2 Fusion Concepts

Good ideas are not adopted automatically.
They must be driven into practice with courageous patience.

– Admiral Hyman G. Rickover

Magnetic Bottles

Early efforts to produce and control fusion reactions were based on then well-known principles of electromagnetic theory. A current passing through a gas was known to strip electrons from the gas atoms (ionization), to raise its temperature, and to produce a magnetic field surrounding the current. Raising the current increased the degree of ionization, the temperature, and the magnetic field strength. The magnetic field exerts a confining force on the column of ionized gas (dubbed "plasma" in a 1928 paper by Irving Langmuir), and as the current and magnetic field is raised, the column of plasma is compressed, raising its density and further raising its temperature. This was known as the "pinch effect" and was the basis of most of the early attempts to produce fusion conditions in the laboratory. The "pinch effect" had been predicted in 1934 by W. H. Bennett and, independently, in 1937 by Lewi Tonks, but little subsequent effort was devoted to pinch plasma properties in the 1930s. Later, pinch devices were fashioned into what came to be called "magnetic bottles" for the plasma. In the 1950s, some of these "magnetic pinch" devices studied for fusion were linear in geometry, and some were donut-shaped (toroidal). They went by a variety of sometimes-colorful names: Perhapsatron and Columbus at Los Alamos and Zeta in the UK [2].

Pinches had serious problems, however. It was observed that, as the plasma column was pinched, the plasma twisted and moved in "unstable" fashion and quickly hit the walls of the chamber. A variety of such "instabilities" were observed in the various pinch configurations, receiving names such as "kink instability" and "sausage instability." Figure 2.1 illustrates a linear pinch configuration (a) before any instabilities develop and (b) with a kink instability which disrupts the discharge. Figure 2.2 illustrates a toroidal pinch configuration. Much of the first two decades

S.O. Dean, *Search for the Ultimate Energy Source: A History of the U.S. Fusion Energy Program*, Green Energy and Technology, DOI 10.1007/978-1-4614-6037-4_2,

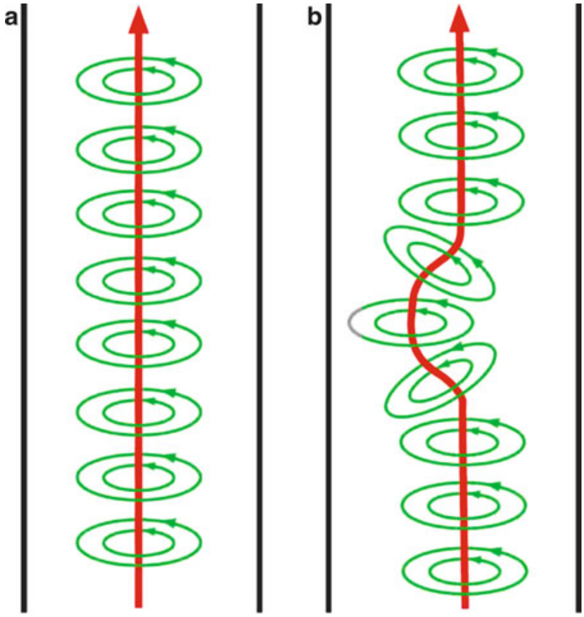

Fig. 2.1 Linear pinch. A current (*red line*) is driven through a gas in a cylindrical chamber, creating a plasma. Currents have magnetic lines of force surrounding them. If the current is increased, the magnetic force becomes stronger, compressing and heating the plasma (**a**). But if a slight asymmetry develops, the force becomes unbalanced, resulting in a "kink instability" (**b**), which drives the plasma into the wall of the chamber where it is cooled and lost (US Atomic Energy Commission; Amasa Bishop, *Project Sherwood*, Addison-Wesley Publishing Company, 1958)

of fusion research was devoted to developing an understanding of these and related instabilities, all belonging to a class to be known as Magnetohydrodynamic (MHD) instabilities or macroscopic instabilities.

It was early recognized that plasma would rapidly leak out the ends of a linear magnetic bottle unless something was done to "plug" the ends. One "solution" already mentioned is the toroidal configuration (which has no "ends"). Another "solution" emerged in the form of strengthening the magnetic field at either ends of the linear configuration. This geometry came to be known as the "magnetic mirror" configuration (Fig. 2.3) and was championed in the USA by Richard F. Post and colleagues at the University of California's Livermore Laboratory [7]. While magnetic mirrors have been largely written-off as fusion power plants, due to the still rapid loss of plasma out the ends while controlling radial transport, there is still belief in some quarters that they could experience a resurgence [8, 9]. If so, they would have attractive power plant features, including simple geometry for maintenance and the potential for more efficient energy conversion, e.g., avoidance of the conventional heat-to-steam-to-electricity cycle.

Another early variant of the toroidal magnetic bottle was invented by Princeton University astrophysicist Lyman Spitzer while riding the ski lifts in Aspen. He asked himself how one might contain on Earth a plasma similar to that existing in stars. He envisioned a magnetic configuration he called the "stellarator" since it was designed to contain a man-made equivalent of a star on Earth. It was similar in some respects to the toroidal pinch configuration but differed in that external magnets produced the primary confining magnetic field rather than a current in the plasma. Even in this case, however, the plasma had many surprises in store for the researchers.

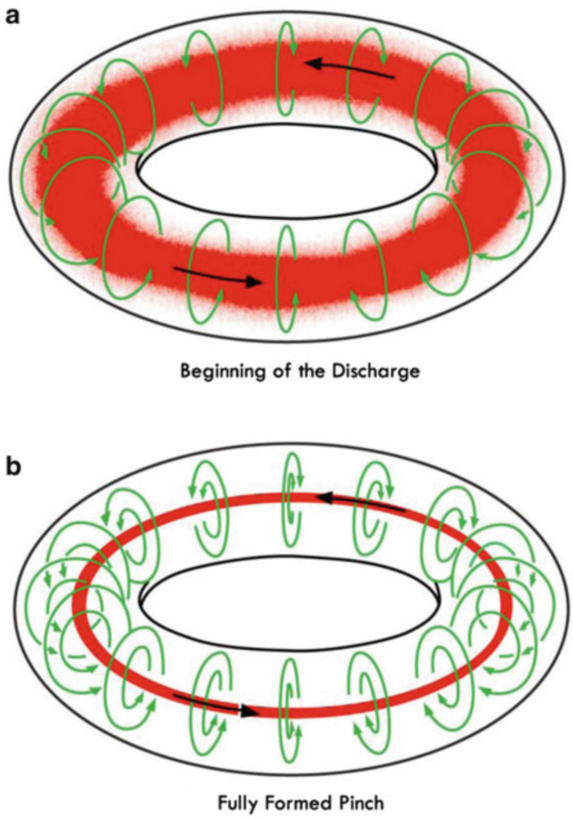

Fig. 2.2 Toroidal pinch. Instabilities (not shown) similar in nature to those seen in linear pinches are present also in toroidal configurations (US Atomic Energy Commission; Amasa Bishop, *Project Sherwood*, Addison-Wesley Publishing Company, 1958)

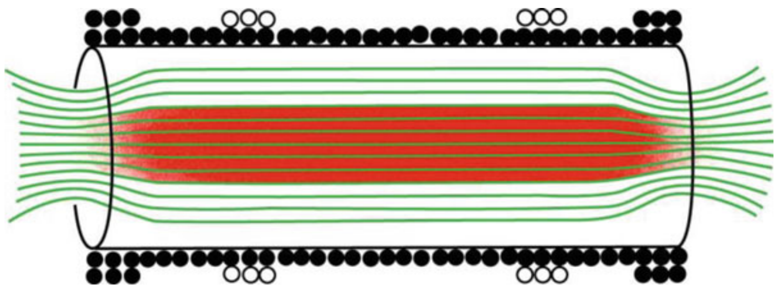

Fig. 2.3 Magnetic mirror configuration: stronger magnetic field strength at ends hampers loss of fusion plasma (US Atomic Energy Commission; Amasa Bishop, *Project Sherwood*, Addison-Wesley Publishing Company, 1958)

These, more subtle, types of plasma loss mechanisms in the stellarator geometry came to be known as "microinstabilities" and are still the subject of active research. The stellarator is still a promising configuration for fusion plasma confinement, although the magnets needed to provide the magnetic field properties necessary to suppress instabilities have become increasingly complex to manufacture. Figure 2.4

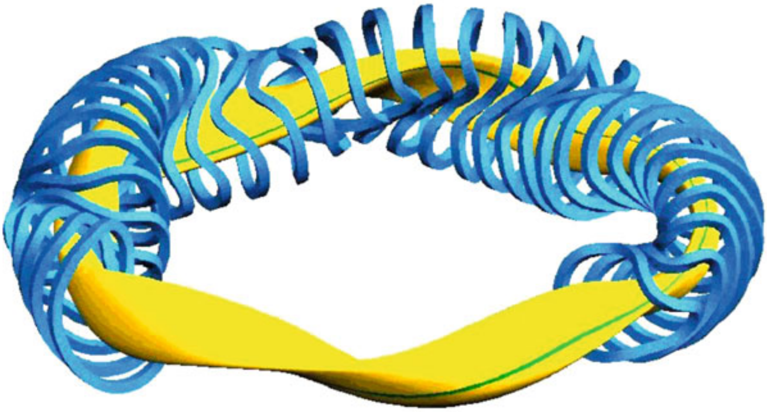

Fig. 2.4 Schematic of W7X stellarator plasma and magnets under construction in Greifswald, Germany. The complex shape of the plasma and magnet coils are believed necessary to provide the desired stability and confinement of the plasma in a stellarator (Max-Planck-Institut fur Plasmaphysik (IPP) in Greifswald)

shows a schematic of a modern stellarator with its complex magnet coils surrounding what is predicted to be a stable plasma.

As part of the Atoms for Peace initiatives of the late 1950s, and as scientists realized the extreme complexity of plasma behavior in fusion experiments, the USA, the UK, and the Soviet Union agreed to remove the veil of secrecy that had surrounded their fusion research efforts and to present their research programs at the Second United Nations Geneva Conference on the Peaceful Uses of Atomic Energy, in Geneva, in 1958. Thus began a spirit of friendly competition and cooperation among fusion scientists worldwide that has lasted to the present day. At the Geneva conference, the Soviets described experiments in which the toroidal pinch geometry was supplemented by fields provided by external magnets. In some ways, the geometry resembled a marrying of the pinch and stellarator ideas being studied separately elsewhere. One version of this configuration that evolved during the 1960s was called tokamak (from Russian words meaning toroidal magnetic chamber). By the late 1960s, this configuration showed dramatic improvement in confining the plasma compared to other geometries. A worldwide shift to this configuration began after the 1968 fusion conference sponsored by the International Atomic Energy Agency (IAEA) in Novosibirsk. The tokamak configuration, shown schematically in Fig. 2.5, now dominates world fusion research.

During the 1970s and 1980s, tokamaks capable of creating "near-breakeven" conditions (in which the fusion energy released approximately equals the energy content of the plasma) were constructed and successfully operated in the USA, Europe, and Japan. The experience gained from these and other tokamaks around the world has led to initiation of the International Thermonuclear Experimental Reactor (ITER) being constructed in France as a joint venture of the European Union and six other country partners and currently scheduled to begin operation about 2020.

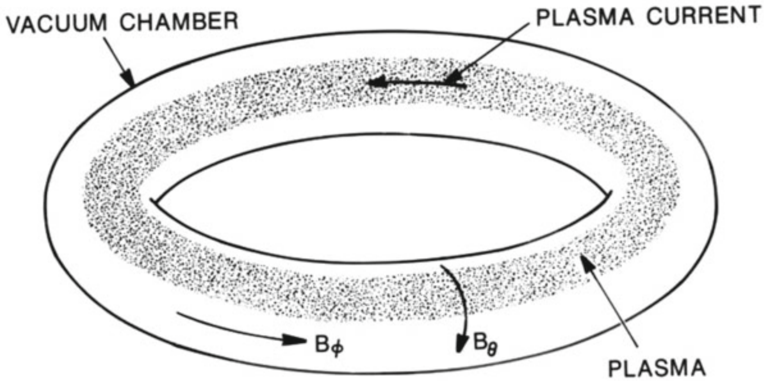

Fig. 2.5 Schematic of tokamak magnetic configuration. Plasma current produces the magnetic field B_θ shown surrounding the plasma, as in the pinch configuration, and magnet coils (not shown) add an additional magnetic field B_ϕ around the torus

Inertial Confinement: Microexplosions

The invention of the laser in 1960 gave rise to a whole new approach to fusion called "inertial confinement fusion." The hydrogen bomb showed that fusion could be initiated by a sufficiently strong compressive force exerted on a small amount of fusion fuel. In the case of the bomb, this force was provided by a fission-based atomic bomb surrounding the fusion fuel. In the 1960s, scientists in and outside the weapons laboratories began to speculate on whether a fusion reaction of practical interest could be initiated by focusing a high-power laser on a small capsule containing fusion fuel. A schematic of this process is shown in Fig. 2.6. Its pioneers compiled a history in 2007 [10]. The early studies showed that, while inertial fusion was theoretically possible, lasers far beyond those available at the time would be required.

Larger and larger lasers were built during the 1970s and 1980s, culminating in the National Ignition Facility (NIF), located at the Lawrence Livermore National Laboratory in California. This 192-beam laser, which began operation in mid-2009, is designed to produce a net output of fusion energy compared to the laser energy required to initiate the fusion reaction. A similar laser is under construction in France, scheduled to be completed in 2014.

In addition to lasers, other forms of pulsed power (ion beams, z-pinch) are potential "drivers" for compressing fusion pellets and are being pursued, e.g., at Lawrence Berkeley National Laboratory, Sandia National Laboratories, and elsewhere.

Other Concepts

The plasma "likes" the "closed" magnetic field geometry of stellarator and tokamak configurations, which provide relatively good plasma confinement. Unfortunately, this physics advantage comes with an engineering disadvantage. The donut-shaped

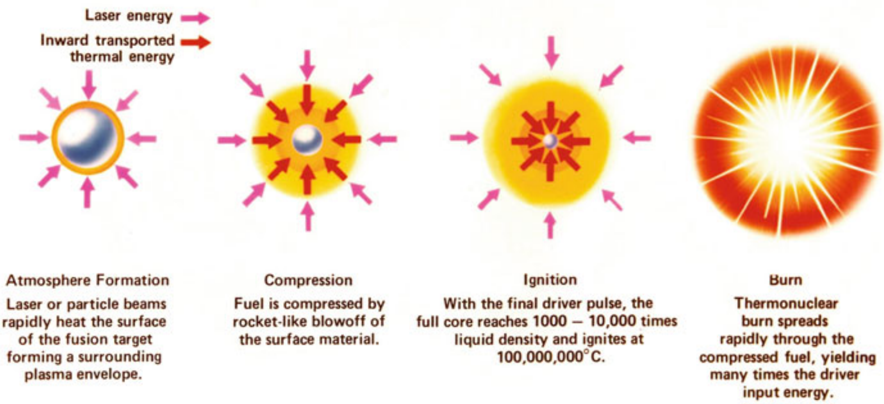

Fig. 2.6 Schematic of inertial confinement fusion (ICF) using a laser or other driver. Energy impinges on a capsule containing fusion fuel, and the resulting compression produces the high density and temperature required to initiate fusion reactions (Lawrence Livermore National Laboratory)

toroidal vessel has a hole in the center, which makes access difficult for maintenance. Neutrons from the fusion reactions also converge inwards, so that materials on the inner section of the vessel may have to be replaced frequently. The ideal geometry for a fusion power plant, from an engineering and maintenance viewpoint, would be one in which the vessel is cylindrical (or perhaps spherical) with the plasma at the center so that all maintenance could be performed from the outer periphery. Several configurations have been identified and studied with this property, including the field reversed concept (FRC) (Fig. 2.7) and the Spheromak. Several investigators are pursuing fusion concepts in which, using an FRC plasma as a starting point, the FRC is manipulated in various ways, e.g., compressed, sustained by beams, translated, and confined.

One of the most advanced concepts incorporating an FRC plasma is magnetized target fusion (MTF), or magneto-inertial fusion (MIF), being pursued at the Los Alamos National Laboratory, Sandia National Laboratories, General Fusion, and elsewhere. In this concept, an FRC plasma is formed either in situ or translated in space to a cylindrical chamber that is surrounded by a conducting shell that is then imploded onto the plasma, compressing and heating it (Fig. 2.8). Of the MTF concept, Freidberg notes [11] that it "offers a true alternative to conventional magnetic fusion concepts, and in this context is certainly worth examining as a potential source of fusion energy." Other variations, similar to the FRC, include the spheromak [12] and the use of an FRC to confine a beam of colliding ions [13] (See also [14]). The private company TriAlpha in California is pursuing the latter.

The company EMC2, founded by Robert W. Bussard, is currently exploring another concept, called inertial electrostatic confinement (IEC). IEC was originally conceived by Philo T. Farnsworth, the inventor of television, and then pursued by Robert L. Hirsch. Later, Bussard would become a major advocate of IEC. In addition to Bussard, aspects of IEC have also been explored by scientists, including Nicholas Krall (consultant), George Miley (University of Illinois), and Gerald

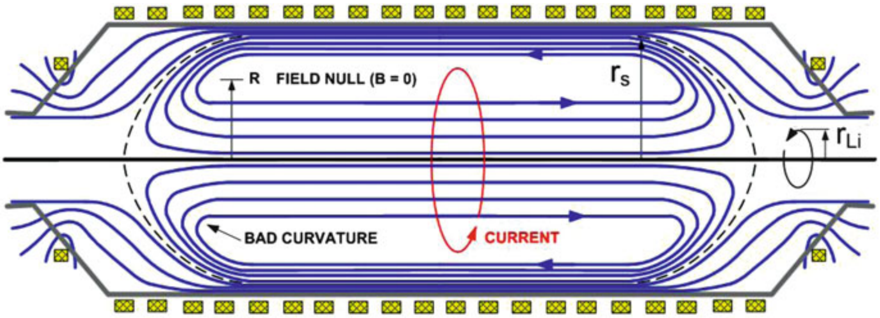

Fig. 2.7 Schematic of field reversed concept (FRC). This configuration combines the advantage of having closed magnetic field lines (as in a torus) with the advantage of having a simpler linear cylindrical vessel (as in a magnetic mirror) (Francis F. Chen, *An Indispensable Truth*, Springer)

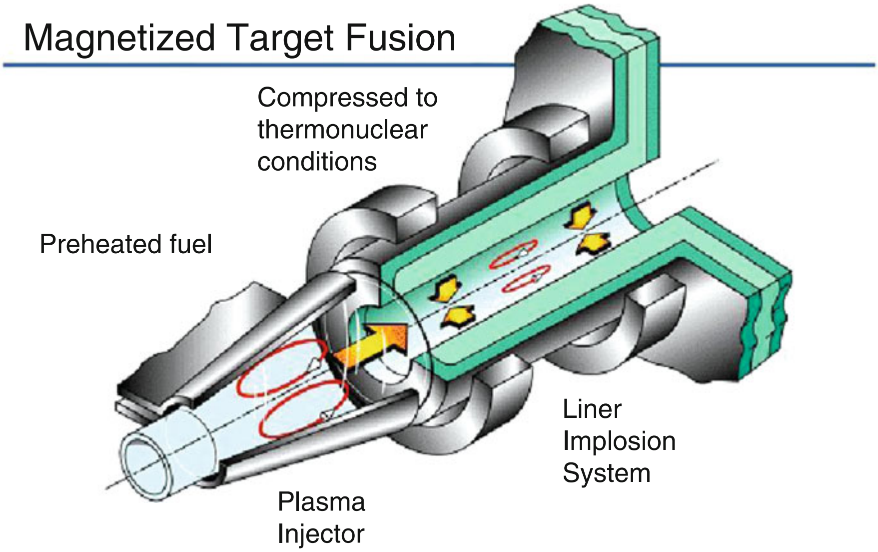

Fig. 2.8 In magnetized target fusion (MTF), a plasma is preheated slightly and injected into a chamber; the walls of the chamber ("liner") are then imploded inwards, compressing the plasma to fusion conditions (Los Alamos National Laboratory)

Kulcinski (University of Wisconsin). IEC has been shown to be a good point source of fusion neutrons for some applications, but its scaling to fusion reactor conditions is still uncertain.

While each of these "other" concepts has attractive power plant characteristics, a "breakthrough" demonstration equivalent to the tokamak has eluded the advocates of these concepts, at least in the small-scale experimental facilities available to them. It remains to be seen whether the attractive features of these concepts can be validated in future facilities. Unfortunately, with limited resources, government managers of the world fusion programs have felt constrained to restrict funding for these "alternate" (to the tokamak) concepts.

http://www.springer.com/978-1-4614-6036-7

Search for the Ultimate Energy Source
A History of the U.S. Fusion Energy Program
Dean, S.O.
2013, XVI, 264 p., Hardcover
ISBN: 978-1-4614-6036-7