A TORSATRON WITH A REVERSED LONGITUDINAL MAGNETIC FIELD AS A MAGNETIC SYSTEM FOR A RESEARCH FUSION REACTOR

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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 unsetlled 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 ~1, r_{pl} –plasma radius,. r_w –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., ~0.3…0.5 MWt/m^2 for the austenitic stainless steel).

In the closed stellarator-type magnetic systems the condtion r_{pl}/r_w<<1 is equivalent to an increase in the distance between the closed magnetic surface region (average radius r_{lc}) and the torus surface (radius a), which is traversed by electrical currents, r_{lc}/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 r_{lc}/a<<1 magnetic configuration creation using a torsatron with an additional reversed longitudinal magnetic field, the direction of which is opposite to the usual one (TRF, see also [4]). The present calculations of the magnetic surfaces and their properties refer to the TRF model with filament-like helical conductors. The TRF magnetic surface configuration with an increased 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 l. In particular, for the l=2 system it has the form:

$$\Psi\ (r,\theta\ ) = (\pm B_o + b_o)\frac{\pi r^2}{L} - \frac{\mu_o I}{2\pi}\ln\left(1 - 2\left(\frac{r}{a}\right)^2\cos 2\theta + \left(\frac{r}{a}\right)^4\right) \quad (1)$$

Here r, ∂, ζ are the cylindrical coordinates, $\theta = \partial - 2\pi\zeta/L$, μ_o 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_o 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).

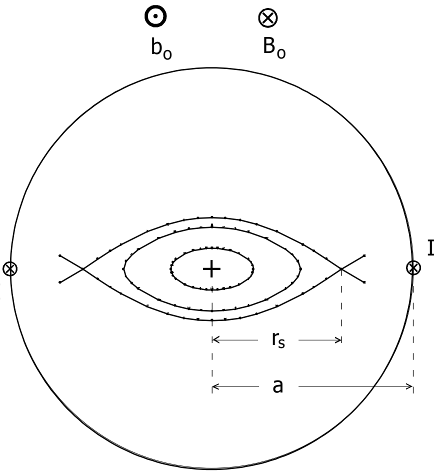

Fig.1. Magnetic surfaces in the l=2 straight torsatron with a reversed additional longitudinal magnetic field. The additional longitudinal magnetic field coils are not shown

It is seen from Fig.1 that the magnetic axis of the magnetic surface configuration is coincident with the geometrical axis, r_{ax}=0, the separatrix ribs are located on the helical conductor azimuths. For the rib radial pozition r_s we have:

$$r_s/a = (1 - L^2/4\pi^2 a^2 (B_o/b_o - 1))^{0,5} \quad (2)$$

It is seen that the presented magnetic surface configuration can be realized if the absolute value of B_o is much greater than b_o, $B_o/\ b_o > 1 + L^2/4\pi^2 a^2$.

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 $\partial = m\varphi$, (cylindrical law), ∂ is poloidal angle, φ is toroidal angle;

3) the uniform additional transverse magnetic field B_z/b_o=1.396. This B_z/b_o value provides that the magnetic axis major radius R_{oax}/R_o=0.9817, the magnetic axis minor radius r_{ax}/R_o=0 (plane magnetic axis regime);

4) the additional longitudinal magnetic field $B_\varphi = -B_o R_o/R$, 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_o=-17.5 and B_o/b_o=-22.5.

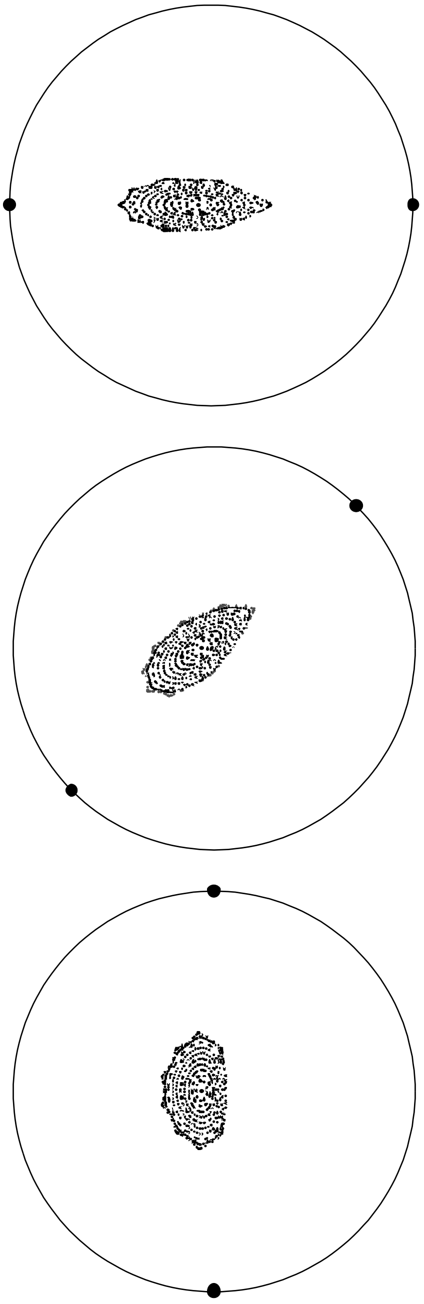

Fig. 2. Magnetic surface cross-sections within ½ magnetic field period for the B_z/b_o=1.396, B_o/b_o=-17.5 regime.

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 $r_{lc}/a\approx0.2$. 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 $r_{lc}/a\approx0.36$.

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 2π) near the magnetic axis and on the LCMS, γ_{ax}, γ_{lc}-the magnetic field mirror ratio values on the magnetic axis and on the LCMS, respectively; r_{lc} is the average LCMS radius.

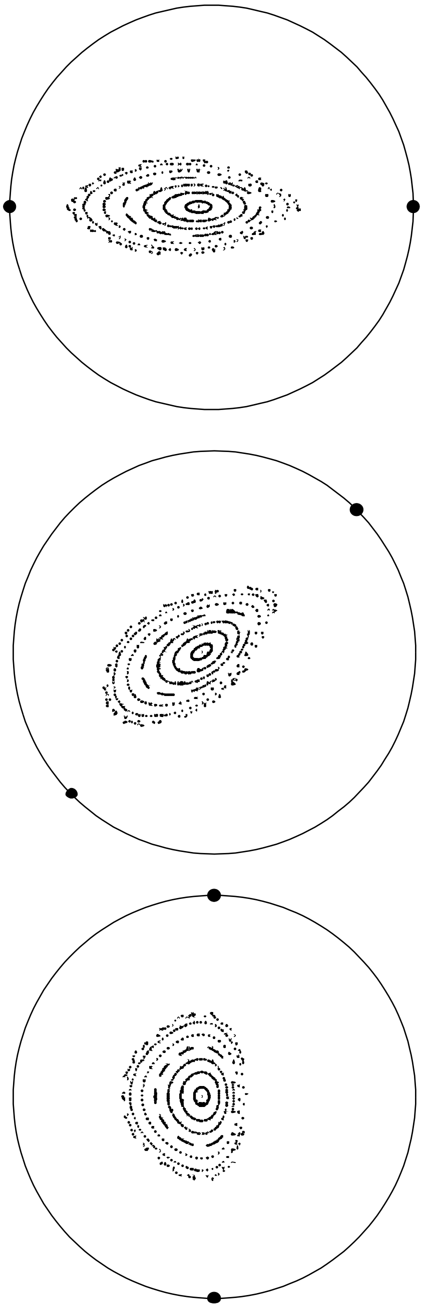

Fig. 3. Magnetic surface cross-sections within ½ magnetic field period for the B_z/b_o=1.396, B_o/b_o=-22.5 regime.

Table 1

B_o/b_o	-17.5	-22.5
B_z/b_o	1.396	1.396
R_{oax}/R_o	0.9817	0.9817
r_{ax}/R_o	0	0
r_k/a	0.2	0.36
$-U_{lc}$	0.04	0.08
i_{ax}	0.22	0.12
i_{lc}	0.25	0.16
γ_{ax}	1.05	1.07
γ_{lc}	1.22	1.41

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 ($R_{oax}/R_o=0.9817<1$). 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 the LCMS average radius and a decrease in the rotational transform angle.

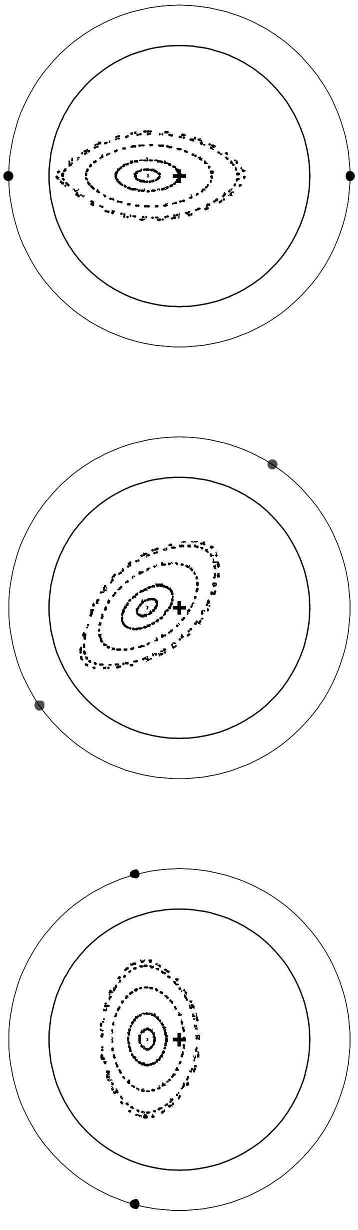

Fig. 4. Magnetic surface cross-sections within ½ magnetic field period for the U-2M -like TRF model. The inner circle is the contour of the vacuum chamber cross-section

SUMMARY

The present numerical calculations give a reason to believe that by the parameters analysed here the l=2, m=1 torsatron with an additional reversed longitudinal magnetic field can be considered as a probable candidate for the RFR magnetic system, where, for example, $r_{pl}/r_w\sim0.3$ and austenitic stainless steel is the main structural material of the 1st wall [2,3]. This torsatron magnetic system can provide the $r_{pl}/r_w\sim0.1…0.4$ configuration and the basically plane magnetic axis. In addition, the magnetic surface parameters can be controlled *in situ* during the running experiment by varying the B_o/b_o ratio, they lie in the range, that meets the present-day demands. This relates, in particular, to the mirror ratio γ, whose value little differs from the γ_{min} value specified by the longitudinal magnetic field toroidicity.

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_z/b_o=0.495 value provides the magnetic axis major radius R_{oax}=0.9505, the magnetic axis minor radius r_{ax}/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 $U_{lc}\sim4\%$, the rotational transform angle $i\sim0.2…0.4$ (in units of 2π, shear), the magnetic field mirror ratio $\gamma\sim1.04…1.3$. 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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