1

Characteristics of the Fusion Reactor

Many kinds of nuclear fusion reactions and plasma confinement concepts can be considered in fusion reactors. This chapter shows the characteristics of the fusion reactor.

1.1 The Fusion Reactor as an Energy Source

1.1.1 Trends in World Energy Consumption

Energy is necessary for humankind to live and work. Human beings have established a civilized society by developing and utilizing energy sources. Figure 1.1-1 shows the transition of world energy consumption by fuel. The world energy consumption increases as the population increases and the economy grows; these are expected to further increase in the future. Meanwhile, with the increase in the use of fossil fuels such as coal, oil, and natural gas, carbon dioxide emissions have greatly increased, causing environmental problems such as air pollution and global warming. For the future survival and growth of human beings, it is important that the increase in energy consumption and countermeasures to environmental problems are compatible.

1.1.2 Energy Classification

Energy taken from nature is called primary energy, and energy converted into a form that makes primary energy easy to use is called secondary energy. Table 1.1-1 shows the classification of energy.

Primary energy includes fossil energy from fossil fuels (coal, oil, natural gas, shale oil, shale gas, methane hydrate, etc.), nuclear fission energy from non-fossil fuels, hydroelectric power energy, and renewable energy (hydroelectric power, solar light, wind power, geothermal power, solar heat, heat existing in nature such as atmospheric heat, biomass, etc.). Hydroelectric power, a form of renewable energy, is particularly targeted at the small and medium scale. Secondary energy includes electricity generated, oil products, gas products, heat, etc. Secondary energy is delivered and consumed as final energy. Final energy can be categorized as electric power and fuel. Electric power, as final energy, is discussed here.

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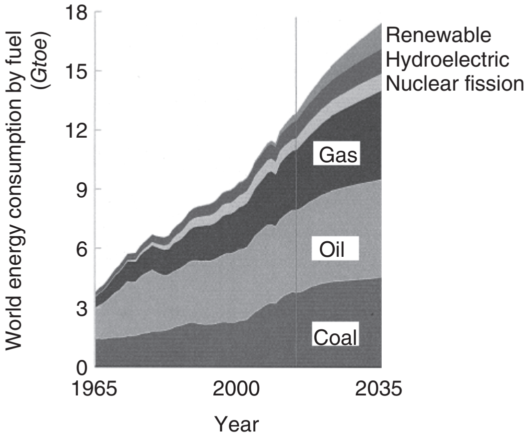


Figure 1.1-1 Transition of world energy consumption by fuel (Gtoe: giga toe; toe: tonne of oil equivalent). Source: Ref. [1]. © 2015 BP p.l.c.

Although thermal power that combusts fossil fuels can be stably supplied on a large scale, a large amount of carbon dioxide is generated during the power generation process. The development of processes to control this carbon dioxide emission is ongoing. Continuous consumption of fossil fuels will result in depletion of the resource in the future. Further efforts are needed to extend minable years.

Nuclear fission power can be generated and supplied stably on a large scale. The fuel supply capacity is comparable to that of fossil fuels, and carbon dioxide emission is minimal. In addition, social acceptability of issues such as safety, disposal of radioactive waste, management of plutonium, etc. is important.

Hydroelectric power generation (large scale) has low carbon dioxide emission, but there is a geographical restriction and less room for development. Renewable energy also has low carbon dioxide emission, but it is important to mitigate the effects of climate and sunshine hours. Therefore, considering the characteristics of these energies, it is important to make a properly combined power supply configuration (energy mix).

1.1.3 Nuclear Fusion Power Generation

The nuclear fusion reactor is roughly categorized by the type of fusion reaction to be used, namely, the first-generation DT reactor, the second-generation DD reactor, and the third-generation $p^{11}B$ (proton-boron) reactor and D^3He reactor. In the first-generation reactor, deuterium (D) and tritium (T) are used as fuels. Deuterium is an abundant and almost inexhaustible resource available in seawater. Tritium is rare in nature, and therefore, it needs to be generated by the reaction between lithium and neutrons generated from the fusion reaction. Lithium can be recovered from seawater beside lithium mines. Therefore, it can be said that the nuclear fusion reactor has abundant resources as a fundamental alternative energy source.

Also, nuclear fusion power generation has no carbon dioxide emissions. In the case of a DT reactor, tritium, which is a radioactive material, is used. Since neutrons are generated in the reaction, the reactor structural material is activated and radioactive waste is required to be disposed. The radioactive waste generated is all low level.

Table 1.1-1 Classification of energy.

Primary energy		Secondary energy	Final energy
Fossil energy	Coal Oil Natural gas	Thermal power generation	Electric power
Nuclear fission energy		Nuclear fission power generation	
Hydroelectric power energy		Hydroelectric power generation (large scale)	
Renewable energy	Hydroelectric power	Hydroelectric power generation (small/medium scale)	
	Solar light	Photovoltaic power generation	
	Wind power	Wind power generation	
Fossil energy	Coal	Coal fuel	Fuel
	Oil	Oil fuel	
	Natural gas	Gas fuel	
Renewable energy	Solar heat Biomass Geothermal	Heat, steam	

The issue of activation is further reduced because neutron energy produced in the second generation is smaller than in the first and no neutron is generated in the third (see Section 1.2.1).

Currently, nuclear fusion power generation is in the development stage with an experimental reactor. Fusion power generation has a high possibility of providing a stable, large-scale supply. There is a high possibility that it will become the key energy source in the power supply configuration.

1.2 Nuclear Fusion Reaction

1.2.1 Nuclear Reaction Used in the Fusion Reactor

Nuclear fusion is the fusion of atomic nuclei of certain elements. When the atomic nuclei are brought close to each other, they electrostatically repel each other. When colliding with a force greater than its repulsive force, the nuclear force works and the nuclei fuse together. In various nuclear fusion reactions used as energy sources, the repulsive force between nuclei needs to be small; that is, the nuclear fusion reaction occurs at low energy, the reaction cross section is large, and the reaction is exothermic. The nuclear fusion reactions currently considered are as follows:

$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \rightarrow ^{3}_{2}\mathrm{He}(0.82\mathrm{MeV}) + ^{1}_{0}\mathrm{n}(2.45\ \ \mathrm{MeV}), \tag{1.2-1}$$

$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \rightarrow ^{3}_{1}\mathrm{T}(1.01\ \ \mathrm{MeV}) + ^{1}_{1}\mathrm{p}(3.03\ \ \mathrm{MeV}), \tag{1.2-2}$$

$$^{2}_{1}\mathrm{D} + ^{3}_{1}\mathrm{T} \rightarrow ^{4}_{2}\mathrm{He}(3.52\,\mathrm{MeV}) + ^{1}_{0}\mathrm{n}(14.06\ \ \mathrm{MeV}), \tag{1.2-3}$$

$$^{2}_{1}\mathrm{D} + ^{3}_{2}\mathrm{He} \rightarrow ^{4}_{2}\mathrm{He}(3.67\ \ \mathrm{MeV}) + ^{1}_{1}\mathrm{p}(14.67\ \ \mathrm{MeV}), \tag{1.2-4}$$

$$^{2}_{1}\mathrm{D} + ^{6}_{3}\mathrm{Li} \rightarrow 2^{4}_{2}\mathrm{He}(22.4\ \ \mathrm{MeV}), \tag{1.2-5}$$

$$^{1}_{1}\mathrm{p} + ^{7}_{3}\mathrm{Li} \rightarrow 2^{4}_{2}\mathrm{He}(17.3\ \ \mathrm{MeV}), \tag{1.2-6}$$

$$^{1}_{1}\mathrm{p} + ^{6}_{3}\mathrm{Li} \rightarrow ^{3}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He} + 4.0\ \ \mathrm{MeV}, \tag{1.2-7}$$

$$^{1}_{1}\mathrm{p} + ^{11}_{5}\mathrm{B} \rightarrow 3^{4}_{2}\mathrm{He} + 8.7\ \ \mathrm{MeV}, \tag{1.2-8}$$

where $^{2}_{1}\mathrm{D}$ is deuterium, $^{3}_{1}\mathrm{T}$ is tritium, $^{1}_{1}\mathrm{p}$ is proton, $^{1}_{0}\mathrm{n}$ is neutron, and $^{4}_{2}\mathrm{He}$ is helium (α particle).

In order to cause these reactions, a method of injecting particles accelerated by an accelerator to solid or gas targets can be considered. But this method mostly causes elastic scattering between accelerated particles and extranuclear electrons of target particles. Since the number of particles to be accelerated is limited, a large nuclear fusion reaction may not be expected. Therefore, the method considered involves, as a whole, a mixture of ions and electrons that are electrically neutral; that is, a plasma is formed and confined in a certain space, and the temperature is raised to cause the fusion reaction. In this method, since the collision frequency increases, there is a high possibility of a fusion reaction. Since it uses high temperature and thermal motion, this reaction is called a thermonuclear fusion reaction.

Nuclear fusion reactions occur in the Sun. It is not possible to allow unlimited release of energy through fusion reactions on the Earth. In order to generate power using the nuclear fusion reaction, it is essential to control the reaction so that it gradually occurs within a limited space. This is why the reaction is called a controlled thermonuclear fusion reaction.

1.2.2 Cross Section of the Fusion Reaction

As described above, the nuclear fusion reaction occurs in the collision process between particles of the plasma in a thermal equilibrium state. In general, the likelihood of occurrence of the collision process is expressed using a cross section. The collision cross section when the particle beam is injected into the target is defined as $\sigma =$ (number of collisions occurring per target particle per unit time)/(injected particle beam intensity).

Figure 1.2-1 shows a schematic diagram of beam injected into a target. Let us consider the case where the particle beam with density n, velocity v, and beam cross section S is injected into a thin plate with thickness Δx containing target particles of density N. The intensity of the injected particle beam is nv. Let Δn be the decrease in

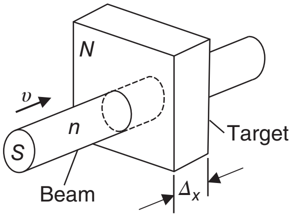


Figure 1.2-1 Schematic diagram of beam injected into a target.

beam particle density due to collision. This decrease occurs due to deflection of the beam due to Coulomb scattering and nuclear reaction. It is assumed that the cross section required here includes all effects.

The volume at which the beam particle intersects the target is $S\Delta x$. The number of target particles in the volume is $NS\Delta x$. The time for the beam particles to pass through this region is $\Delta x/v$, and the number of collisions occurring during that time is $\Delta nS\Delta x$ in this region. Therefore, since the number of collisions occurring per target particle per unit time is $\Delta nS\Delta x/(\Delta x/v)/(NS\Delta x)$, the collision cross section becomes

$$\sigma = \frac{\Delta nS\Delta x/(\Delta x/v)/(NS\Delta x)}{nv} = \frac{\Delta n}{Nn\Delta x}. \tag{1.2-9}$$

Let $n(x)$ be the injected particle density after passing through the target material by the distance x. A negative sign is added to the decrement of the particle density of the beam in Eq. (1.2-9). Then it becomes

$$\frac{dn}{dx} = -\sigma Nn. \tag{1.2-10}$$

When it is integrated, it becomes

$$n(x) = n_0 \exp(-\sigma Nx), \tag{1.2-11}$$

where n_0 is the particle density before being injected into the target. Notation barn ($=10^{-24}\mathrm{cm}^2$) is used as the unit of collision cross section. When the macroscopic cross section is represented by $\Sigma = \sigma N$, the mean free path of the beam is $\ell = 1/\Sigma$.

The typical fusion reaction cross sections obtained by experiment are shown in Figure 1.2-2 [2]. The DD reaction shows the sum of the cross sections of Eqs. (1.2-1) and (1.2-2). In the experiment, one particle is fixed in the laboratory and the other particle is injected to obtain the cross section. The DT reaction has a larger cross section from a lower energy region than other reactions. For this reason, the first-generation realization of a fusion reactor using the DT reaction is being pursued.

1.2.3 Fusion Reaction Rate

To obtain the power of a nuclear fusion reaction, it is convenient to use the fusion reaction rate R representing the number of reactions occurring per unit volume and unit time. When considering the collision between plasma particles in thermal equilibrium, Eq. (1.2-9) is not directly used and the average operation in the velocity space is necessary, since the plasma particles are not at a single velocity.

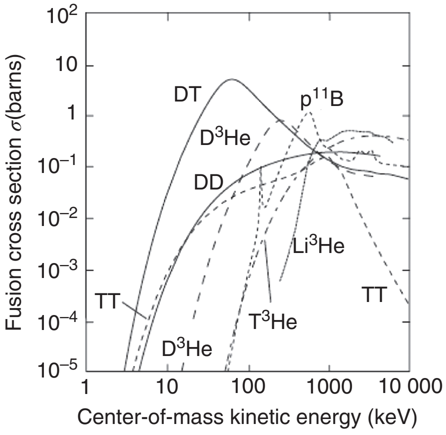


Figure 1.2-2 Cross sections of fusion reactions. Source: Atzeni and Meyer-ter-Vehn [2]. © 2004 Oxford University Press.

Let n_1, $\mathbf{v}_1$, and $f_1(\mathbf{v}_1)$ be the density, velocity, and velocity distribution function of the beam particles and n_2, $\mathbf{v}_2$, and $f_2(\mathbf{v}_2)$ be the density, velocity, and velocity distribution function of the target particles, respectively. When particles with density $dn_1 = n_1 f_1(\mathbf{v}_1)d\mathbf{v}_1$ included in volume element $d\mathbf{v}_1$ of velocity space collide with particles with density $dn_2 = n_2 f_2(\mathbf{v}_2)d\mathbf{v}_2$ contained in volume element $d\mathbf{v}_2$ of velocity space at relative velocity $\mathbf{v}_r = \mathbf{v}_1 - \mathbf{v}_2$, the number of collisions occurring in unit time, dR, becomes

$$dR = dn_1\, dn_2 \sigma(v_r) v_r, \tag{1.2-12}$$

where $v_r = |\mathbf{v}_r|$.

When Eq. (1.2-12) is integrated in the velocity space, the reaction rate in the unit volume of the plasma and unit time is obtained as

$$R = n_1 n_2 \langle \sigma v_r \rangle. \tag{1.2-13}$$

Here, the fusion reactivity is given by

$$\langle \sigma v_r \rangle = \int_{\mathbf{v}_1} d\mathbf{v}_1 \int_{\mathbf{v}_2} d\mathbf{v}_2 \sigma(v_r) v_r f_1(\mathbf{v}_1) f_2(\mathbf{v}_2). \tag{1.2-14}$$

A velocity distribution function of thermal equilibrium is used to obtain $\langle \sigma v_r \rangle$. Going forward, this is simply denoted by $\langle \sigma v \rangle$.

In the DT reaction, since the reaction energy $E_f = 17.6$ MeV is given by Eq. (1.2-3), the nuclear fusion power output generated per plasma volume is

$$P_f = n_{\mathrm{D}} n_{\mathrm{T}} \langle \sigma v \rangle_{\mathrm{DT}} k E_f. \tag{1.2-15}$$

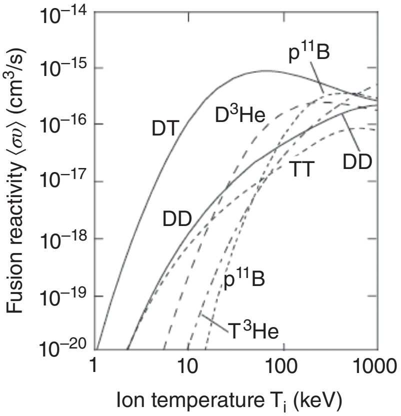
Here, n_{D} and n_{T} are the densities of D and T, respectively, and $k = 1.60 \times 10^{-19}$ J/eV, $1\ \mathrm{eV} = 1.60 \times 10^{-19}\ \mathrm{J} / (1.38 \times 10^{-23}\ \mathrm{J/K}) = 1.16 \times 10^4$ K.

The fusion reactivity is shown in Figure 1.2-3 [2]. When the plasma temperature in the fusion reactor using DT reaction is near 10–30 keV, $\langle \sigma v \rangle_{\mathrm{DT}}$ can be approximated to

$$\langle \sigma v \rangle_{\mathrm{DT}} = 1.1 \times 10^{-24} T_{i\mathrm{keV}}^2\ (\mathrm{m}^3/\mathrm{s}). \tag{1.2-16}$$

Here, $T_{i\mathrm{keV}} = T_i/1000$ is in the unit of keV [3].

Figure 1.2-3 Fusion reactivity. Source: Atzeni and Meyer-ter-Vehn [2]. © 2004 Oxford University Press.



1.3 Plasma Confinement Concept

Plasma is an electrically almost neutral ionized gas consisting of ions and electrons. When plasma is confined in a container such as metal, it hits the container wall and becomes a neutral gas. Therefore, various plasma confinement concepts have been proposed as listed in Table 1.3-1.

The confinement concepts are divided into magnetic confinement, which uses a magnetic field, and inertial confinement in which the plasma inertia confines the plasma before it starts to expand.

1.3.1 Magnetic Confinement

The magnetic confinement concepts have a linear system (open-end system) and a toroidal system.

1.3.1.1 Linear System (Open-End System)

The simplest of the open-end systems is the simple mirror. As shown in Figure 1.3-1, it consists of two circular coils, and current flows in the same direction. In this case, there is an end loss from the open end of the magnetic mirror that the plasma leaves along the magnetic field lines [4]. The tandem mirror is an improvement of the simple mirror. As shown in Figure 1.3-2, the end loss can be suppressed by arranging the coils in tandem [5].

In the cusp field of Figure 1.3-3, currents flow in two circular coils in the opposite direction. A zero point in the magnetic field is called the minimum magnetic field. This also has plasma end loss. In the ϑ pinch, a plate-shaped coil is wrapped around a cylindrical container, and a large current is instantaneously flowed in this coil to induce a magnetic field, in which plasma is confined as shown in Figure 1.3-4.

The ratio of the magnitude of the magnetic field at both ends of the mirror magnetic field and the one at the center of the device is called the mirror ratio. As this ratio becomes larger, more particles are reflected at both ends and confined well. The yin-yang coil is a coil made to increase the mirror ratio.

Table 1.3-1 Plasma confinement concepts.

Classification				**Concepts**
Magnetic confinement	Linear system (open-end system)			Simple mirror, tandem mirror
				Cusp
				ϑ pinch
	Toroidal system	No rotational transform system		Field reversed mirror (FRM)
				Field reversed configuration (FRC)
		Rotational transform system	Axisymmetric system	Tokamak
				Spherical torus
				Spheromak
				Reversed field pinch (RFP)
				Internal conductor system
			Non-axisymmetric system	Helical system (stellarator, torsatron, heliotron)
				Nonplanar magnetic axis
				Bumpy torus
Inertial confinement	Laser			Glass laser
				Carbon dioxide laser
				Excimer laser
	Charged particle beam			Electron beam
				Light ion beam
				Heavy ion beam

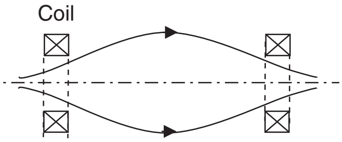


Figure 1.3-1 Simple mirror.

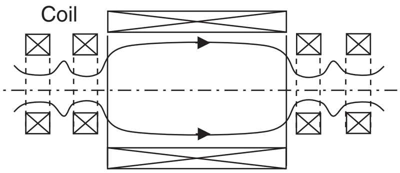


Figure 1.3-2 Tandem mirror.

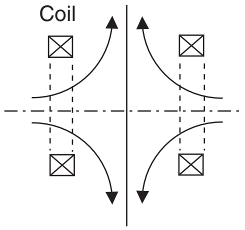


Figure 1.3-3 Cusp.

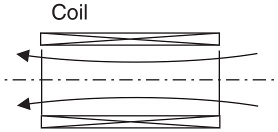


Figure 1.3-4 ϑ pinch.

1.3.1.2 Toroidal System

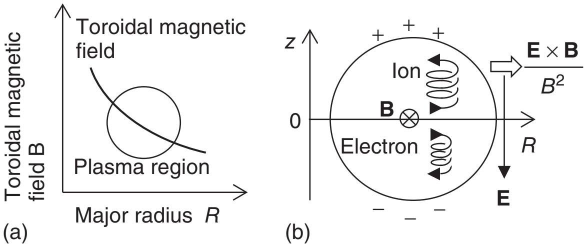
In order to eliminate the end loss in the open-end system, an improved toroidal system (torus system) is considered by connecting both ends. However, as shown in Figure 1.3-5a, the magnetic field is large at the center of the torus and decreases as it goes to the outside with the radial direction. Then the Larmor radius of the particle is changed and the particle drifts in the direction as shown in Figure 1.3-5b, when connecting both ends of the toroidal magnetic field simply. As the electrons and ions drift in the opposite direction, charge separation occurs, an electric field is induced, and the plasma particles escape out of the system by a $\mathbf{E}\times\mathbf{B}$ drift. In order to prevent this, a magnetic field (poloidal magnetic field) is needed to connect the upper part and the lower part of the plasma and short-circuit the space charge.

Combining the toroidal magnetic field B_t and the poloidal magnetic field B_p constitutes magnetic field lines. When turning around the torus along the magnetic field line, the angle of rotation in the poloidal direction is called the rotational transform angle. The toroidal system is classified by the method of making this poloidal magnetic field, that is, rotational transform.

1.3.1.2.1 No Rotational Transform System

The field reversed mirror (FRM) and the field reversed configuration (FRC) are in the no rotation transform system without the toroidal magnetic field [4]. In the FRM shown in Figure 1.3-6, a particle beam is injected into the mirror magnetic field from the outside to generate a current in the toroidal direction. A poloidal magnetic field is generated by the current, and the direction of the magnetic field at the center of

Figure 1.3-5 Charge separation. (a) Profile of toroidal magnetic field. (b) $\mathbf{E}\times\mathbf{B}$ drift.



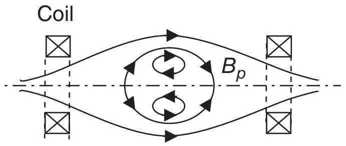


Figure 1.3-6 Field reversed mirror.

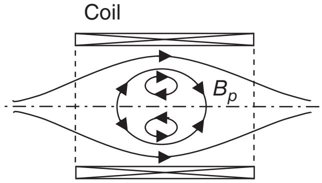


Figure 1.3-7 Field reversed configuration.

the mirror magnetic field is reversed. As a result, a torus-type closed magnetic field line is created inside the mirror magnetic field. This is the FRM.

At first, FRC creates plasma by generating a magnetic field with a current flowing through the ϑ pinch coil placed outside a cylindrical container. Next, by raising the coil current in the reverse direction, a magnetic field in the opposite direction to the one initially produced near the inner wall of the cylindrical container is induced. As a result, as shown in Figure 1.3-7, a closed poloidal magnetic field is generated in the plasma.

1.3.1.2.2 Rotational Transform System

Axisymmetric System The rotational transform system with the toroidal magnetic field is classified into an axisymmetric system and a non-axisymmetric system by methods of making rotational transform. If the system does not change even if it is rotated around the torus axis, the system is said to be axisymmetric (also called rotationally symmetric) and the rest is called non-axisymmetric (rotationally asymmetric). The non-axisymmetric system has a helical symmetry system that does not change even if it moves spirally.

The tokamak is a system that confines plasma by a combination of the toroidal magnetic field produced with coils and the poloidal magnetic field produced with plasma current that is flowed round the torus as shown in Figure 1.3-8.

Spherical torus (ST, spherical tokamak) is a confinement concept in which the aspect ratio ($A = R_0/a$; the major radius R_0 of plasma and the minor radius a) is set to be two or less than two in the tokamak. As shown in Figure 1.3-9, the plasma cross section becomes a D shape and the appearance looks spherical, so it is called the spherical torus [6].

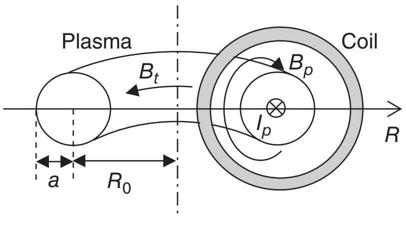


Figure 1.3-8 Tokamak.

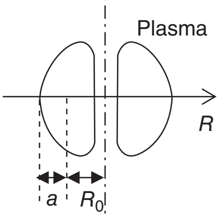


Figure 1.3-9 Spherical torus.

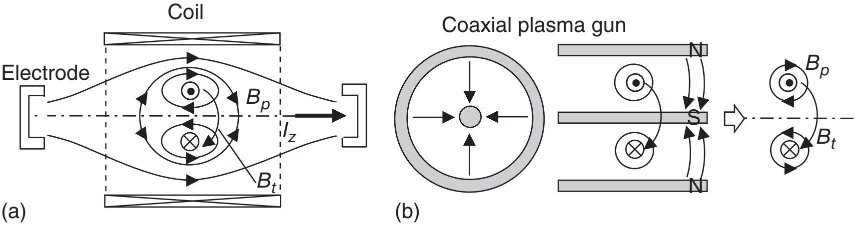


Figure 1.3-10 Spheromak. (a) Induction method. (b) Plasma gun method.

As shown in Figure 1.3-10, spheromak [7] is a confinement concept where the toroidal magnetic field is added in the FRC. The generation method of the spheromak includes an induction method and a plasma gun method. The induction method is similar to the method of generating the FRC, but electrodes are installed at both ends as shown in Figure 1.3-10a. The poloidal magnetic field is generated by injection of the reverse magnetic field. At the same time, a voltage is applied to the plasma at the electrodes to induce an electric current I_z in a pulsed manner in the axial direction, and the toroidal magnetic field caused by this is also injected.

In the plasma gun method, a coaxial plasma gun is used. At first, a radial magnetic field is prepared at the outlet of the plasma gun. When the plasma is in the coaxial plasma gun, it holds the toroidal magnetic flux. Next, when the plasma is radiated from the tip part of the plasma gun, the plasma draws out the magnetic field in the radial direction, obtains the poloidal magnetic flux, and becomes the spheromak. The plasma cross section is as shown in Figure 1.3-10b. Compact torus means spheromak, FRM, and FRC.

Like the tokamak, the reversed field pinch (RFP) confines plasma by the toroidal magnetic field produced with an external coil and the poloidal magnetic field produced with the plasma current flowing round the torus. The main difference is that the toroidal magnetic field decreases as the major radius increases in the tokamak but the toroidal magnetic field decreases as the minor radius increases in the RFP as shown in Figure 1.3-11. It becomes the opposite near the plasma edge. The magnitude of the magnetic field in the plasma has the relation of $B_t \gg B_p$ in the tokamak but $B_t \approx B_p$ in the RFP. In order to generate this reversed magnetic field configuration, there are two methods involving exploiting the property that plasma relaxes under certain conditions spontaneously into this magnetic configuration and making the magnetic field in the opposite direction from the outside at a high speed after the generation of the plasma [8].

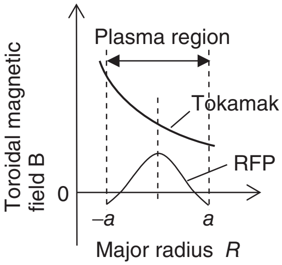


Figure 1.3-11 Magnetic field profile of reversed field pich.

Internal conductor system is a device in which copper or superconductor is installed in a torus vacuum vessel and a magnetic field is generated by flowing current. The magnetic levitation internal conductor system can be considered by using the superconducting coil because the supporting structure of the current lead or the coil crosses the magnetic surface for the copper coil.

Non-Axisymmetric System It is possible to create the poloidal magnetic field with only the external coil without using the plasma current. As shown in Figure 1.3-12a, the stellarator uses the toroidal magnetic field coils and ℓ pairs of helical coils ($\ell = 1$, 2, 3, …), which have opposite current direction to each other, to create the poloidal magnetic field.

Torsatron in Figure 1.3-12b and heliotron in Figure 1.3-12c use ℓ helical coils with the same current direction in which coils with opposite current direction are removed. In the ℓ helical coils, the toroidal magnetic field can also be generated. The torsatron has eliminated the toroidal magnetic field coil by appropriately selecting the pitch of the helical coil. In the heliotron, toroidal magnetic field coils are used as an auxiliary. Since the ℓ helical coils generate a vertical magnetic field, the vertical magnetic field coil is installed (not shown in Figures 1.3-12b and 1.3-12c) to cancel this in the torsatron and heliotron [9].

The toroidal magnetic field and the poloidal magnetic field can be generated by twisting the toroidal magnetic field coil. When the toroidal magnetic field coil is arranged so that the magnetic axis of the toroidal magnetic field coil becomes spiral, the toroidal magnetic field and the poloidal magnetic field can be generated too. This is the nonplanar magnetic axis (spatial magnetic axis, three-dimensional magnetic axis). Figure 1.3-13 shows an example of the nonplanar magnetic axis.

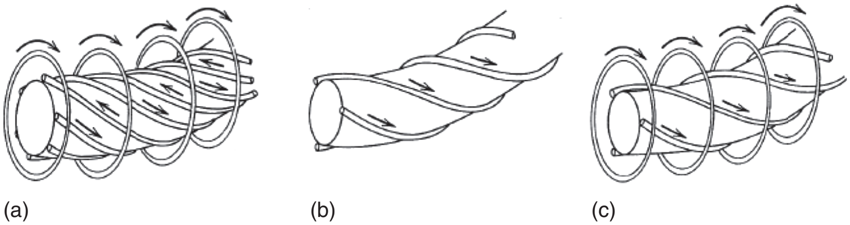


Figure 1.3-12 Confinement concepts using helical coils. (a) Stellarator (ℓ = 3). (b) Torsatron (ℓ = 3). (c) Heliotron (ℓ = 3). Source: Stacey [9]. © 1984 John Wiley & Sons.

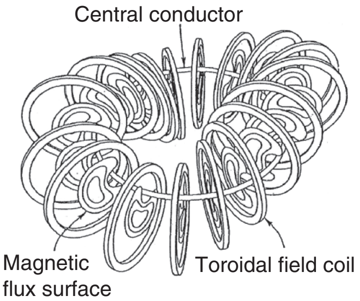


Figure 1.3-13 Nonplanar magnetic axis. Source: From [10]/with permission of The Japan Society of Plasma Science and Nuclear Fusion Research.

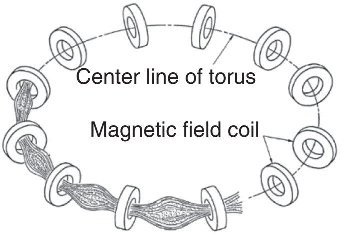


Figure 1.3-14 Configuration of magnetic field coil in bumpy torus. Source: From [11]/Lexington Books.

As shown in Figure 1.3-14, the bumpy torus removes the end loss by arranging simple mirror coils in a toroidal direction. When mirror magnetic fields are connected in a torus, the magnetic field becomes larger inside the torus and smaller on the outside, resulting in charge separation. Generally, when the magnitude of magnetic field has a gradient, the guiding center of the particle has a drift (∇B drift). Since the mirror magnetic field has its gradient that decreases radially outward from the center, the plasma particles rotate in the poloidal direction with this ∇B drift. This plays the same role as the rotational transform of the stellarator magnetic field and cancels the charge separation.

Also, the magnetic field between the mirror field coils is smaller and unstable than near the coil. For this stabilization, there are two methods, one involving applying a radial electric field to the plasma and confining it by $\mathbf{E} \times \mathbf{B}$ drift. Another method involves injecting microwave between the mirror coils to form an electron ring composed of relativistic electrons (several 100 keV) and confining the plasma by the magnetic field made by the electron ring.

1.3.2 Inertial Confinement

Inertial confinement is a method in which energy is injected and nuclear fusion reaction takes place before the plasma expands and dissipates. This name is given because of the property that plasma keeps staying on the spot, that is, using inertia. Figure 1.3-15 shows the principle of inertial confinement fusion (ICF). Small balls (called pellets) of the target diameter 1–2 mm have a multilayer structure. Figure 1.3-15a shows the case of a basic three-layer structure. First, the ablator layer of the pellet's outermost shell is plasmatized by energy injection with laser light or the like and is jetted outward. As a result, as shown in Figure 1.3-15b, the pusher layer is pushed inward by the reaction of the jet of the ablator layer and compresses

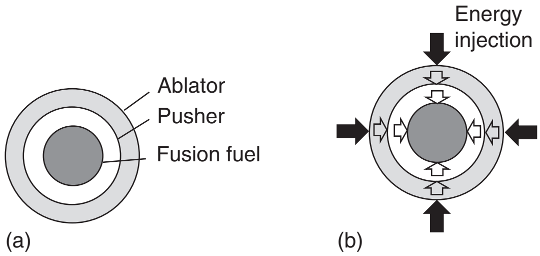


Figure 1.3-15 The principle of inertial confinement fusion. (a) Pellet structure. (b) Implosion and ignition.

the fusion fuel material such as D, T, etc. inside thereof. This rapid compression heating (implosion) of the fusion fuel material induces a fusion reaction (ignition). Fuel pellets should be spherical so that the implosion is performed symmetrically.

In this method, it is also necessary to inject energy uniformly to the pellet surface. The energy injector is called an energy driver. Although the required specification for the energy driver varies depending on the structure of the pellet and the inertial confinement time, the driver may have the requirements such that the pulse width is about 10 ns, the pulse waveform is close to a rectangle with early rising edge, the energy absorption efficiency is high in high-density plasma, and the wavelength of the laser is specified in order to avoid phenomena such as preheat.

There are lasers and charged particle beams in energy drivers. As high-power lasers, Nd glass lasers, carbon dioxide lasers, and so on are used currently. Xenon gas lasers and KrF lasers that belong to excimer lasers, solid state lasers, etc. can be considered as future energy drivers.

Charged particle beams include relativistic electron beams (REB), light ion beams (LIB), and heavy ion beams (HIB). In the REB, the beam with 1 MeV, 1 MA, and the pulse width of 1 ns can be generated in the Marx generator. Conversion efficiency from electric power to beam power exceeds 90%. In LIB, for example deuterium ions, beam propagation is easier than REB. The conversion efficiency is smaller than the one of REB, but it is much bigger than the one of laser. In HIB, by accelerating ions heavier than LIB, such as uranium, it is aimed to reduce the influence of the magnetic field, to increase the injection momentum, and to inject energy by nuclear fission.

Classifying by the irradiation method, the direct irradiation method has a laser or a charged particle beam directly irradiated on a fuel pellet and the indirect irradiation method has a laser or a charged particle beam changed into X-rays in a cavity of a heavy metal such as gold and a pellet irradiated with the rays.

Ignition schemes include the central spark ignition scheme and the fast ignition scheme. The central spark ignition scheme causes a fusion reaction by using the high-temperature plasma naturally occurring at the center of the imploded plasma. The fast ignition scheme causes the fusion reaction by injecting an ultrashort pulse, high-intensity laser into a low temperature and high-density imploded plasma and additionally heating the plasma [12]. A combination of the irradiation method and the ignition scheme can be used after considering the characteristics of the energy driver.

As described above, there are many conceptual schemes for plasma confinement. A power plant is required to supply steady and stable power. Since a large plant itself becomes complex in terms of reactor engineering, it is desirable that the structure is as simple as possible and is easy to manufacture and maintain. In the fusion reactor, it is necessary to select the plasma confinement concept that can respond to the steady and stable power supply. The following chapters describe a tokamak-type nuclear fusion reactor which is considered as one of the concepts satisfying the above requirements.

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