INTRODUCTION

Research fusion reactor (RFR) [1-3] is meant for investigations at full-scale conditions of self-sustained plasma in order to obtain an exhaustive information about a possibility of creating an economically profitable (commercial) fusion reactor. The time allowed for obtaining this information must not exceed the service life of the RFR 1st wall, because the replacement of the 1st wall at high induced radioactivity conditions is the next unsettled problem. That is why the RFR is projected as a reactor with an increased service life of the 1st wall up to 10...20 years (instead of 5...6 years in existing designs, where \( r_{pl}/r_{w} \sim 1, r_{w} \) –plasma radius, \( r_{o} \) –1st wall radius). This can be achieved through an increase of the 1st wall surface area as compared to the plasma surface area \( (r_{pl}/r_{w}<<1) \), that will permit an essential reduction in the specific load on the 1st wall, approaching the present state of the art (e.g., \( \sim 0.3...0.5 \) MWT/m² for the austenitic stainless steel).

In the closed stellarator-type magnetic systems the condition \( r_{pl}/r_{w}<<1 \) is equivalent to an increase in the distance between the closed magnetic surface region (average radius \( r_{o} \)) and the torus surface (radius \( a \)), which is traversed by electrical currents, \( r_{w}/a<<1 \). The possibility of realizing this condition in the classical stellarators and torsatrons without an additional longitudinal magnetic field was partially discussed in [1-3]. In this communication, we pay attention to the possibility of realizing this condition in the classical stellarators and torsatrons with an additional longitudinal magnetic field, the direction of which is opposite to the magnetic field of the helical system can generally be formed with the help of a torsatron with an additional reversed longitudinal magnetic well value is also considered.

MAGNETIC SURFACES IN THE LINEAR APPROXIMATION

The initial idea of the magnetic field structure in a helical system can generally be formed with the help of a linear approximation. In this case, the magnetic field has a helical symmetry and can be described analytically [5,6]. If \( (2\pi a/L)^{2}<<1 \), where \( a \) is the radius of the cylinder on the surface of which the same-direction helical currents \( I \) flow, \( L \) is the pitch of helical winding, then in accordance with [5], one can determine the magnetic surface function \( \psi(r,\theta) \) with any polarity \( I \). In particular, for the \( l=2 \) system it has the form:

\[
\psi(r,\theta) = \left( B_{o} + B_{l} \right) \frac{\pi r^{2}}{L} - \frac{\mu}{2a} \cos \theta \left( \left( \frac{r}{a} \right)^{2} - 1 \right) \left( \ln \left( \frac{r}{a} \right) - 1 \right).
\]

Here \( r, \theta, \zeta \) are the cylindrical coordinates, \( \theta = \varphi - 2\pi \zeta / L, \mu \) is the magnetic constant. Figure 1 presents the crosssection for the magnetic surfaces calculated by eq.(1) with the sign “+” in the right-hand first term (i.e., the additional longitudinal magnetic field \( B_{l} \) is reverse as its direction is opposite to the magnetic field \( B_{o} \) generally formed by helical currents \( I \) on the geometrical axis of the system).

\[
r_{w}/a = (1-L_{o}^{2}/4\pi^{2} a^{2}(B_{o}/B_{r}=-1))^{0.5}
\]

It is seen from Fig.1 that the magnetic axis of the magnetic surface configuration is coincident with the geometrical axis, \( r_{w}/a=0 \), the separatrix ribs are located on the helical conductor azimuths. For the rib radial position \( r_{s} \), we have:

\[
r_{s}/a = (1-L_{o}^{2}/4\pi^{2} a^{2}(B_{o}/B_{r}=-1))^{0.5}
\]

CALCULATIONS OF TOROIDAL SYSTEMS

The list of the calculation model input data looks as follows:
1) \( l=2, m=1 \) torsatron-like magnetic system, toroidicity \( a/R_{o} = 0.3, R_{o} \) is the major radius;
2) the winding law of filament-like helical conductors \( \varphi = m \varphi \) , (cylindrical law), \( \varphi \) is poloidal angle, \( \varphi \) is toroidal angle;
3) the uniform additional transverse magnetic field \( B_{o}/B_{r}=1.396 \). This \( B_{o}/B_{r} \) value provides that the magnetic axis major radius \( R_{eq}/R_{o}=0.9817 \), the magnetic axis minor radius \( r_{w}/R_{o}=0 \) (plane magnetic axis regime);
4) the additional longitudinal magnetic field \( B_{o}/B_{r}=B_{o}/R_{o} \), axisymmetrical, \( R \) is the radial position of the observation point, reckoned from the principal straight \( z \) axis of the system. The calculations were carried out for \( B_{o}/B_{r}=\sim 17.5 \) and \( B_{o}/B_{r}=\sim 22.5 \).
Fig. 2. Magnetic surface cross-sections within ½ magnetic field period for the $B_z/b_o=1.396$, $B_o/b_o=-17.5$ regime.

Fig. 2 shows the cross-sections of the closed magnetic surface region within ½ magnetic field period for the $B_z/b_o=1.396$, $B_o/b_o=-17.5$ regime, provided that $r_{lc}/a=0.2$. It is evident that the assumed plasma confinement region is rather well centered.

Fig. 3 shows the cross-sections of the closed magnetic surface region within ½ magnetic field period for the $B_z/b_o=1.396$, $B_o/b_o=-22.5$ regime, provided that $r_{lc}/a=0.36$.

The magnetic surface characteristics of the regimes under comparison are given in Table 1. Here $-U_{lc}$ is the magnetic well value on the last closed magnetic surface (LCMS), $i_{ax}$, $i_{lc}$ are the rotational transform angles (in units of $2\pi$) near the magnetic axis and on the LCMS, $\gamma_{ax}$, $\gamma_{lc}$-the magnetic field mirror ratio values on the magnetic axis and on the LCMS, respectively; $r_{lc}$ is the average LCMS radius.

<table>
<thead>
<tr>
<th>$B_z/b_o$</th>
<th>-17.5</th>
<th>-22.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_o/b_o$</td>
<td>1.396</td>
<td>1.396</td>
</tr>
<tr>
<td>$R_{cc}/R_o$</td>
<td>0.9817</td>
<td>0.9817</td>
</tr>
<tr>
<td>$r_{lc}/a$</td>
<td>0.2</td>
<td>0.36</td>
</tr>
<tr>
<td>$-U_{lc}$</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>$i_{ax}$</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>$i_{lc}$</td>
<td>0.25</td>
<td>0.16</td>
</tr>
<tr>
<td>$\gamma_{ax}$</td>
<td>1.05</td>
<td>1.07</td>
</tr>
<tr>
<td>$\gamma_{lc}$</td>
<td>1.22</td>
<td>1.41</td>
</tr>
</tbody>
</table>

From the analysis of Table 1 it becomes clear that in the TRF the magnetic well does exist in spite of the magnetic surface configuration displacement inward the
torus ($R_{ax}/R_o=0.9817<1$). The magnetic well value increases if the $B_o/b_o$ value increases. This can be observed in situ during the running experiment at a fixed $B_o$ value by decreasing the helical current. The magnetic well increase is accompanied by an increase in the rotational transform angle. A further development of the thesis about the capability of the $l=2, m=1$ torsatron with an additional reversed longitudinal magnetic field to be the base for the RFR magnetic system calls for theoretical, experimental and engineering-technical investigations of this torsatron as a plasma trap. To a certain extent, this can be done with the help of the $l=2, m=2, a/R_o=0.26$ torsatron U-2M device (IPP NSCKIPT) [7], which has powerful coils to provide the additional longitudinal magnetic field, and is the nearest variant among the now-existing toroidal magnetic systems similar to the system considered here. Preliminary calculations of the U-2M-like TRF configuration model show that the $B_o/b_o=0.495$ value provides the magnetic axis major radius $R_{ax}=0.9505$, the magnetic axis minor radius $r_{in}/R_o=0$ (plane magnetic axis regime). The LCMS wholly falls within the vacuum chamber cross-section (see Fig.4) for the $B_o/b_o\geq 8.125$ value. The magnetic hill value on the LCMS is $U_{w}\sim-4\%$, the rotational transform angle $i=0.2...0.4$ (in units of $\pi$, shear), the magnetic field mirror ratio $\gamma=1.04...1.3$. Compared to the ordinary U-2M configuration for the same fixed plasma confining magnetic field strength, the helical current will decrease by factor of ~2.3, the toroidal coil current will increase by factor of ~1.7 in the U-2M-like TRF configuration. The transverse magnetic field coil current, the helical coil ponderomotive forces, and the helical component of the mirror ratio are supposed to be decreased, too.

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REFERENCES