Shape, cross-section, and relative sizes of the vacuum vessel of an ideal tokamak

Askar Abdukadyrov

Kyrgyz State Technical University, Bishkek, Kyrgyzstan
E-mail: abdukadyrov64@mail.ru

Abstract
A tokamak is type of a practical fusion reactor that uses a magnetic field to hold plasma in the shape of a torus. Research has been conducted since the mid-50s of the last century, but it has still not been possible to carry out economically profitable thermonuclear fusion. The article shows that the fundamental reason for the failure is the completely wrong approach to creating these reactors. To implement cost-effective controlled fusion, it is necessary to change the shape and proportions of the vacuum vessel and winding of tokamaks.

Keywords: tokamak, vacuum vessel, plasma, ring current, magnetic field

> The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore progress depends on the unreasonable man. *Bernard Shaw*

1. Introduction

At very low temperatures, close to absolute zero, all substances are in a solid state. Heating causes a substance to transition from solid to liquid, and then to gas.

At sufficiently high temperatures, gas ionization begins due to collisions of very fast moving atoms or molecules. The substance passes into a new state called plasma – a partially or fully ionized gas.

The tokamak is type of practical fusion reactor that uses a magnetic field to contain the plasma. Experiments in tokamaks aim to reproduce the processes occurring in stars, namely, the transformation of the nuclei of two isotopes of hydrogen - deuterium and tritium - into helium nuclei, with the emission of neutrons and the release of enormous energy.

The central part of the tokamak is a vacuum vessel inside which hydrogen is converted into plasma using a strong electric current (passed through an external winding) and other external heaters. This vessel has the shape of a toroid (a hollow "donut") and the cross-section of circular shape or form of the letter «D». To capture high-energy neutrons, there is a special wall (blanket) inside the vacuum chamber. In addition, there is a diverter for diverting particles leaving the magnetically confined plasma into special components. However, due to plasma instability, to implement the economically viable fusion is still not possible. Therefore, it is necessary to understand the fundamental reason for failure.

2. Result and Discussion

As is known, a constant current flowing through a conductor creates a magnetic field. Magnetic field lines form in concentric circles around a straight cylindrical current-carrying conductor (wire).

It should be said that a circle is *an ideal curve of constant width*.

If a thin current-carrying wire is rolled into a loop, the magnetic field lines take the shape shown in Figure, remaining the curves of constant width.

Plasma is an electrical conductor, so the current passing through the electromagnetic coils creates a toroidal magnetic field inside the toroid and induces a ring current in the plasma, which has poloidal magnetic field lines around it.

In general, these magnetic lines are a set of closed contours of decreasing sizes, placed one inside the other (like nesting dolls).

One closed contour from this set is particularly interesting (and is highlighted in bold) because we can easily determine that it has a relatively small inner radius r, about an order of magnitude smaller than its external radius R: $r/R \sim 10^{-1}$.

For other magnetic lines located outside (one such closed curve is shown in the figure), the inner radius decreases slightly, and the outer radius increases very significantly, i.e. the r/R ratio *decreases* rapidly.

For other magnetic lines located inside the selected (bold) contour, on the contrary, the inner radius increases slightly, while the outer radius decreases noticeably, i.e. the r/R ratio *increases* rapidly. The width ($R - r$) of the closed magnetic lines decreases and their shape approaches to the shape of a perfect circle.

Consequently, the smallest closed contour has the shape of *a perfect circle*, whose value r is only slightly less than R, i.e. the ratio $r/R \sim 0.99$ (or even greater). This means that the radius (r_o) of this circle is very small compared to the value of r: $r_o << r$.

For example, if $r = 0.99R$, then the circle radius $r_o = (R - r)/2 = 0.01R/2 = 0.005R$, the ratio $r/r_o = 198$ or $r/r_o \sim 2\times10^2$, i.e. the value of r is approximately two orders of magnitude greater than the radius of a circle.

The first tokamaks also had a vacuum vessel with a circular cross-section (its radius should be written as r_o), however, they *could not provide* a positive energy output at all.

The reason is that the proportions of their vacuum chamber *do not correspond at all* (one might say, catastrophically) to the relative sizes of the magnetic line (of ring current) in the shape of an ideal circle.

For example, these reactors have the ratio $r/R \sim 0.1\div0.5$, the ratio of the hole radius to the chamber radius is $r/r_o = 0.2\div2$ [1].

A magnetic line in the shape of a perfect circle, as we previously showed, has the ratio $r/R \sim 0.99$, and the ratio $r/r_o \sim 2\times10^2$.

From a practical point of view, the difference is simply huge. This means that the O-shaped vacuum chamber must have the hole radius of at least 200 times the radius of its cross-section. For example, if the section radius $r_o = 0.1$ m, then the hole radius r must be about 20 m (in the ideal case).

However, as we now understand, *there is no need to build* the O-shaped tokamaks.

In the early 1970s, it was proposed to change the chamber cross-section so that it was shaped like the letter «D». This decision was made for both theoretical and practical reasons. Several D-shaped plasma machines have been built (for example, the JET in the UK, D-IIID in the US, JT-60 in Japan); the class of such machines is known as "advanced tokamaks". The D-shape demonstrated an advantage over the normal round section and now this arrangement is considered universal.

Decades of fusion research have shown that the larger the reactor, the better its indicators. Therefore, a trend has emerged to build ever larger and more powerful installations.

Currently, high hopes are placed on the International Thermonuclear Experimental Reactor (ITER), which is being built in southern of France. ITER will have a D-shaped vacuum vessel of enormous dimensions: its volume ~840 m^3, the major radius 6.2 m, the height 11.3 m [2].

It should be noted that the D-shaped cross-section of the vacuum chamber (and winding) *is elongated along the main axis* and its height is approximately 1.7 times *greater* than its width. In addition, the inside part of the D-shaped cross-section is *a straight line*.

Thus, we conclude that the generally adopted D-shape *does not correspond at all* to the shape of the magnetic lines of a ring current (which, as we mentioned earlier, are the curves of constant width).

3. Conclusion

First of all, we note that since the mid-50s of the last century more than 100 (O- and D-shaped) tokamaks have been built, but success has not yet been achieved. For 70 years now, scientists have been unable to understand what is wrong with the tokamak design.

The hopes placed on ITER are linked to its colossal size. However, simply increasing the reactor's size cannot guarantee success. For example, Japanese JT-60SA is the largest tokamak in operation today [3]. The volume of its chamber (~140 m^3) is approximately 1.7 times greater than the plasma volume of JET (~80 m^3), however, it does not demonstrate a clear advantage. Since ITER (in the sense of the vessel shape) is not fundamentally different from other machines with a D-shaped plasma, then it will not be able to give outstanding results either. This is a clear example of gigantomania associated with the senseless waste of enormous material resources.

Generally speaking, the situation with tokamaks looks absurd:

- first, the developers design the D-shaped vacuum vessel (and external winding), the cross-section of which *does not correspond* to the shape of the magnetic lines of a ring current (which are the curves of constant width);
- then, when the tokamak is operating, using external magnetic fields, they try to force the plasma (i.e. the magnetic lines of a current) *not to touch* the inner surface (blanket) of the chamber.

To be clear, the magnetic field of the D-shaped coils changes the shape of these magnetic lines, *stretching* them along the main axis and *compressing* them in the transverse direction.

It is the forced change in the natural shape of the magnetic lines of the ring current that disrupts the force balance in the plasma and *is the main reason* for the emergence of various kinds of instabilities in it.

To understand what has been said, let's give an example from ordinary life.

When we buy, for example, a hat, we choose a thing of the appropriate size. But we're not trying to change the size of head to fit the first specimen we see.

Namely, a similar situation occurs with tokamaks.

Using B. Shaw's phrase, the scientists are trying to adapt the world (nature) to themselves.

Naturally, the question arises: how to adapt to nature in this case?

The answer is simple. To do this, it is need to fundamentally change the approach to creating the tokamaks:

- first, *a specific magnetic line* of the ring current *is selected* (which is a curve of constant width), and its exact shape and relative dimensions (the ratio r/R) are determined;
- then, the sizes of a vacuum chamber are determined, the cross-section (and the ratio r/R) of which exactly corresponds to the selected magnetic line (i.e. *the chamber cross-section must also have the shape of a curve of constant width*);
- only after this does the actual design begin, and the shape of the toroidal field coils *must differ* from the cross-section of the chamber (since the magnetic lines of the ring current differ from each other).

If the specified requirement is met, then during operation of an ideal tokamak the situation will be as follows:

- the hot plasma (i.e. the magnetic lines of a current) *will not touch* the inner surface (blanket) of the vacuum vessel;
- the plasma particles (electrons and ions) moving along the magnetic lines *will not collide with the inner surface of the vessel*, losing their energy.

As a result, the current-carrying ring *will be stable* (possibly even without the use of additional stabilizing magnetic fields). And this is a necessary condition for the relatively quiet occurrence of a fusion reaction with a large energy release.

Thus, to carry out an economically profitable controlled fusion, *it is necessary to change* the shape and proportions of the vacuum vessel (and winding) of tokamaks. To test this proposal, *it is necessary to build at least one small reactor that meets the specified condition*.

If this change is carried out, then we can be sure that in foreseeable future thermonuclear energy will be obtained on an industrial scale.

Competing Interests: The author declares no competing interests.

References

1. Smirnov V. P. (2010) Tokamak foundation in USSR/Russia 1950–1990 *Nucl. Fusion* **50**(1) 014003, doi:10.1088/0029-5515/50/1/014003
2. ITER project website, https://www.iter.org/
3. JT-60SA project website, https://www.jt60sa.org/wp/main-research-objectve/

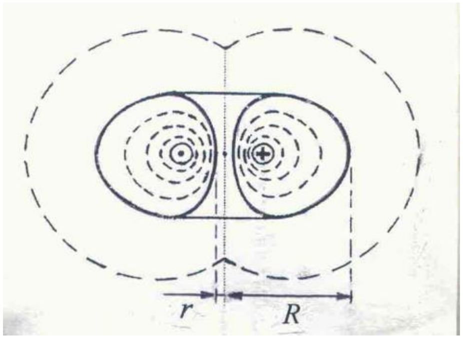

Figure. Magnetic field lines of the ring current. [The figure is taken from the book: Abdukadyrov A. B. (2005) *Physics – unity in diversity* (Bishkek)]