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SPHERICAL TOKAMAKS WITH OUTBOARD STELLARATOR WINDINGS

P.E. MOROZ
Department of Engineering Physics,
University of Wisconsin,
Madison, Wisconsin,
United States of America

ABSTRACT. The possibility of adding stellarator features to the extremely compact configuration of a spherical tokamak (ST) is analysed. This is accomplished by introducing outboard stellarator windings (OSWs). Two types of OSW are studied, a classical stellarator type and a torsatron type, and both are shown to be effective. Numerical calculations are presented for a simplified model of the NSTX tokamak. Among the main potential advantages of using OSWs in a ST are the possibility of non-inductive plasma startup or improved inductive operation caused by the existence of closed vacuum flux surfaces and an external rotational transform.

1. INTRODUCTION

Significant interest has developed in the last few years in the spherical tokamak (ST) concept [1–10], which promises a more compact, less expensive, less disruptive and higher β approach when compared with a standard tokamak. Quite a few ST type configurations have been explored experimentally. Among them are START [1, 2], CDX-U [3, 4], HIT [5] and TS-3 [6]. A number of new ST experimental devices are presently under construction: MAST [7], NSTX [8], GLOBUS-M [9] and PEGASUS [10].

Two of the challenges for the ST programme, when extrapolated to an economical fusion reactor, are the plasma startup and steady state operation. These problems are partially caused by the nature of the ST design with very little space available near the narrow central post, which must carry large currents. As a result, the central post cannot be effectively protected from neutron, fast particle and heat fluxes and a central ohmic current transformer cannot be used. The use of auxiliary current drive methods (such as neutral beam injection or various standard methods of radiofrequency current drive (RFCD)), although possible, is difficult and expensive, especially at the startup phase when the plasma is relatively cold.

The spherical stellarator (SS) concept [11–17] is being developed, partially to overcome the above mentioned problems of STs. However, an SS requires that the main toroidal field (TF) coils be able to produce an external rotational transform, which means that they cannot be just vertical planar coils, as they are in STs. The transformation of an ST into an SS is usually not a simple engineering task.

In this paper, we would like to stress another possible way of introducing the external rotational transform to the ST configurations without replacing the main TF coils of the system. It is clear that because of the very tight aspect ratio of STs it is impossible to put any standard kind of stellarator coils inside or outside the TF coils because such coils have to encircle the plasma in the poloidal direction and go through the central post area where there is no space available. However, the opportunity, which we would like to discuss here, exists to use only outboard stellarator windings (OSWs) that do not encircle the plasma in the poloidal direction.

The idea of using OSWs, although not in respect to ST configurations (nobody thought about STs at that time), appeared long ago [18]. The authors of Ref. [18] considered OSWs that we classify here as a standard stellarator type OSW. The purpose of that paper was just to present the approximate analytical arguments about why OSWs might produce stellarator effects. The first numerical calculations of the vacuum fields produced by OSWs, again for relatively large aspect ratios and with 'stagnation' or compensation loops located at the small major radii, were published in Ref. [19] (such loops are acceptable for the large aspect ratios but they cannot be used in the ultra-low aspect ratio devices such as STs). A small experimental tokamak with an additional OSW (it was called a semi-stellarator) was constructed [20], and the positive effects of OSWs on

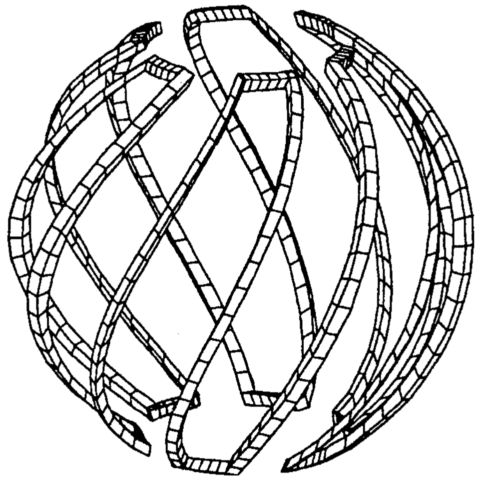

FIG. 1. Classical stellarator type OSW.

plasma stabilization were found. However, the type of OSW used in Ref. [20] did not allow the vacuum flux surfaces to exist. In the numerical calculations described in Ref. [20], the closed flux surfaces were found only in cases with loops modelling the plasma current. The ideas of using OSWs, consisting of a sawtooth shaped coil, for the suppression of current disruptions in a standard large aspect ratio tokamak, Phaedrus-T, have been the central part of the USDOE proposal developed by the Phaedrus-T group in collaboration with Georgievskij and Rudakov [21, 22].

In this paper, we present new results on OSWs. We consider two in principle different types of OSW and show that both of them have significant advantages and potential when used in low aspect ratio devices. One type of OSW is somewhat similar to the classical stellarator windings and includes helical elements with currents in opposite directions, while the second type is similar to the typical torsatron windings and includes helical elements with unidirectional currents only. Configurations of practical interest with large enclosed volume and substantial rotational transform are found and described in detail. Numerical calculations are carried out for a simplified model of the NSTX tokamak with twelve TF coils and three pairs of outboard poloidal field (PF) rings. The OSW is positioned close to the plasma inside the TF and PF coils.

We did not try to make a careful engineering design of OSWs for NSTX, since this would have required special resources and close collaboration with the NSTX team engineers to satisfy all the requirements of the experiment. Instead, we considered a simplified model of the NSTX coils that was easy to parametrize

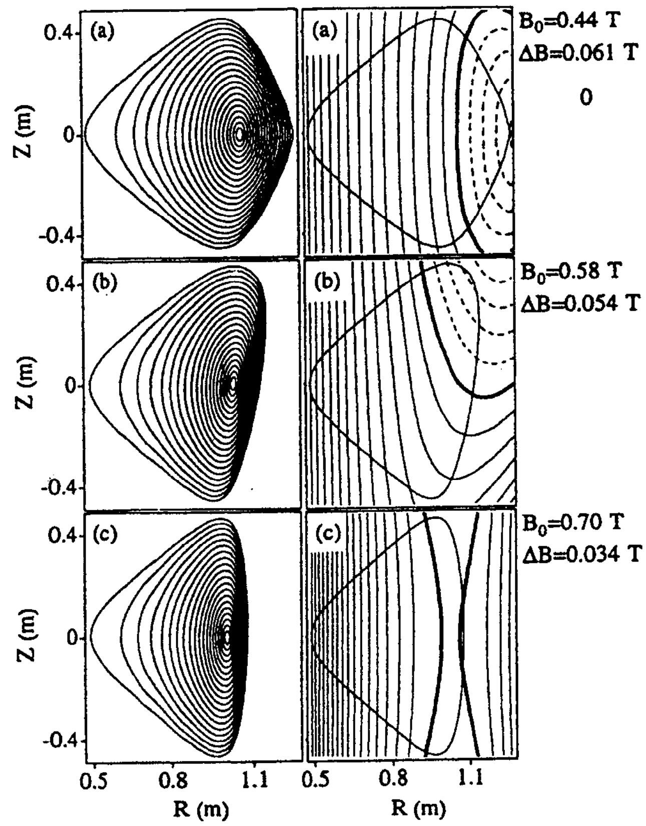

FIG. 2. Left side, closed vacuum flux surfaces produced by the classical stellarator type OSW: (a) $\varphi = 0$, (b) $\varphi = \pi/(2N)$ and (c) $\varphi = \pi/N$. Right side, $|B|$ distributions in the corresponding cross-sections, where B_0 corresponds to the bold contour lines and ΔB is the difference between neighbouring contours.

for the numerical calculations. The NSTX coil system was modelled by single filament currents flowing through the D shaped TF coils and circular PF rings. The vertical centre post contained the currents of the central parts of all the TF coils. The PF rings were located within the TF coils (as in the actual NSTX tokamak), and the outboard parts of the TF coils were modelled as being half-elliptical. All dimensions were chosen to be close to those of the NSTX tokamak. This paper shows the feasibility and advantages of using OSWs in an ST device, with NSTX used as an example.

2. STELLARATOR EFFECTS PRODUCED BY OSWs

In a 'classical' stellarator with continuous helical windings (for example, the stellarators Wendelstein 7-A [23] and L-2 [24]), $2L$ helical windings are used, L being the poloidal multipolarity. The currents in

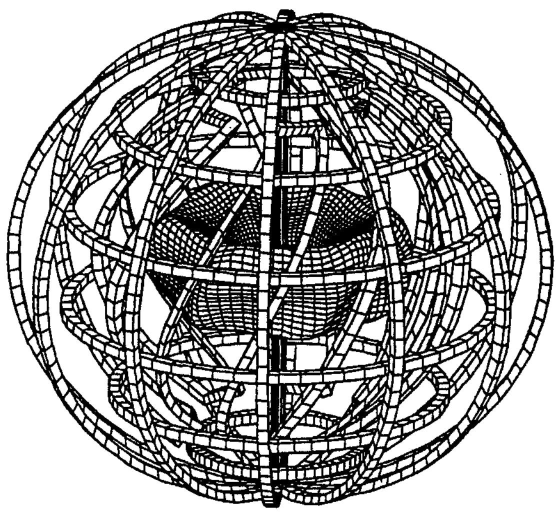

FIG. 3. Side view on the configuration with the classical stellarator type OSW.

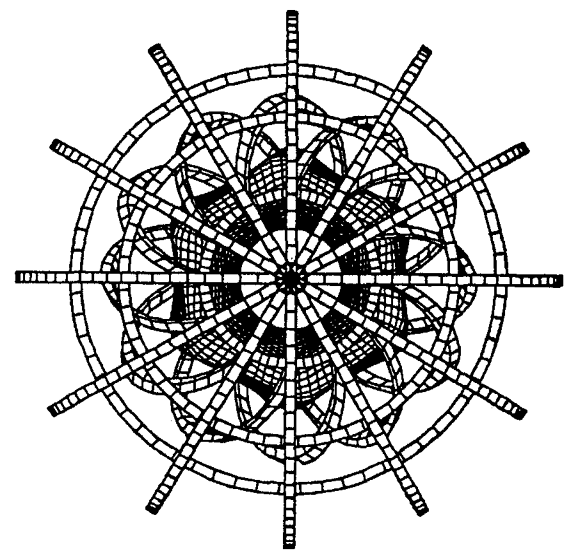

FIG. 4. Top view on the configuration with the classical stellarator type OSW.

adjacent windings have opposite signs. The toroidal magnetic field is produced by a separate set of the planar TF coils. The advantage of this configuration is that the average vertical magnetic field, produced by the helical windings with alternating currents is compensated, and hence the system usually requires less current in the PF rings to control the equilibrium. Also, the capability of independently regulating the helical field component permits significant variation of magnetic configuration properties.

The general idea behind introducing OSWs is the possibility of effectively using only the outboard parts of the helical windings, which is crucial for low aspect ratio devices. The six period classical stellarator type OSW, considered in this paper, is presented in Fig. 1. The currents in the PF rings are required to compensate for the vertical magnetic field produced by the horizontal parts of the OSW (and not by the main helical parts).

To obtain the vacuum flux surface geometry and other characteristics of the magnetic field, we have used the field line tracing code, UBFIELD (see, for example, Ref. [25]). A few optimization rules, formulated in Ref. [25], have been used to find the currents in the PF rings to optimize the characteristics of the magnetic field configuration. However, the size and location of the TF coils and PF rings have not been optimized because we were trying to use approximately the same coils that were originally designed for standard NSTX operation.

Figures 2 to 4 correspond to the following currents (normalized to the current in a TF coil): $I_{OSW} = 4$, $I_{PF1} = 0.036$, $I_{PF2} = 0.144$, $I_{PF3} = 2.16$. The

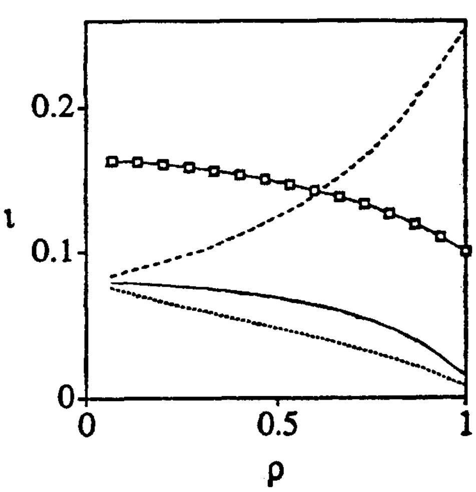

FIG. 5. Radial profile of the total rotational transform (solid curve) and its outboard (dashed) and inboard (dotted) components. The curve with squares corresponds to the increased current, I_{OSW}.

subscripts PF1, PF2 and PF3 denote PF rings with the values of (major radius/height), correspondingly, of 2.0/0.5, 1.55/1.35 and 0.8/1.9 metres.

The resulting set of closed vacuum flux surfaces is given in the left part of Fig. 2, where three main poloidal cross-sections are shown: (a) $\varphi = 0$, (b) $\varphi = \pi/(2N)$ and (c) $\varphi = \pi/N$ (half-period), where $N = 6$ is the number of field periods and φ is the toroidal angle. The right part of Fig. 2 shows the $|B|$ distribution in the corresponding cross-sections. One can see that, as in a case of an SS [11–17], the inboard parts of the flux surfaces feature toroidal symmetry while the outboard parts are clearly three dimensional, as

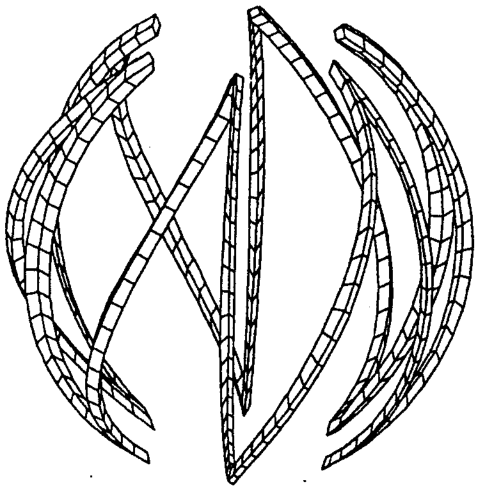

FIG. 6. Torsatron type OSW.

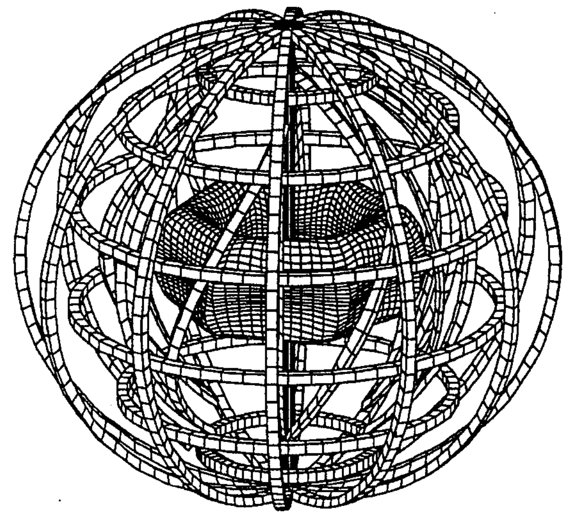

FIG. 7. Side view on the configuration with the torsatron type OSW.

in a typical stellarator. A side view on the configuration, which includes all the coils and the last closed vacuum flux surface, is presented in Fig. 3, while the top view is shown in Fig. 4.

The vacuum flux surfaces shown have a strong magnetic well of $W = 65\%$, which is important for good plasma stability. The aspect ratio is about $A \approx 2$. The total rotational transform is not high for this particular configuration and is about $\iota = 0.08$ (which corresponds to the safety factor $q = 1/\iota = 12.5$). However, the rotational transform is strongly asymmetric poloidally, and the local values of ι at the outboard locations are substantially higher. Figure 5 shows the radial dependence (ρ is the normalized minor radius) of the total rotational transform, ι, as well as its outboard, ι_{out}, and inboard, ι_{in}, parts [11]. The value of ι_{out} reaches 0.26 at the plasma edge. The enclosed volume is also rather large and thus the initial plasma of interest might be produced non-inductively in this device. The rotational transform can be increased, in principle, by either increasing the OSW current or lowering the TF field. For illustration, the curve indicated by squares in Fig. 5 shows the radial profile of the total rotational transform for the same case but with a lower current in the TF coils, so $I_{OSW} = 12$. In that case, the vacuum ι is greater than 0.1 everywhere in the plasma region. However, the price that one has to pay for such an increase in ι is a significant reduction (by a factor of 4 in this example) in the enclosed volume. Lowering the TF field further ($I_{OSW} = 100$), we were able to reach $\iota(0) = 0.4$. However, the enclosed volume of the vacuum flux surfaces was very small.

Torsatron type OSWs feature helical currents in one direction only. One possible OSW of this type, again with six field periods, is shown in Fig. 6. Opposite to the previous case, the helical parts of the OSW produce the vertical magnetic field, which has to be compensated for by the currents in PF rings, while the vertical parts of the OSW do not produce such a vertical magnetic field.

Again, optimization has been performed in respect to current magnitudes, while the location of the TF and PF coils was the same as in the previous case. Qualitatively, the properties of this magnetic configuration were close to those of the previous case. Figure 7 thus shows only a side view of the whole ST configuration with the torsatron type OSW and the last closed vacuum flux surface obtained in our calculations. This case corresponds to the following normalized currents: $I_{OSW} = 4$, $I_{PF1} = 1.1$, $I_{PF2} = 0.88$, $I_{PF3} = 0.66$. Thus, both types of OSW considered might be effective for use in an ST.

3. EFFECTS OF THE PLASMA CURRENT

The ST devices normally operate with a large plasma current. Thus, after the initial plasma startup which can, in principle, be currentless in an ST with an OSW similar to that in a typical stellarator, the plasma current has to be induced to make a transition to the standard ST operation. To study the effects of the plasma current on the properties of an ST with an OSW, we have used a three dimensional (3-D) MHD equilibrium code, VMEC [26, 27], with the free boundary solver [28] included. The main results of these calculations can be formulated as follows.

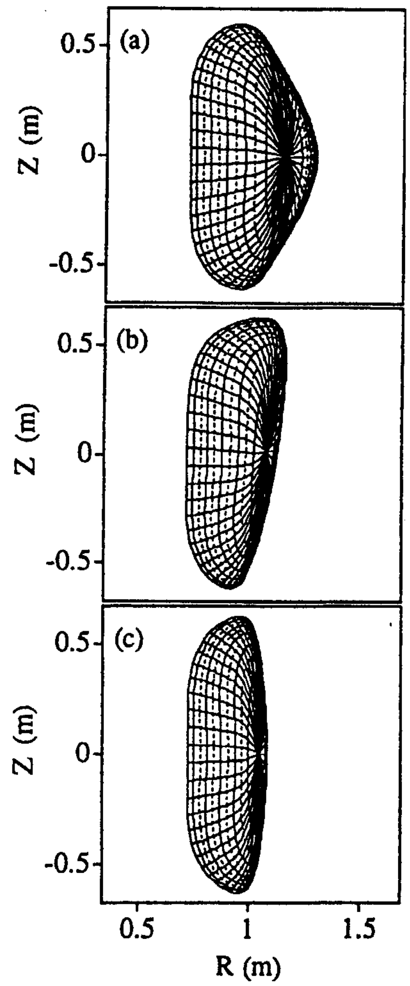

FIG. 8. Currentless MHD equilibrium at $\langle\beta\rangle \approx 1\%$.

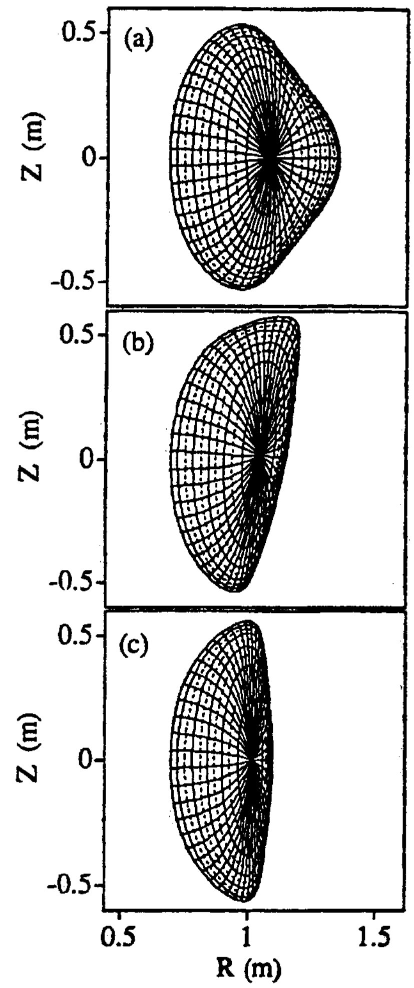

FIG. 9. MHD equilibrium with I_p = 120 kA and $\langle\beta\rangle \approx$ 4%.

In general, the magnetic configuration of an ST with an OSW improves with addition of the plasma current: the total rotational transform increases in comparison with the currentless case, the horizontal plasma position can be effectively controlled by the currents in the PF rings, the magnetic axis location can be effectively controlled to produce a more symmetric positioning and MHD equilibria with much higher beta values can be obtained.

To illustrate these features, we show the results of MHD equilibrium calculations for the case of finite beta and no plasma current (Fig. 8), and for a similar case but with higher beta and with plasma current (Fig. 9). Figure 8 corresponds to beta values that are close to the equilibrium limit for the currentless configuration. Even so, the beta values are not high, the central $\beta(0) \approx 3\%$ and the volume average $\langle\beta\rangle \approx 1\%$. When plasma current is present (the centrally peaked current density profile is considered here, $j \sim 1 - \rho^2$) the situation improves significantly. Figure 9 corresponds to the case with a plasma current of only I_p = 120 kA (which is significantly less than the plasma current planned for the standard NSTX operation). The beta values in this case are much higher, $\beta(0) \approx 13\%$, $\langle\beta\rangle \approx 4\%$, but even this equilibrium is far from the beta limit. Radial profiles of the total rotational transform for both cases are shown in Fig. 10 (solid curve, for the currentless case of Fig. 8; dashed curve, for the case with the plasma current of Fig. 9). All the above mentioned advantages can be clearly seen.

4. DISCUSSION AND CONCLUSIONS

This paper discusses a configuration that integrates stellarator properties into an ultra-low aspect ratio device such as an ST. This is accomplished through the use of OSWs that are located totally outboard of the plasma. Two in principle different types of OSW, the classical stellarator type and the torsatron type, are presented, and shown to be

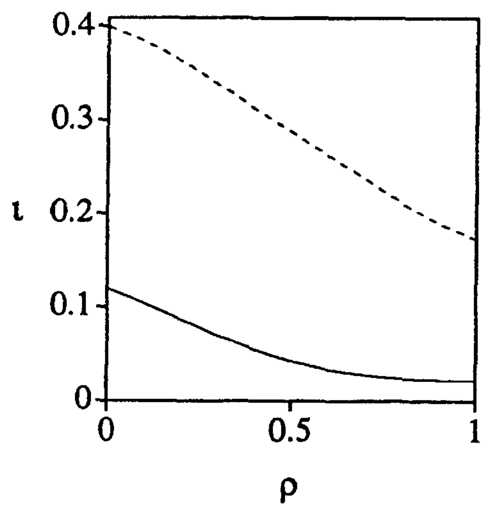

FIG. 10. Total rotational transform for the currentless equilibrium of Fig. 8 (solid curve), and for the current carrying equilibrium of Fig. 9 (dashed curve).

effective in an ST. Numerical calculations for an ST with the parameters of the NSTX tokamak illustrate the results obtained with the addition of OSWs.

Among the main advantages of OSWs are the following:

(a) Generating a set of closed vacuum flux surfaces with finite rotational transform for efficient plasma startup. This might save a significant amount of available volt-seconds of the ohmic current transformer, which is very limited for the ST experiments. It is especially important for a future ST fusion reactor where the central ohmic current transformer cannot be used.

(b) OSWs can be turned on or off (as supplementary coils) when necessary. In particular, OSWs can be turned off at the later stage when the hot plasma is obtained, to enter the typical toroidally symmetric regime of STs.

(c) It might be advantageous (there are a few theoretical and experimental publications, for example, Refs [24, 29–31], stating that stellarator effects might be profitable) to use OSWs even at the later hot plasma stage for stabilization of the disruptive instability, which otherwise might be a total disaster for a reactor. At least, an OSW might be necessary for controlling this instability.

It is also shown that the operation of OSWs in the regimes with plasma current allows better control over the plasma position and magnetic axis location, and permits MHD equilibria with much higher beta values.

In contrast to the standard tokamak or stellarator coils, the OSWs do not encircle the plasma in the poloidal direction. The OSWs, of both types considered in this paper, however, have encircled the plasma in the toroidal direction. In principle, this is not a necessary requirement. An OSW design as a set of modular coils located outboard of the plasma has been mentioned in Ref. [19] and can be applied, probably with some modifications, to the low aspect ratio configurations. However, using an OSW that encircles the plasma in the toroidal direction might have additional advantages. Such an OSW can be used as an induction coil to generate the startup plasma current.

The loss of toroidal symmetry caused by OSWs might, in principle, enhance the particle transport in STs. It is not, however, a very important issue during the plasma startup when the plasma temperature is low. Using OSWs at the later hot plasma stage might have a more profound effect on transport, and thus OSWs should be optimized more carefully, which might be a topic of a separate publication.

While this paper was under review, new results have been obtained for OSWs in STs, which we would like to mention here. It has been demonstrated [32, 33] that very high beta equilibria can be obtained in configurations with OSWs and a plasma current in cases when the current in the TF coils is reduced to zero. This corresponds to a novel concept of a stellarator spheromak that does not have any material structures such as magnet coils or conducting walls linking the torus, and thus has significant advantages for a fusion reactor. The external rotational transform and the strong outboard magnetic field produced by OSWs are important elements of this concept. In a similar way to the standard spheromak configurations, the toroidal magnetic flux is generated by the plasma current.

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(E-mail address of P.E. Moroz:
moroz@engr.wisc.edu)