There are two approaches to solving this problem. One is to try to stop up the ends with a magnetic mirror, and the other is to eliminate the ends altogether by bending the field lines around to close on themselves. A simple toroidal field, however, provides poor confinement because the radial gradient of the field strength results in a drift in the direction of the axis.

An early attempt to build a magnetic confinement system was the stellarator, introduced by Lyman Spitzer in 1951. Essentially the stellarator consists of a torus that has been cut in half and then attached back together with straight "crossover" sections to form a Figure 8. This has the effect of propagating the nuclei from the inside to outside as it orbits the device, thereby canceling out the drift across the axis, at least if the nuclei orbit is fast enough. Newer versions of the stellarator design have replaced the "mechanical" drift cancelation with additional magnets that "wind" the field lines into a helix to cause the same effect.

In 1968 Russian research on the toroidal tokamak was first presented in public, with results that far outstripped existing efforts from any competing design, magnetic or not. Since then the majority of effort in magnetic confinement has been based on the tokamak principle. In the tokamak a current is periodically driven through the plasma itself, creating a field "around" the torus that combines with the toroidal field to produce a winding field in some ways similar to that in a modern stellarator, at least in that nuclei move from the inside to the outside of the device as they flow around it.

In 1991, START was built at Culham, UK, as the first purpose-built spherical tokamak. This was essentially a spheromak with an inserted central rod. START produced impressive results, with β values at approximately 40%—three times that produced by standard tokamaks at the time. The concept has been scaled up to higher plasma currents and larger sizes, with the experiments NSTX (United States), MAST (United Kingdom), and Globus-M (Russia) currently running. Spherical tokamaks have improved stability properties compared to conventional tokamaks, and as such, the area is receiving considerable experimental attention. However, spherical tokamaks to date have been at low toroidal field and as such are impractical for fusion neutron devices.

However, nuclear energy, either fission or fusion, is playing a vital role in the life of every man, woman, and child in the United States or around the world today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

This book takes a holistic approach to plasma physics and controlled fusion via magnetic confinement fusion (MCF) techniques, establishing a new standard for clean nuclear power generation. No prior knowledge of laser-driven fusion and no more than basic background in plasma physics is required.

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