Magnetic Nuclear Fusion Reactor of New Type : Main Physical Aspects

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Abstract

Peculiar properties of a magnetic nuclear fusion reactor of innovative type [1] are discussed where the functions of plasma confinement and its thermal insulation are separated. Whereas reducing heat transfer is fulfilled using magnetic field, a hot plasma confinement is maintained by gas of high pressure. In the system considered the plasma is in a local equilibrium state and, as a consequence, the electron (ion) concentration is a function of local temperature. In the frames of a the simplified model a approximate stationary solution of the problem concerning nuclear fusion burning in a D-T mixture is found and the reactor dimensions are determined. A series of obvious advantages of using high-pressure gas for the confinement of plasma pressure are noted, e.g. absence of interaction fast charged particles and first-wall components, small sizes of the reactor and opportunity for using other fuel mixtures (*f.e.* $D+He^3$).

Keywords:

plasma confinement, high pressure gas, thermal isolation, magnetic field configuration

1. Introduction

For about 15 – 20 past years the experimental procedure and techniques in tokamaks have made great progress that enabled the plasma parameters to be effectively enough controlled and in some cases a number of dangerous instabilities to be suppressed; besides the plasma confinement was improved. However, the experimental reactor, ITER, being designed with due account of the progress made is oversized and considered as an undue expensive facility. Hence there naturally, arise a question: if the chosen way to develop tokamaks, i.e. permanent increase of their sizes (and cost), the only one correct? In fact, since major physical tokamak concepts were stated [2], main efforts have been undertaken in the development of the experimental procedures and techniques and "the arm race", i.e. a competition in building larger and larger facilities.

If one lets the "ideology" of the tokamak creation to be unchangeable, then the only correct way left is to increase its size. As follows from the Lawson criterion the ignition may be achieved by increasing either the plasma density (this is the case of laser nuclear fusion) or the confinement time. As the plasma density in the tokamaks is limited by the magnitude of the magnetic field, one needs to increase the time of confinement. In its turn, this time in the existing tokamaks (stellarators) is limited because of the fact that their plasma proves to be in substantially non-equilibrium and suffers numerous instabilities.

Below a physical concept of a magnetic fusion reactor is considered where the plasma is in a state close to local equilibrium.

2. Plasma confinement with high pressure gas

Within large plasma pressures exceeding the magnetic field one the plasma appears to be close to a thermally equilibrium and, hence, must be more stable. As lots of experiments show with an increase in the plasma density, as a rule, the global confinement time also rises and at plasma densities which are close or exceed $n \geq 10^{14}\,\mathrm{cm}^{-3}$ the rate of anomalous electron energy transfers significantly diminishes and becomes comparable with the ion energy transfer which, in its turn, close to neoclassical. In addition, increasing by density of reacting particles means rising the rate of nuclear fusion reactions and as a result the requirements to the confinement time and, thus, to the installation size are reduced. That is why the investigation of possible methods of increasing plasma density is of vital importance.

In our paper the plasma pressure exceeding the magnetic field pressure ($\beta > 1$) is discussed; as a result

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2.1 Equilibrium plasma state

In conventional tokamaks the plasma pressure p is balanced by forces arising at interaction of electric currents j with a magnetic field $\boldsymbol{B}$

$$\nabla p = 1/c(\boldsymbol{j} \times \boldsymbol{B}) \tag{1}$$

In the devices with a small aspect ratio of $\varepsilon = a/R \ll 1$ where a, R are the minor and major radii of the plasma column, respectively, we have

$$\nabla p + \nabla_{\perp} B^2/8\pi = 0 \tag{2}$$

where p is the plasma pressure At confinement of hot plasma with a gas the second member in the left side (2) can be neglected ($\beta \gg 1$), and we have $\nabla p \approx 0$ or $p \approx$ const, i.e. a hot plasma pressure along the radius is unchangeable. At high plasma temperatures $T \gg 1$ eV the quantity of neutral particles in plasma is small (at $T \sim 10$ keV their concentration does not exceed $\sim 10^{-6} - 10^{-7}$). In contrast, nearer to the plasma boundary where its temperature is quite low ($T \leq 1$ eV) the concentration of charged particles is insignificant and the total pressure is almost entirely defined by neutral gas. In the stationary state the total pressure including that of plasma and neutral gas remains constant, $p_e + p_i + p_a \approx$ constant, where e, i and a designate electrons, ions and neutral respectively. The hot plasma pressure in the center of plasma column and the cold gas pressure on the boundary are about equal. Thus, in the center of the plasma column is hot plasma with its temperature being dropped towards the periphery. And, correspondingly, a concentration of charged particles increases. However at low temperatures $T \sim 1$ eV plasma changes into a partially ionized gas. In the vicinity of the wall we deal with neutral gas, its temperature is equal to that of the surface. As it is known, at magnetic confinement plasma pressure is maximum in the center of the system ("plasma diamagnetism") with $\beta = 8\pi p/B^2 \ll 1$; towards the plasma boundary its density and temperature fall off. The plasma in its full volume is almost completely ionized and a noticeable component of neutral particles is revealed only near the boundary itself. The plasma itself being separated from walls proves to be highly non equilibrium that is the cause of numerous instabilities. In contrast to this, a locally equilibrium plasma is less susceptible to instabilities.

The conditions and parameters of burning should be chosen such as the wall surface had an acceptable temperature. At gas pressure $p \sim 1-100$ bar the charged particles length paths in gas do not exceed $\sim 10\,\mu$m. So these particles are incapable of penetrating through the neutral gas shell to the solid surface. The first wall surface is mainly heated by plasma radiation and neutral gas heat conduction. In order to exclude plasma polarization in the vertical direction it is necessary that a poloidal field B_θ should be included (*f.e.*, by using lasers [3]). Let us estimate the value of bootstrap current J_B using the expression for J_B from Ref. [4] and taking into account of $p = 2nT =$ const, where n is ion (electron) concentration; at $B \sim 1$ T, $n \sim 10^{15}$ cm^{-3} and $T \sim 10$ keV we find $J_B \sim 10^4$ A/cm^2 that is quite sufficient for maintaining a poloidal magnetic field. Hazard of arising the Relaygh-Taylor instability can be prevented on account of poloidal rotation of the plasma column at a velocity defined by a "thermal force" $R_T = -(\boldsymbol{h} \times \nabla T/\omega\tau_e$ [5] where $\omega\tau_e$ is a ratio of cyclotron frequency to collision one for electrons.

2.2 Nuclear fusion burning

In lots of experiments it was observed that with increasing the plasma density the global time of confinement increases and the rate of the electron energy transfer becomes comparable with a neoclassical ion energy transfer.

As it was noted, there are two ways to substantially reduce the reactor sizes, i.e. to increase the time of the plasma confinement or to raise (significantly) the plasma pressure. The second variant appears to be the most optimal as, in addition, the plasma confinement improves. At an increase in the plasma density the global time of confinement grows and at large plasma densities the energy transfer becomes comparable with neoclassical one. Thus it is reasonable to suppose that at the high plasma densities considered below one can employ in calculations neoclassical coefficients for ions in the description of heat transfer in the magnetized plasma. With increasing the plasma density the rate of proceeding the reaction ($\sim n^2$) rapidly grows. Using a simplified model find a stationary solution to the problem of burning in the D-T mixture assuming the heat transfer due to the neoclassical mechanism:

$$(-1/r)\mathrm{d}/\mathrm{d}r(r\chi_{neo}\mathrm{d}T/\mathrm{d}r) = Q_\alpha - Q_{rad} \tag{3}$$

where T is the common temperature of electrons and ions (in a high density plasma this approximation is justified) and Q_{rad} is the plasma radiation. Note that at high temperatures Q_{rad} is mainly defined by bremsstrahlung [6]. And only at temperatures below ionization potential I, i.e. $T < I$, recombination radiation becomes prevailing. In its turn, the radiation of excited atoms starts playing its part only at the plasma edge where the degree of ionization of atoms is below 100 %. So at high temperatures $T \gg 13,6\,\mathrm{eV}$ we have $Q_{rad} \sim n^2\sqrt{T}$ [6]. For the boundary conditions we have:

$$T = T_0;\ \mathrm{d}T/\mathrm{d}r = 0 \text{ at } r = 0$$

In equation (3) we will use the simplified expression for neoclassic thermal conductivity $\chi_{neo} = \chi_{clas}\ q^2\varepsilon^{-3/2}$ [4,6] where χ_{clas} is so called "classical" thermal conductivity [5]:

$$\chi_{clas} \sim n^2T^2B^{-2}/T^{5/2} \qquad (4)$$

In the temperature range $5 < T < 20\,\mathrm{keV}$ the heat release rate Q_α, as a result of the nuclear fusion reaction is quite well approximation by the expression ($\varepsilon_\alpha = 3.5\,\mathrm{MeV}$ is the α- particle energy) [7]:

$$Q_\alpha = kn_Dn_TT^2\varepsilon_\alpha \qquad (5)$$

where n_D and n_T are the concentrations of deuterons and tritons, respectively and k is the numerical coefficient [7]. For the temperature range where $Q_{rad} \ll Q_\alpha$ from equation (3) together with the boundary condition (4) we find the approximate solution:

$$1/T^{3/2} - 1/T_0^{3/2} = (3/8)(E/A)r^2/4 \qquad (6)$$

where $E/A = B^2/100$ (at $q^2\varepsilon^{-3/2} \approx 30$), with the magnetic field measured in units of 5 T. An example in the figure shows the temperature profile for $B = 0.3$ and $T_0 = 10\,\mathrm{keV}$; as is seen, the burning area has a small enough radius and of about the same thickness are both the plasma with a lowered temperature $T < 4\,\mathrm{keV}$ from where the energy is removed by radiation and the neutral interlayer between the plasma and chamber "wall". At the same at $B = 0.3$ cyclotron radius of α-particles is compared with the thickness of a burning area and consequently the α-particle energy will be "spread" on plasma column radius. Note, that in the temperature range where the approximate relation for the velocity of heat release by α- particles (5) is true, solution (6) does not depend on nT. It means that the reactor power can be regulated by reducing or raising the plasma pressure. Note that at the aspect relation $\varepsilon \sim 1/3$ for the main radius we have estimate $R \sim 1\,\mathrm{m}$. Since the plasma pressure stays on constant along the plasma turn cross-section, it follows that the plasma density should be a growing function of the radius. The neoclassical coefficient of heat conductivity at $nT = \mathrm{const}$ is proportional to $\chi_{neo} \sim n^2T^2/T^{5/2}$, i.e. it reduces with the plasma temperature. Thus the burning mode considered can be unstable with the plasma transition into a state with a high temperature of $T \sim 70 - 100\,\mathrm{keV}$. So $D + He^3$ (or other

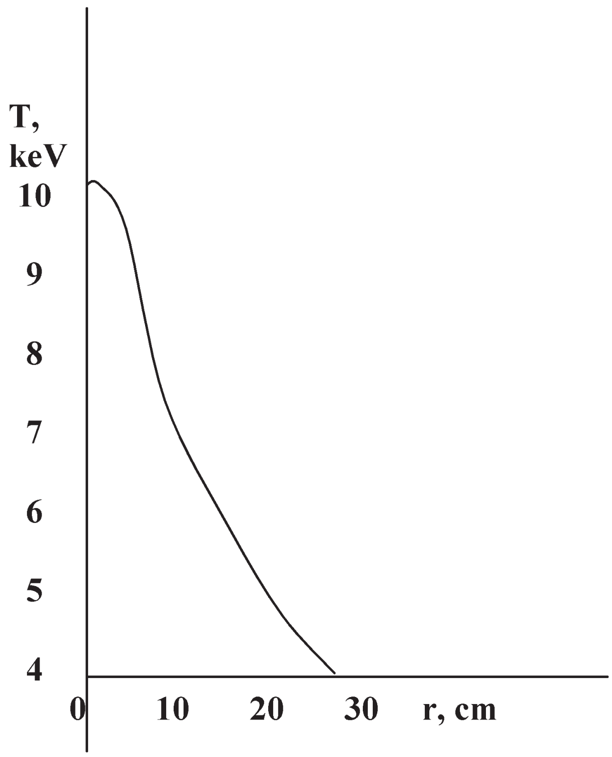

Fig. 1 Temperature distribution at nucler fusion burning using D + T mixture.

fuel mixtures) can be used in the reactor. One more important aspect should be noted. As it follows from the equality of the pressure $nT = \mathrm{const}$ at a plasma temperature falling along the radius the plasma density, on the contrary, should rise (at least in the central "hot" area). It means that the cyclotron radiation will be blocked inside the plasma and the main danger in building a reactor on the working mixture $D + He^3$, i.e. extremely high losses by cyclotron radiation, does not exist in the case considered. On the basis of the model equation (3) employed above one may also estimate a characteristic size of the area of burning when $D + He^3$ is used as fuel. Taking into account that a dependence of the reaction cross-section $D + He^3 \rightarrow He^4 + p$ is similar D + T reaction and the reaction cross-section $D + He^3$ at $T = 100\,\mathrm{kev}$ coincides with that of DT at $T = 10\,\mathrm{keV}$, but the energy release (18,65 MeV) is about five times greater, from (3) we find that the size of the area of burning in the $D + He^3$ mixture is about 4-5 times larger ($\sim 1\,\mathrm{m}$). To start burning when a high pressure gas interlayer is available in the tokamak chamber seems to be possible with using, *e.g.* CO_2- lasers [3]. By the author's estimate 5 – 6 MJ in a pulse of ~ 100 ns are the necessary parameters for the CO_2- laser. Creation of a CO_2- laser with a similar parameters is an engineering problem which can be resolved, if necessary, for 3 – 5 years. Besides, the HF plasma heating is possible which showed good results in tokamaks.

3. Conclusion

The results of the approximate analysis show that the suggested innovative concept of a fusion reactor with its plasma confined by a high pressure gas is characteristic of some properties:

(1) plasma is in a local equilibrium state and, hence, it is less susceptible to hazardous instabilities;

(2) in reactor a high pressure of plasma can be easily established, i.e. heat transfer, in accordance with existing knowledge will have a neoclassical character;

(3) reactor can have quite moderate sizes, about ~ 1 m;

(4) energy released in the process of burning is carried away by neoclassical thermal conductivity, bremsstrahlung produced radiation and recombination radiation (low temperatures);

(5) in the reactor $D + He^3$ mixture can be used as fuel. A very useful feature of the reactor is that a powerfull cyclotron radiation is trapped inside hot plasma.

In the author's opinion the creation of a reactor with plasma confinement by using of high-pressure gas appears to be a quite real problem. Desired gas pressures of ~ 10 to 100 bar are within the pressure range well worked out. The construction of lasers with desired parameters does not look like a serious engineering problem. Besides, the existing powerful HF generators can be used for plasma heating.

Essential is the fact that the reactors under consideration can be used for burning different fuel mixtures, such as $D + He^3$, etc.

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