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# Perspective of Creation of the Ambipolar D-T Fusion Reactor

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## Abstract

The ambipolar D-T fusion reactor with total axial symmetry and double end mirrors is offered as the prospect variant. The energy balance is estimated and conditions of MHD-stability are determined. A possibility to decrease the reactor length is pointed out.



## Key words:

ambipolar trap, MHD stability, power balance


## 1. Introduction

Several variants of the D-T fusion reactor on the basis of the ambipolar trap can be realized in principle. For realization total axial symmetric geometry we suggested to confine in trap a high pressure plasma ($\beta \sim 1$) and maintain its MHD stability by conducting walls and the FLR effect [1-4]. We think that double end mirrors suggested in [5] with thermal barrier for electrons are most prospect scheme.

This scheme is shown in Fig. 1. Plasma density in the thermal barrier mirror "m-h" is determined by passing ions from solenoid with density $n_{\rm ipas}$ and trapped ions with density $n_{\rm itr}$. ECR heating in the vicinity of point "b" produces a population of hot, magnetically trapped electrons with density $n_{\rm eh}$. At point "b" the ion density $n_{\rm bi} = n_{\rm bipas} + n_{\rm bitr}$ and the electrons density $n_{\rm be} = n_{\rm beh} + n_{\rm beth} + n_{\rm bepas}$, where $n_{\rm eth}$ and $n_{\rm epas}$ are densities of thermal electrons and passing electrons. The thermal barrier $\varphi_{\rm b} = T_{\rm s}\cdot\ln(n_{\rm s}/n_{\rm beth})$, where $n_{\rm s}$ and $T_{\rm s}$ are density and temperature of the solenoid plasma. If magnetic field at point "h" $B_{\rm h} \geq B_{\rm m}$ the plasma density in plug at point "p" is [6]

$$n_{\rm p} = n_{\rm s}\sqrt{\frac{T_{\rm ep}}{T_{\rm s}}}\ \exp\left(\frac{\varphi_{\rm c}+\varphi_{\rm b}}{T_{\rm ep}}\right)\exp\left(-\frac{\varphi_{\rm b}}{\varphi_{\rm c}}\right), \qquad (1)$$

where $T_{\rm ep}$ and $\varphi_{\rm c}$ are electron temperature in plug and

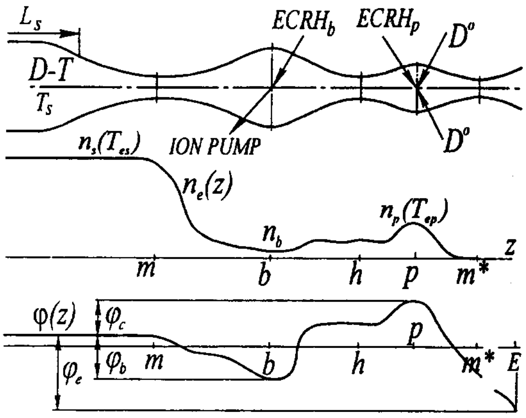


Fig. 1 The scheme of double end mirrors, $n_e(z)$ and $j(z)$ are longifudinal distributions of the plasma density and potential, $L_S$ is the solenoid length.

confinement barrier. The ECR heating power and the power of the $D^+$ ion injection into plug are approximately proportional to $n_{\rm beh}{}^2$ and $n_{\rm p}{}^2$. It is required to reduce the power consumption in end mirrors. Therefore densities $n_{\rm beh}$ and $n_{\rm p}$ are in need of decrease. To achieve small value of $n_{\rm p}$ and $n_{\rm beh}$ it is necessary that $\varphi_{\rm b} \gg T_{\rm s}$ and $n_{\rm beh} \ll n_{\rm beth} \sim n_{\rm bi} \ll n_{\rm s}$. A decrease of the density

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$n_{\rm bipas}$ is attained by increasing the mirror ratio $R_{\rm mb}$. Limitation of the density $n_{\rm itr}$ is obtained by ion pumping from the thermal barrier.

## 2. Solenoid

Parameters of the thermonuclear plasma in the solenoid depend primarily on its radius $r_{\rm ps}$ and power of the neutron flow per unit area of the first wall "q". On the plasma radius depend transverse plasma energy losses, which are assumed to be approximately equal to the longitudinal losses. We take the plasma radius in the solenoid $r_{\rm ps}$ = 1m.

For MHD stabilization of the plasma using conducting walls, the radial plasma pressure profile is of importance. We assume $p = {\rm const}(r)$ for $r < r_{\rm p} - \Delta r_{\rm p}$, and at the periphery in the interval $\Delta r_{\rm p}$ the pressure falls. In view of the dependence of the critical $\beta(\Delta r_{\rm p}/r_{\rm p})$ [7], we set $\Delta r_{\rm p} = 0.2\ r_{\rm p}$. In this case $\langle n_{\rm s}\rangle = 0.78\ \bar{n}_{\rm s}$ and and $\langle n_{\rm s}^2\rangle = 0.707\ \bar{n}_{\rm s}^2$, where $\bar{n}$ is the plasma density for $r < r_{\rm p} - \Delta r_{\rm p}$.

Assume that the temperature of the D-T plasma $T_{\rm s}$ = 25 keV. The gap $\Delta r_{\rm ws} = r_{\rm ws} - r_{\rm ps}$ must be larger than two maximum gyroradii of $\alpha$-particles. Here $r_{\rm ws}$ is the wall radius. From this condition we assume $\Delta r_{\rm ws}$ = 30 cm and $r_{\rm ws} = 1.3\ r_{\rm ps}$. Let us set the density $\bar{n}_{\rm is} = 1.5 \times 10^{14}{\rm cm}^{-3}$. Thence we find $q = 1.82$ MW/m$^2$. The fusion power multiplied in the blanket per unit length of the solenoid is obtained $P_{\rm sol}/L_{\rm s}$ = 24 MW.

Provision is made for the ripple wall MHD stabilization of the plasma in the solenoid [2]. Consider the modulation depth $\varepsilon_{\rm r} = \Delta B_{\rm r}/B_{\rm vs} = \pm 0.04$. For the radius of the solenoid coils 2.4 m, the length of a single ripple 6 m. For the length of the solenoid $L_{\rm s} \approx 150$ m the ripple number $N_{\rm r} \approx 25$. For the solenoid with vacuum mirror ratio $R_{\rm msv} = 7$, $2\varepsilon_{\rm r} \approx 0.08$, $2\varepsilon_{\rm r}N_{\rm r} \approx 2$, $r_{\rm w} = 1.3\ r_{\rm p}$ and $\Delta r_{\rm p} = 0.2\ r_{\rm p}$ from the results of calculations presented in [2,7] follows $\bar{\beta}_{\rm s}$ that must be larger than the critical value $\beta_{\rm cr} \approx 0.75$. Therefore we take with safety margin the value averaged over the length $\bar{\beta}_{\rm s} = 0.8$. Thence the magnetic fields, average over the solenoid length $B_{\rm sv}$ = 2T in vacuum and $\bar{B}_{\rm s} \approx 0.9$T in the plasma.

Magnetic field in the solenoid mirror throats $B_{\rm m}$ is taken to be 14 T and magnetic field in the plugs $\bar{B}_{\rm p}$ = 3.18 T. The ion confining potential $\varphi_{\rm c} = 4.2\ T_{\rm is}$ makes possible to have $n\tau_{\rm p\|} = 19 \times 10^{15}{\rm cm}^{-3}$ sec in the solenoid [8]. The electron confining potential $\varphi_{\rm e}$ (see Fig. 1) is determined by the formula from [9,10]. For $\tau_{\rm e\|} = \tau_{\rm i\|}$ we obtain $\varphi_{\rm e} = 11.2\ T_{\rm s}$. Thence we find longitudinal energetic life-time of the plasma $\tau_{\varepsilon\|}$ and $n\tau_{\varepsilon\|} = 3.47 \times 10^{14}{\rm cm}^{-3}$ sec. For ignited regime in the solenoid it is necessary to have $n\tau_{\varepsilon} = n\tau_{\rm L}\,(1 - \alpha_{\varepsilon 1})^{-1}$, where according to Lawson, $n\tau_{\rm L} = 1.61 \times 10^{14}{\rm cm}^{-3}$ sec and $\alpha_{\varepsilon 1}$ is the fraction of energy lost by ($\alpha$-particles into the loss-cone. From estimates $\alpha_{\varepsilon 1} \le 0.1$. Therefore $n\tau_{\varepsilon} = 1.79 \times 10^{14}{\rm cm}^{-3}$ sec and $n\tau_{\varepsilon\|} = 1.94\ n\tau_{\varepsilon}$. Thus at $\varphi_{\rm c} = 4.2\ T_{\rm is}$ transverse energy losses of the thermonuclear plasma in the solenoid close to the longitudinal ones are allowed.

## 3. Double End Mirror

The main problem in designing end mirrors where confining potential $\varphi_{\rm c}$ is created, is to decrease the power injected there. Although magnetic fields in the plugs $B_{\rm p}$ and in the thermal barriers $B_{\rm b}$ are moderate, to reduce the power there is a need to create maximum achievable magnetic fields in the mirror throats. We evaluated possible geometry of the superconducting mirror coils, generating fields of 14 T [11]. The system of such coils is shown in Fig.2. Fig 3 presents longitudinal distribution of magnetic field.

The main plasma parameters in the plug are the density and temperature of hot ions $n_{\rm ih}$ and $T_{\rm ih}$, and also the value $\beta_{\rm p}$ sufficient for MHD stability. To decrease the consumed power, $n_{\rm p}$ should be decreased and $T_{\rm ih}$ should be increased. However, in this case decreases the fraction of particles being trapped into the plasma during deuterium atom injection. We put $\bar{n}_{\rm p} = 5 \times 10^{13}{\rm cm}^{-3}$ and $T_{\rm ih}$ = 400keV. Using (1) we select the values of the thermal barriers $\varphi_{\rm b} = 4.5\ T_{\rm s}$ and the

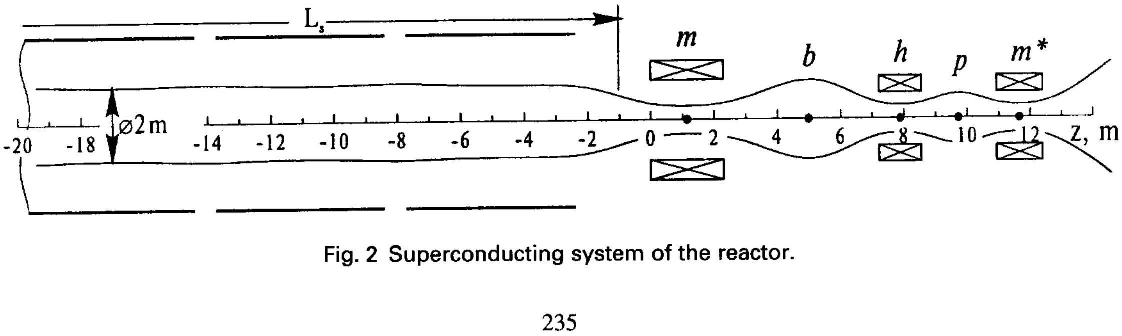


Fig. 2 Superconducting system of the reactor.

temperature of the plug electrons $T_{ep} = 3.07\ T_s$. Magnetic field $\bar{B}_p$ is determined from condition $n_{cr} \approx 1.5\ n_p$, where $n_{cr}$ is the critical density for ECR heating. It is designed injection at an angle ~70° to reduce microinstabilities in the midplane "p". We calculated angular and longitudinal distribution of hot ions in the plug and found the ratio of transverse pressure of hot ions to longitudinal one $p_\perp/p_\parallel = 2.4$ and $\bar{\beta}_{p\perp} = 0.65$ (the vacuum field $B_{pv} \approx 4.3$ T). Condition of the wall stabilization of m MHD mode is $G_w^{|m|} > 1$ [1,4]. For $r_w = 1.2\ r_p\ G_{w\,all}^{|1|} \sim 2.3$. The modes $m = 2, 3$ are stabilized by wall also. The modes $m > 3$ are stabilized by FLR effect [1].

The main plasma parameters in the barrier "b" are the density and $\beta$. For $\varphi_b = 4.5\ T_{es}$ the density of thermal electrons $n_{beth} = 1.67 \times 10^{12}\text{cm}^{-3}$. For suppression of the counter-stream instability we take $n_{bitr} = 2.5\ n_{bipas}$ and $n_{bi} = 10^{13}\text{cm}^{-3}$. For this $n_{bi}$ we find the mirror ratio $\bar{R}_{mb} = 12$ and corresponding magnetic field $\bar{B}_p$ = . We put $\bar{\beta}_{p\perp} = 0.7$. For the ion charge squared $\langle z_i^2 \rangle = 2$ and $n_e = 1.25\ n_i$ in the thermal barrier mirror, we find the temperature of the hot electrons $T_{eh}$ = 360 keV. If electrons are heated at the 2-nd harmonic ($\bar{\lambda}_2$ = 7.7 mm at the plateau), $n_{cr} \approx 1.5\ n_{be}$.

The evaluated anisotropy of hot electrons in thermal barrier is $p_\perp/p_\parallel = 1.9$. For $r_w = 1.2\ r_p$ the wall MHD stability factor $G_{w\,all}^{|1|} \sim 2.6$. Some modes m < 5 are stabilization by wall also. FLR effect in the barrier is weak, therefore higher MHD modes can be stabilized only by neighboring cells.

## 4. Power Balance

The energy consumption in the end mirrors by hot electrons $n_{eh}$, hot ions $n_{ih}$ and electrons $n_{ep}$ heated in the plug is determined with distributions of the different particle populations. The calculated longitudinal distributions of particles are presented in Fig.4. They allow to self-consistently define potential distribution $\varphi(z)$, shown in Fig.1. In accordance with Fig.3 the plasma volume is 1.9 m$^3$ in the plug and 7 m$^3$ in the thermal barrier mirror.

Below are presented the calculated different parts of consumption power in the end mirrors. The power devoured by the trapped hot D$^+$ ions in the plag "p" is about 1.15MW. Because of the low trapping coefficient of 30%, the power of injected atomic beams will be 3.8MW. The hot electrons lose their energy by scattering into the loss-cone 47.5MW, by heating thermal and passing electrons in the region m-h 5.2MW and by cyclotron radiation 14.6MW. The barrier hot

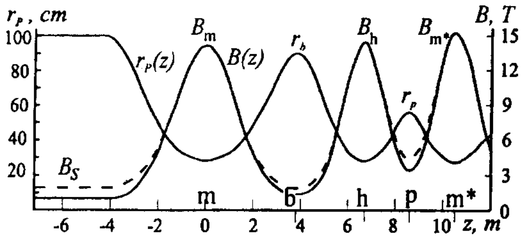


Fig. 3 The plasma radius $r_p(z)$ and magnetic fields $\bar{B}(z)$ (solid curve) and $B_V(z)$ (dashed curve).

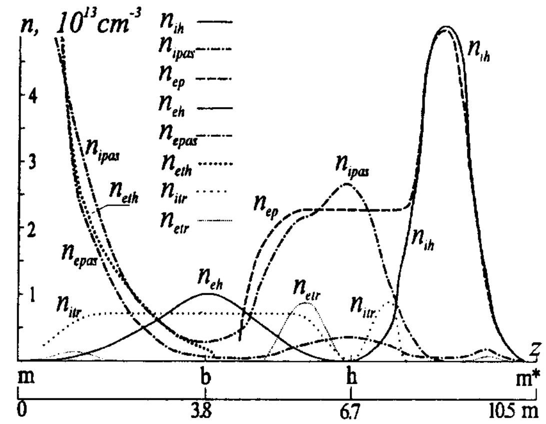


Fig. 4 Distributions of different particle populations in the double end mirror.

electrons also heat the plug electrons $n_{ep}$ in the region b-h (see Fig. 4). This heating consumes about 2.8MW. In the end the ECR-heating power in the barrier mirror is about 70MW. The heated plug electrons scatter from an electrostatic well, being substituted by warm electrons from the solenoid. The power expended in heating the latter is about 8.2MW. In addition, 9MW is expended by the plug electrons in heating the passing electrons, particularly, about 5MW in the plug. Cyclotron radiation consumes about 2.3MW. Total power losses add up to 19.5MW, in particular, 8.5MW in the barrier mirror. The ECR-heating power in the plug is about 16.7MW.

In result, the power consumption in each end-mirror system $P_{end} \approx 88$MW. For the solenoid length $L_s$ = 150m we obtain the power gain factor $Q = P_{sol}/2P_{end}$ = 20.45. The summary power is 3600MW, particularly the fusion power 2830MW and the fast ions power escaping the end mirrors about 560MW.

## 5. Conclusion

In the considered double end mirrors, the main part of power is consumed by hot electrons in thermal barrier. There is possibility to create the thermal barrier by passing ions spontaneously without ECRH in the thermal barrier mirror [3]. In this case

$$\frac{n_{\mathrm{beth}}}{n_{\mathrm{s}}}\sqrt{\ln\frac{n_{\mathrm{s}}}{n_{\mathrm{beth}}}} \approx \frac{1}{\sqrt{\pi}}\left(1+\frac{n_{\mathrm{bitr}}}{n_{\mathrm{bipas}}}\right)\left(1+\frac{n_{\mathrm{bepas}}}{n_{\mathrm{beth}}}\right)^{-1}\frac{1}{R_{\mathrm{mb}}}.$$

At $B_{\mathrm{m}} \sim 20\mathrm{T}$ it is possible to achieve $R_{\mathrm{mb}} \sim 30$. As a result, it is attained small value $n_{\mathrm{beth}}$ and relatively large value of $\varphi_{\mathrm{b}}$. From estimations, in this case the power consumption in the double end mirrors can be reduced twice compared to the end mirrors considered. For $Q = 20$ the solenoid length can decrease to 75m. The superconducting "choke" coils, generating field of 20T can be developed.

For creation of the ambipolar D-T reactor a number of physical and physics-technique problems must be experimentally studied. The key problems are: ion pumping and suppression instabilities of passing ions in the thermal barriers, increase of the first wall lifetime in the solenoid.

Creation of the ambipolar D-T reactor will open the way to realization of low radioactive ambipolar D-$^3$He fusion reactors [12].

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