BIOSCIENCES BIOTECHNOLOGY RESEARCH ASIA, April 2015. Vol. **12**(1), 647-651

Closed Magnetic Trap for Confining and Heating Plasma

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DOI: http://dx.doi.org/10.13005/bbra/1708

(Received: 14 December 2014; accepted: 22 January 2015)

For confining and simultaneous heating of high temperature plasma, it is proposed to use a magnetic trap that creates a closed rotating magnetic field. Such a magnetic field is created by applying magnetic fields from nine open traps placed in triads in three orthogonal planes. Each trap is connected to one of phases of a three-phase AC circuit and is set at 120 degrees to the other two traps located in this plane.

Key words: high temperature plasma, controlled thermonuclear reaction, trap, toroidal component of magnetic field, poloidal magnetic field, reactor, magnetic induction, skin effect, equilibrium plasma, closed magnetic trap, high frequency vortex currents.

Issues of creating conditions for controlled thermonuclear reactions in the past six decades were considered by many research teams and enthusiasts[1,2]; most of whom propose to confine plasma with magnetic fields of various configurations and to ensure its heating in different ways[3] within fractions of seconds. As early as in the 50s of the last century open type traps were proposed and widely studied, in which the problem of simultaneous creation, accumulation, heating and retention was initially solved.

Solution of these problems led to discovery of various kinds of instabilities in plasmas with increasing plasma density and temperature. In addition, plasma escape was detected along the magnetic field and the fundamental inability to resist this escape due to the use of mirror-type structures, or magnetic plugs.

Disadvantages of the construction arrangement of open type traps and these instabilities have led physicists to the idea of using magnetic arrangements in which it would be possible to create a closed plasma configurations of toroidal shape[4,5,6]. But after a simple analysis of the toroidal plasma column behavior it became obvious that it is impossible to simultaneously create, confine and heat the ring cord in a simple toroidal field.

Please remember that for confining plasma, equation $P + B_i^2/8\pi = B_0^2/8\pi$ should be true on its boundary, where: Bi is the value of magnetic field inductance in the area of plasma, B0 is the value of magnetic field inductance outside the area of plasma, and P is kinetic pressure of plasma. Since the magnetic field in the toroid formed by the area of plasma is inhomogeneous (since it is inversely proportional to the distance from the axis of the toroid B ~ 1R), in order to compensate for particle drift, the toroid was, after suggestion of Lyman Spitzer, turned into an “eight”. This has led to modernization of the traditional toroid with introduction of a combination of two magnetic fields, one of which is the field of the toroidal coil

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Bθ, and another is field Bφ, which is created by circular current flowing through the plasma itself. This made it possible to compensate for the drift of plasma particles and compress plasma cord under the influence of an external magnetic field[7,8,9,10]. With plasma confinement time (T~d0.1-1sec) in tokamaks under (nT~1020 m3c), where n is the plasma density, and the threshold temperature of 10 keV (in D-T reactions), a thermonuclear reaction is expected.

In recent years, the main efforts of the scientific community of the planet in solving the problem of obtaining controlled thermonuclear fusion (CTF) is focused on the International Thermonuclear Experimental Reactor (ITER) project, i.e., the project for construction of a tokamak-type nuclear installation in the South of France to be launched in 2027. The fact that the participants of construction of this installation in the Cadarache research center are countries of the European Union, acting as one Union, India, China, Republic of Korea, Russia and Kazakhstan, USA, Canada, Japan, explains the close attention to the construction and financing of the facility from both the scientific community and the media, which provide advertising support for the methods of plasma confinement and heating in a toroid. However, the progress in this direction does not yet make it possible to speak about imminent CTF adoption as the source of energy, even though a number of editions promised transition to an industrial scale by the middle of this century.

Against this background, attention to the second method of obtaining CTF is increasing, namely, the inertial thermonuclear fusion in powerful laser installations, construction of which has increased markedly in recent years. Commissioning of projects such as Laser Megajoule in France, High Power Laser Energy Research Facility (HiPER) and UFL-2M installation built in Diveyevo rated at 2.8 MJ is planned soon. Already built facilities for obtaining controlled thermonuclear fusion reaction include the National Ignition Facility (NIF). It includes a total of 192 lasers with the total emitted energy of 1.8 MJ, which create the so-called "X-ray oven", which heats a spherical target 2 mm in diameter, inside which a $1.5 \cdot 10^{-4}$ g mixture of deuterium and tritium is present in frozen state. This very "bead" with a mixture of deuterium and tritium is located inside a cylindrical chamber referred to as "hohlraum" made of uranium and coated with gold. Simultaneous pulsed exposure to 192 lasers with the total capacity of 5‡10^{15} W evaporates hohlraum and sends powerful X-ray emission to the target. As a result, the inside of the target is to be compressed due to the jet effect under pressure up to 1011 atmospheres and heat up to 10^6 K. At the same time, as developers hope, deuterium and tritium will fuse to form helium and a free neutron.

Methodology

The possibility to use vortex high frequency currents to heat plasma was expressed as early as in the middle of the last century. So, the original system for confinement of spherical plasma blob using three mutually perpendicular magnetic fields was proposed in 1957 by B. A. Trubnikov from the Institute of Atomic Energy n.a. I.V. Kurchatov. But this method of heating failed to become popular due to the fact that the magnetic field was pushed out from the volume occupied by plasma due to the skin effect and, as a consequence, termination of plasma heating. Based on this historical experience, the authors suggest using magnetic fields generated by industrial frequency current (50-60 Hz).

If we consider that the only way to effectively confine plasma in a certain volume is the magnetic field of a trap of a particular configuration, it is proposed to create a reactor based on a combination of nine magnetic traps. These traps block plasma escape in all three directions, and at the same time allow it to heat up to the fusion temperature of several tens of keV due the rotating magnetic fields in three orthogonal planes.

The magnetic field of the proposed reactor is created by a combination of spatially overlapping magnetic fields of the simple open traps. The traps are placed in triads in three orthogonal planes. Each of them is connected to one phase of the three-phase AC power grid with industrial frequency. Coplanar traps are placed on a circle with a common center, each at 120 degrees to the other two.

Coils of these nine traps lie in a sort of spherical surface and due to overlapping of the magnetic fields create in its center the total magnetic field with a constant magnetic induction vector, which rotates with the frequency of the three-phase current supplied to the coil.

Three open traps in the same plane create a magnetic field rotating in this plane with the frequency of the three-phase current supplied to the coils, and a constant vector of the magnetic induction B. Such a magnetic field is created in asynchronous motors with a short-circuited armature. Each coil creates its own magnetic field

$$B_A(t) = B_m \sin \omega t\,,$$

$$B_B(t) = B_m \sin(\omega t - 120^o)\,,$$

$$B_C(t) = \sin(\omega t + 120^o)\,.$$

The total magnetic induction vector in the center is 1.5B_m, and rotates with angular frequency ω

Main

Let's see how the solenoids of the traps placed in three orthogonal planes are to be phased, in order to obtain a closed magnetic field, the total magnetic induction vector of which rotates continuously in all three dimensions.

In the X-Y plane, projections of the total vector of the magnetic induction on the X and Y axes will be:

$$B_{x1}(t) = 1.5B_m \cos(\omega t + \varphi_1)\,,$$

$$B_{y1}(t) = 1.5B_m \sin(\omega t + \varphi_1)\,,$$

In the Z-X plane, projections will be equal to:

$$B_{z2}(t) = 1.5B_m \cos(\omega t + \varphi_2)\,,$$

$$B_{x2}(t) = 1.5B_m \sin(\omega t + \varphi_2)\,.$$

In the Y-X plane, projections will be equal to:

$$B_{y3}(t) = 1.5B_m \cos(\omega t + \varphi_3)\,,$$

$$B_{z3}(t) = 1.5B_m \cos(\omega t + \varphi_3)\,,$$

where φ_1, φ_2, φ_3 are initial phases of total vectors of magnetic induction in the planes in question.

Thus, the projection of the total magnetic induction vector on the orthogonal axes will have the following dependence on time:

$$B_x(t) = B_{x1}(t) + B_{x2}(t) = 1.5B_m[\cos(\omega t + \varphi_1) + \sin(\omega t + \varphi_2)],$$

$$B_y(t) = B_{y1}(t) + B_{y3}(t) = 1.5B_m[\cos(\omega t + \varphi_3) + \sin(\omega t + \varphi_1],$$

$$B_z(t) = B_{z2}(t) + B_{z3}(t) = 1.5B_m[\cos(\omega t + \varphi_2) + \sin(\omega t + \varphi_3)].$$

In the central part of this three-dimensional trap, the squared total magnetic field induction is equal to:

$$B^2(t) = B_x^2(t) + B_y^2(t) + B_z^2(t) = (1.5B_m)^2\{[\cos^2(\omega t + \varphi_1) + 2\cos(\omega t + \varphi_1)\sin(\omega t + \varphi_2) + \sin^2(\omega t + \varphi_2)] + [\cos^2(\omega t + \varphi_3) + 2\cos(\omega t + \varphi_3)\sin(\omega t + \varphi_1) + \sin^2(\omega t + \varphi_1)] + [\cos^2(\omega t + \varphi_2) + 2\cos(\omega t + \varphi_2)\sin(\omega t + \varphi_3) + \sin^2(\omega t + \varphi_3)]\} = (1.5B_m)^2[2\cos(\omega t + \varphi_1)\sin(\omega t + \varphi_2) + 2\cos(\omega t + \varphi_3)\sin(\omega t + \varphi_1) + 2\cos(\omega t + \varphi_2)\sin(\omega t + \varphi_3) + 3] = (1.5B_m)^2[\sin(\omega t + \varphi_1 + \varphi_2) + \sin(\varphi_1 - \varphi_2) + \sin(2\omega t + \varphi_2 + \varphi_3) + \sin(2\omega t + \varphi_3 + \varphi_1) + \sin(\varphi_3 - \varphi_1)].$$

If we assume that φ_1=0,φ_1=-120°, φ_3=120°, then

$$B^2(t) = (1.5B_m)^2[\sin(2\omega t - 120^0) + \sin 120^0 + \sin(2\omega t) + \sin(-240^0) + \sin(2\omega t + 120^0)\ \sin 120^0 + 3].$$

Given that and, the expression in square brackets will be equal to $\left(4.5 + \sqrt{3}/_2\right)$ for any moment in time, and in the end we get $B^2(t) = (1.5B_m)^2\left(4.5 + \sqrt{3}/_2\right)$.

Therefore, $B(t) = 1.5B_m\sqrt{4.5 + \sqrt{3}/_2} \approx 3.47B_m$, where B_m is the module of the magnetic field induction vector to one of the nine traps generated in the center of the proposed reactor, i.e. the module of the magnetic induction vector of the total magnetic field remains constant in time. Let us define the frequency of vector **B**rotation in the three orthogonal planes.

In the Z-X plane, change of α(t) along the Z-axis (in the direction of the X axis) is equal to:

$$\tan\alpha(t) = \frac{1.5B_m \sin \omega t}{1.5B_m \cos \omega t} = \tan \omega t.$$

Therefore, α(t) = ωt

In the X-Y plane, change of β(t) along the X-axis (in the direction of the Y-axis) is equal to:

$$\tan\beta(t) = \frac{1.5B_m \sin(\omega t - 120^0)}{1.5B_m \sin(\omega t - 120^0)} = \tan(\omega t - 120^0)$$

Therefore, $\beta(t) = (\omega t - 120^0)$.

In the Y-Z plane, change of $\gamma(t)$ related to the Y-axis (in direction of the Z-axis) is equal to:

$$\tan\gamma(t) = \frac{1.5B_m \sin(\omega t + 120^0)}{1.5B_m \cos(\omega t + 120^0)} = \tan(\omega t + 120^0).$$

Therefore, γ(t) = ωt + 120°

Hence we can make the following conclusion: all projections of the resultant magnetic induction vector B(t) rotate with the same angular velocity, each in its plane, and each is offset in time by one third of the period with respect to each other, where each projection B(t) is formed by superposition of the magnetic fields of the three open traps located in the same plane and offset in space of this plane by one third of the circle. These traps induce sinusoidal magnetic fields in time, which are also offset in time relative to each other by one third of the period.

The resulting configuration of the magnetic field allows asserting that the area in the center of the reactor will look like a cage, spokes of which will be lines of the magnetic field obtained by over-imposing three equal magnetic fields rotating in three orthogonal planes. Such a closed configuration does not guarantee the possibility of obtaining required concentration and temperature of heated plasma.

To solve this problem, authors propose to initially place a capsule in the form of a layered capsule in the form of calibrated ball of deuterium-tritium (D-T) mixture with the density of $10^{19}\ cm^{-3}$ in the center of the reactor. The ball should be made as a set of coaxial spherical D-T layers separated by thin metal shells made of sheets of lithium 6. When plasma with the energy of $10^2 - 10^3$keV is injected, the target will heat up, and concentration of plasma will gradually rise simultaneously in the whole volume due to the vortex currents induced by external rotating magnetic fields of closed configuration. This design of the source of D-T mixture will make it possible to, if not eliminate, then to significantly reduce uneven heating of the plasma on the surface layer of the container.

CONCLUSION

For the implementation of a controlled thermonuclear reaction in tokamaks, the plasma density should be $n=10^{21}m^{-1}$, temperature - $T=10^8K$, induction of the external magnetic field - ≥7T, Debye shielding distance for isothermal plasma in this case $r_D = 10^{-5}m$, kinetic pressure of the plasma is 2nkT, where k is the Boltzmann's constant.

If we neglect penetration of the magnetic field inside the plasma, the magnetic pressure of the external field can be taken as ${B_0}^2/2\mu_0$ where μ_0 is the magnetic constant of vacuum.

Let's calculate what the external magnetic field should be equal to in order to compensate for plasma pressure $B_0 = \sqrt{4\mu_0 nkT} = 2.63\text{T}.$

In a first approximation, using a system of traps that create a rotating magnetic field can ensure plasma confinement. To do so, in the center of the spherical volume of the reactor a container with a D-T mixture with specified density should be placed. The target should be heated by the high temperature plasma injected into the working volume from an external source. After getting into the working volume and warming up due to vortex currents induced by external magnetic fields, it will heat up in the center of the container with the D-T mixture. As the container heats up and is destroyed, the mixture will ionize, heat up and will be kept in the central area of the working volume due to collisions of neutral atoms of deuterium and tritium with ions of initially injected plasma and ionized ions of the target.

CONCLUSIONS

1. A possibility appears for simultaneous plasma heating and confinement in a given volume.
2. The need to use superconductivity in order to achieve magnetic field intensity up to 7 T is excluded.
3. Possible escape of the plasma from the specified volume when the current velocity vector becomes parallel to the induction vector of the resulting rotating magnetic field in a short time, can, with sufficient density of the equilibrium plasma, be compensated for by electrostatic processes inside the plasma. Therefore, the D-T mixture should be heated with both ionization and confinement.

REFERENCES

1. Hegler, M. and M. Christiansen, Introduction to controlled thermonuclear fusion. Mir, 1980; 229.
2. Frank-Kamenetsky, D., Lectures on plasma physics. URSS, 2008; 280.
3. Artsimovich, L.A., Elementary plasma physics. Gosatomizdat, 1963; 98.
4. Leontovich, M.A., *Problems of Plasma Physics,* 1980; **10**: 321.
5. Budker, G.I., Controlled thermonuclear fusion in installations with dense plasma. *Nature,* 1974; **5**: 14-21.
6. Begum, M., S.Baruah and N.Das, Thermodynamic properties of strongly coupled plasma in presence of external magnetic field.*Plasma Physics,*2014; **40**(7): 676-682.

7. Movsesyants, Yu.B. and P.M.Tyuryukanov, Special features of the radial equilibrium of the flow noncolliding plasma. *EngineeringPhysics,* 2011; **3**: 21-25.
8. Leontovich, M.A., *Problems of Plasma Physics,* 1980; **10**: 321.
9. Skovoroda, A.A., Magnetic traps for plasma confinement. *Physmathlit*, 2009; 216.
10. Miyamoto, K., Fundamentals of plasma physics and controlled fusion. *Physmathlit*, 2007; 425.
11. Gasanov, I.S., Plasma and beam technology. Elm, 2007; 125.