

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

A. 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. Here we show that the fundamental reason for the failure is the completely wrong approach to creating these reactors.

Keywords: Thermonuclear fusion, tokamak, vacuum vessel, plasma, ring current

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. Due to their high mobility, charged particles of plasma easily move under the influence of electric and magnetic fields. As the degree of ionization increases, the conductivity of the plasma increases. At high temperatures, fully ionized plasma approaches superconductors in its conductivity [1].

The overwhelming (about 99%) part of the visible matter of the Universe is in the plasma state. Due to the high temperature, the Sun and other stars are composed of plasma.

Physicists see the most significant prospects in the use of high-temperature plasma (with temperatures of hundreds of millions of degrees) to create controlled thermonuclear reactions.

A tokamak is one of several types of practical fusion reactor that uses a magnetic field to contain the plasma.

The first tokamaks appeared in the USSR, but at first they did not arouse much interest among Western scientists. At the end of 1968, the Russians reported that plasma temperature in their Tokamak T-3 had reached 10 million degrees (for comparison, the temperature of the Sun's core is ~15 million degrees).

The report was met with disbelief because this result was a full order of magnitude higher than in any other fusion machine. The British experts carried out independent measurements on T-3 and confirmed the Soviet result. Their publication [2] became a sensation: a confidence has emerged that thermonuclear fusion is possible in the fairly near future.

Over the next decade, dozens of tokamaks were built and used around the world; these machines had reached all of the conditions needed for practical fusion.

The design of the tokamaks has constantly improved and become more complex, but at the same time, the experiments demonstrated problems and optimism gave way to disappointment.

Currently, high hopes are placed on the International Thermonuclear Experimental Reactor (ITER), which is being built in southern of France.

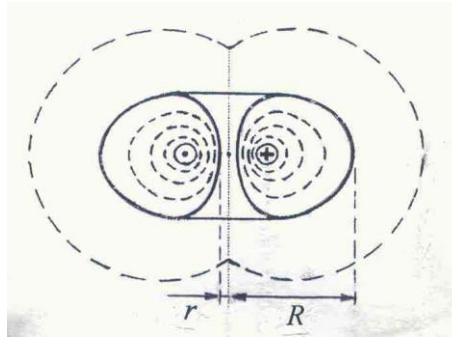
Experiments in tokamaks aim to reproduce the processes occurring in stars, namely, the transformation of the nuclei of two isotopes of hydrogen - deuterium and tritium - into helium nuclei, with the emission of neutrons and the release of enormous energy.

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. 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. Discussion

Plasma is an electrical conductor, so current passing through the electromagnetic winding causes a ring current in the plasma.

As is known [3], when current flows along a closed loop, the magnetic field lines take a form very similar to the *curves of constant width*, as shown in the figure.



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 slowly decreases and the outer radius quickly increases, i.e. the r/R ratio *decreases* rapidly. This ratio at least reaches the value of 10^{-2} .

For other magnetic lines located inside the selected (bold) contour, on the contrary, the inner radius slowly increases and the outer radius quickly decreases, 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.

The magnitude r/R cannot increase indefinitely and there must be a limit. Consequently, the smallest closed contour has the shape of a perfect circle, whose value r is only slightly less than R , i.e. $r/R \sim 0.99$. This means that the radius (r_0) of this circle is very small compared to the value of r : $r_0 \ll r$.

For example, if $r = 0.99R$, then the circle radius $r_0 = (R - r)/2 = 0.01R/2 = 0.005R$, the ratio $r/r_0 = 198$ or $r/r_0 \sim 2 \times 10^2$, 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.

In the early 1970s, it was proposed to change the chamber cross-section so that it was shaped like the letter «D». Several D-shaped plasma machines have been built, for example, the Joint European Torus (JET) in the UK. 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.

ITER will be the largest of fusion reactors built and will have a D-shaped vacuum vessel of enormous dimensions: its minor radius 2 m, the major 6.2 m (the ratio $r/R \sim 0.3$), its height 11.3

m and is approximately 1.7 times greater than its width. In addition, the inside part of the D-shaped cross-section is a straight line [4].

Thus, the generally adopted D-shape is completely inconsistent with the shape of the ring current magnetic line (with same ratio r/R) which, as we said, is practically a curve of constant width.

Since ITER (in the sense of the vessel shape) is not fundamentally different from other machines with a D-shaped plasma (e.g., JET), then most likely it will not be able to give outstanding results either.

As for tokamaks with a circular cross-section (its radius should be written as r_o), they could not provide a positive energy output.

The reason is that the proportions of their vacuum chamber even more (one might say catastrophically) do not correspond 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 $r/R \sim 0.1 \div 0.5$ [5], the ratio of the hole radius to the chamber radius is $r/r_o = 0.2 \div 2$.

A magnetic line in the shape of a perfect circle, as we previously showed, has the ratio $r/R \sim 0.99$ (or even greater), and the ratio $r/r_o \sim 2 \times 10^2$. 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 $r_o = 10$ cm, then the hole radius r must be at least 20 m.

However, there is no need to build the O-shaped tokamaks.

3. Conclusion

Generally speaking, the situation with tokamaks looks absurd:

- first, the scientists design a vacuum vessel the cross-section of which does not correspond to the shape of the magnetic line of the ring current (i.e., in fact, they arbitrarily choose the shape, cross-section and relative sizes of the vessel);
- then, when a tokamak is operating, with the help of external magnetic fields they try to force the magnetic lines not to touch the inner surface (blanket) of the chamber (i.e. they try to shape these magnetic lines the cross-sectional shape of the chamber).

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 resize the 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 and its exact shape and relative dimensions are determined;
- then, the sizes of a vacuum chamber are determined, the cross-section of which exactly matches the shape of the selected magnetic line; only after this the actual design begins.

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

- the magnetic lines 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 thermonuclear reaction with a large energy release.

Thus, to carry out an economically profitable synthesis reaction, it is necessary to change the shape and proportions of the vacuum vessel of tokamaks.

If this requirement is met, then we can hope that in foreseeable future thermonuclear energy will be obtained on an industrial scale.

Funding

This research received no external funding.

Competing Interests

The author declare no competing interests.

References

1. J.A. Bittencourt, *Fundamentals of Plasma Physics* (Springer, 2004)
2. N.J. Peacock, *et al.* Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3. *Nature* **224** (5218), 488–490 (1969), <https://doi.org/10.1038%2F224488a0>
3. P. Hammond, *Electromagnetism for engineers* (Pergamon Press, 1981)
4. ITER project website, <https://www.iter.org/>
5. Russian generation of tokamaks, http://www.iterru.ru/FusionCentre/FCMain/FCHistory/russian_tokamaks.html