A Brief, Nontechnical Survey of Magnetic Mirrors, their Shortcomings, and Modern Magnetic Confinement Fusion Reactors

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Nuclear fusion relies on combining light nuclei in a plasma. This plasma must be sufficiently confined to generate a surplus in energy, and the magnetic mirror was one of the original confinement concepts. It was determined that magnetic mirrors were infeasible due to plasma loss. Efforts to circumvent the shortcomings of the magnetic mirror led to more complex designs including tokamaks and stellarators.

Introduction

The goal of fusion research is to derive energy from the fusion of light nuclei, where the light nuclei usually consist of hydrogen isotopes (deuterium and tritium)[1]. For a fusion reaction to occur, two nuclei must be brought close enough to each other for the strong nuclear force to take over and fuse the two nuclei together. The challenge, however, is that these two nuclei are both positively charged, and thus they experience electrostatic (Coulomb) repulsion. To overcome the Coulomb repulsion, the collection of light nuclei is heated to high temperatures, so that some of the nuclei have enough thermal (kinetic) energy to overcome the Coulomb (potential) energy barrier. At such high temperatures, the collection of light nuclei usually exists in an ionized gaseous state called a *plasma*, which is a collection of unbound positively charged ions and unbound negatively charged electrons[2]. To generate substantial fusion power, the plasma must be confined long enough for a significant number of fusion reactions to occur. While large extraterrestrial objects can use gravity to accomplish confinement, realistic reactors on earth would need to utilize either magnetic confinement, where magnetic field lines prevent the plasma from expanding, or inertial confinement, where nuclear fuel is rapidly heated and compressed before it disassembles. (Note that wall confinement – plasma in contact with the container wall – is not practical, because plasma in contact with massive, cold walls rapidly cools and extinguishes the plasma.) One of the earliest magnetic confinement concepts is the magnetic mirror. We will discuss the magnetic mirror concept and explore one of its shortcomings. We will then examine two magnetic confinement designs (tokamaks and stellarators) that attempt to circumvent these shortcomings.

Magnetic Mirrors

Magnetic mirrors, sometimes called magnetic bottles, attempt to confine plasma with magnetic field coils, increasing the coil density (and thus the magnetic field strength) at the edges and decreasing it in the middle[3]. This creates magnetic field lines that ultimately resemble a football. This can be seen in Figure 1. Particles (ions and electrons) will travel along the field lines in a gyrating motion, circling the field lines. Upon reaching the edges of the bottle, some particles feel the mirror force F_m and get reflected back into the bottle. F_m is a result of the curved field lines. Only some of

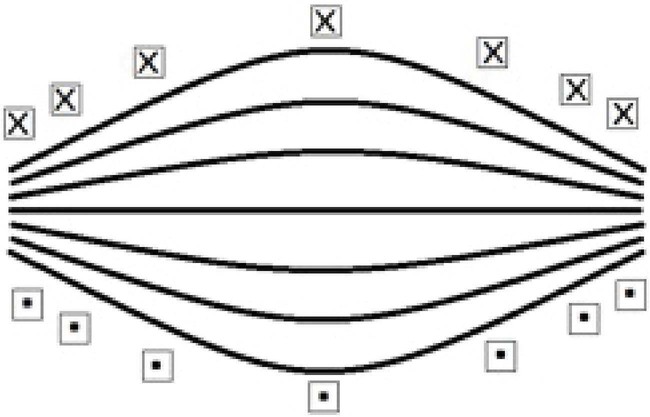

Figure 1. Field lines in a magnetic mirror design. The vertically-stacked boxes represent field coils with electrical currents going into the page at the top and coming out of the page at the bottom.

the particles are reflected because F_m only acts on particles with a velocity component $v_\perp$ perpendicular to the z-axis, the axis defined by the vector passing through the centers of the coils. This means that particles having only parallel components of velocity $v_{||}$ will not be reflected and will indeed escape the magnetic mirror. In fact, even particles with finite $v_\perp$ will escape the magnetic mirror if their $v_\perp$ values are too small. Experiments showed that the loss of plasma was too great to attain fusion conditions in magnetic mirrors. This led to the next generation of designs that attempted to mitigate the plasma loss.[4-6]

2.1 Torus-Shaped Magnetic Mirrors

An initial attempt to eliminate plasma loss through the ends of the magnetic mirror was to connect the ends and to adopt a toroidal design with a constant minor radius[7]. Here, coils of constant radius are used whereas coils of varying radius were used in the magnetic mirror.

The field lines in the torus adaptation are circular, having greater radius the farther they are from the center. This leads to two types of particle drifts: *curvature drift* due to centrifugal force and *grad-**B** drift* due to the decrease in magnetic field strength with increasing radius. The two drifts add together, and the resulting drift depends on particle charge. This means that ions and electrons drift in opposite directions. Subsequently, charge separation occurs and an electric field normal to the circular field lines is induced. This results in the "E-cross-B" drift, which acts on all particles the same way (i.e. independent of particle charge and mass). This means that both electrons and ions drift towards the wall of the torus. Upon contact with the wall, the plasma cools and there is a loss of confinement. Thus, a simple torus inherently cannot support plasma confinement.

Modern Magnetic Confinement Designs

Modern magnetic confinement designs are adaptations of the simple torus. In this section, the fundamental designs of tokamaks and stellarators are discussed and the major, current projects of each are described.

3.1 Tokamaks

In Section 2.1, we explained that the toroidal field lines caused a chain of events that resulted in loss of plasma confinement. Tokamaks attempt to overcome this obstacle by imposing helical field lines instead. The helical field is produced by superimposing poloidal and toroidal fields with poloidal and toroidal coils respectively. This can be seen in Figure 2.

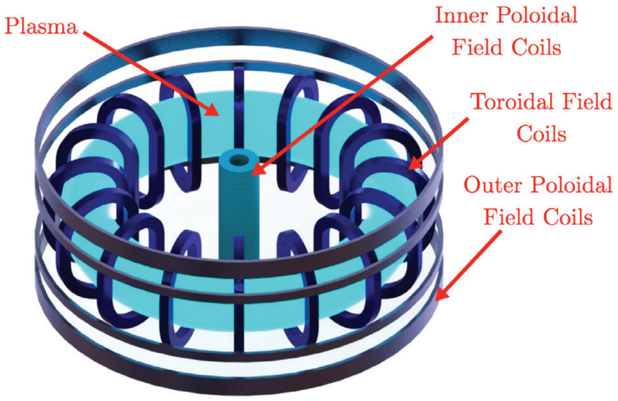

Figure 2. A rendering of a tokamak showing the poloidal and toroidal field coils.

ITER is the International Thermonuclear Experimental Reactor (and means "the way" in Latin)[8]. As its name may imply, it is an international collaboration between the United States, European Union, India, Japan, China, Russia, and South Korea, and the device is in France. It is the largest tokamak in the world, although its construction has not been completed. Construction is expected to finish in 2021 and the first plasma experiments are expected to start in 2025.

3.2 Stellarators

While tokamaks use two types of field coils to obtain helical field lines, stellarators are founded on using only one type of field coil. To accomplish this, the field coils are twisted and are very complex, and this can be seen in Figure 3. Subsequently, the plasma also becomes twisted and axial symmetry is lost (whereas the symmetry is maintained in tokamaks).

In tokamaks, the inner poloidal field coils must be pulsed which means that the confinement scheme is not continuous, whereas stellarators can be operated continuously. A drawback of the complex field coils is that they are much more expensive.

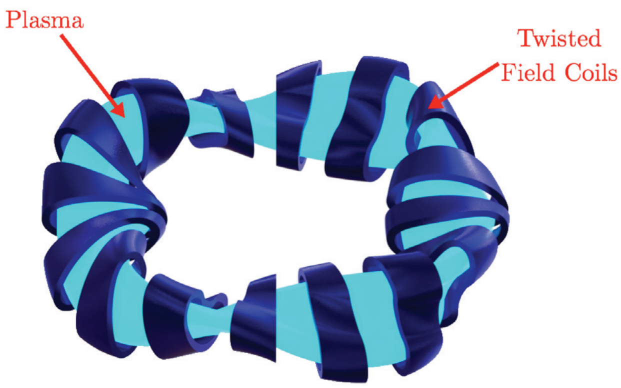

Figure 3. A rendering of a stellarator showing the twisted field coils and the resulting plasma shape.

The most advanced and largest stellarator experiment in the world is the Wendelstein 7-x located at the Max Planck Institute of Plasma Physics in Germany[9]. Construction was completed in 2015 and experiments producing 30 continuous minutes of plasma are expected by the early 2020s.

Summary

The future of fusion energy relies on the proper confinement and sufficient heating of plasmas. Several experiments with magnetic confinement have found that simple magnetic mirror designs do not properly confine plasmas, resulting in too much plasma loss to sustain fusion. Tokamaks and Stellarators (e.g. ITER and Wendelstein 7-x respectively) are modern magnetic confinement designs that aim to accomplish the plasma confinement that magnetic mirrors could not.

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