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Stellarator-spheromak

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Abstract

A novel concept for magnetic plasma confinement, the stellarator-spheromak (SSP), is considered. Actually, this is a non-axisymmetric spheromak where the outboard stellarator windings are used to produce the stellarator effects and the strong outboard magnetic field. The MHD equilibrium in an SSP with very high β (plasma pressure/magnetic field pressure) of the confined plasma is demonstrated. This configuration retains the main advantages of spheromaks, such as compact design and absence of material structures in the center of the torus. At the same time, an SSP has a potential for improving the spheromak concept regarding its main problems: the difficulty of plasma start-up and steady-state operation, and the tilt/shift instability. © 1997 Elsevier Science B.V.

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An enormous potential payoff of a spheromak as a fusion reactor has sustained the spheromak research for many past years (see, for example, Refs. [1–13]). Spheromaks differ markedly from many other toroidal systems as they do not have any material structures such as magnet coils or conducting walls linking the torus. As a result, the charged well-confined thermal particles "see" the toroidal topology of the plasma, similar to that in tokamaks or stellarators, while the fusion neutrons or even energetic particles "see" the topology as spherical, as they can go through the area of the torus hole. Another distinguished peculiarity of a spheromak is that the magnetic field structure is self-generated by the large internal plasma currents, and the toroidal and poloidal magnetic field components have comparable magnitudes.

Because of the attractiveness of spheromaks as a base concept for a fusion reactor, there were a number of reactor-relevant studies (see, for example, Refs. [4,12,13]) stressing various advantages of spheromaks. Among them are a compact and simple magnetic field geometry with a natural divertor, supporting the high energy density plasma (in the compact torus experiment (CTX) at a magnetic field of $B_0 \approx 0.25$ T, a line average plasma density of $n_e > 10^{20}$ m^{-3} and a volume average $\langle\beta\rangle \approx 8$–10% have been reported [5], while the experiments on the S-1 spheromak at $B_0 \approx 0.1$ T demonstrated similar plasma densities and $\langle\beta\rangle$ up to 40% [6,11]), nearly force-free equilibrium ($\boldsymbol{J} \times \boldsymbol{B} \approx 0$) minimizing stresses, and a simply connected fusion blanket. Because of the relatively small size and engineering simplicity, the initial capital cost of a spheromak reactor is estimated to be substantially lower than that based on the other more standard approaches such as tokamaks, stellarators, or RFPs.

However, the experimentally obtained spheromak plasmas are short-living, even when they are confined

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in flux conservers. Without continuous helicity injection [5], the plasma density decay time is substantially less than 1 ms, even for such a relatively large spheromak as CTX (minor plasma radius is about 20–25 cm) confined in a thick solid-wall high-conductivity flux conserver [10]. For fusion reactor applications, however, it is important to have the long-living spheromak plasma (better if it will be steady-state), and without the flux conserver.

In this Letter we present a novel concept (we call it stellarator-spheromak (SSP)) which might be able to resolve the above-mentioned spheromak problems while maintaining the main advantages of a spheromak. This type of fusion device represents a hybrid between a stellarator and a spheromak. It is clear, of course, that one cannot use the standard stellarator coils in a spheromak as they encircle the plasma in poloidal direction and go through the central hole. However, the opportunity exists in using the outboard stellarator windings (OSW) first considered in Ref. [14] and recently discussed for the low-aspect-ratio configurations in Refs. [15,16]. Actually, an SSP is a non-axisymmetric spheromak where OSWs are used to produce the stellarator effects (such as external rotational transform) and the strong outboard magnetic field. Below we present initial results of calculations carried out via the field-line tracing code, UBFIELD (see, for example, Ref. [17]), and the MHD equilibrium code, VMEC [18], running in its free-boundary mode.

In searching for the suitable SSP configuration, we took the following approach. First, we have found an efficient stellarator coil configuration utilizing the OSW and capable of producing the strong stellarator effects, such as the existence of closed vacuum flux surfaces with significant enclosed volume and appreciable rotational transform. The possible coil system is shown in Fig. 1. It includes the classical-stellarator-type OSW [15], the poloidal field (PF) rings, and a few TF coils. The last closed vacuum flux surface is shown as well. To avoid confusion, we should say from the beginning that the center conductor (center post) in this configuration is used only to search for spheromaks, and finally it will carry no current.

The poloidal cross section, showing all coil projections and the dimensions chosen, is presented in Fig. 2. In this case, the current in the OSW is three times less than the total current in the center post (which

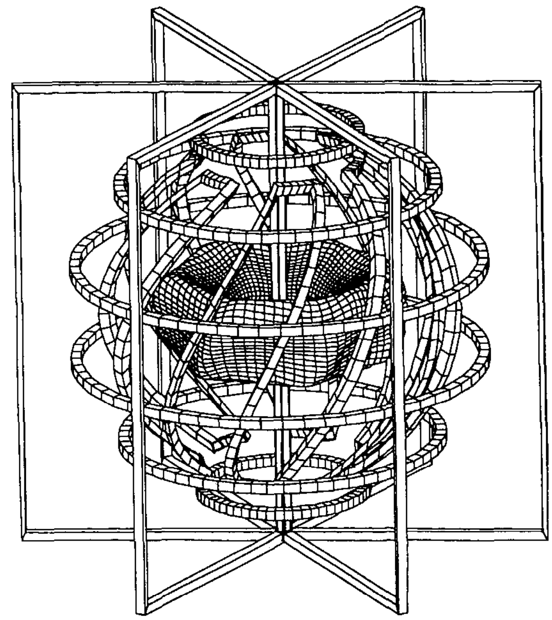

Fig. 1. Side view of the device considered and the last closed vacuum flux surface. The corresponding SSP is obtained by removing the rectangular TF coils.

is the sum of the currents in all TF coils), $I_{cp}/I_{osw} = 3$. The total vacuum rotational transform produced is $\iota = 1/q \approx 0.08$, q being the safety factor. The local rotational transform calculated for the outboard parts of flux surfaces is higher and reaches 0.25 near the plasma edge. The value of the external rotational transform, $\iota \approx 0.08$, is fairly low when compared with $\iota \sim 1$ for the standard large-aspect-ratio stellarators. However, for the low-aspect-ratio machine discussed it is not as low. Actually, these values of ι are only a factor of three lower than that considered for stable regimes in spherical tokamaks with a relatively large plasma current [19]. Also, the value of ι produced by the OSW can be increased further (in principle, up to $\iota \approx 0.4$, for this particular OSW) by decreasing the ratio of I_{cp}/I_{osw}.

The system of Fig. 1 represents the configuration that we classify as the spherical stellarator (SS) type [20] but with the utilization of an OSW. The TF coils are needed as they produce the toroidal magnetic field necessary for the vacuum stellarator configuration to exist. The methods of finding the proper location and balance of all currents were similar to that described in Refs. [17,20]. The transition

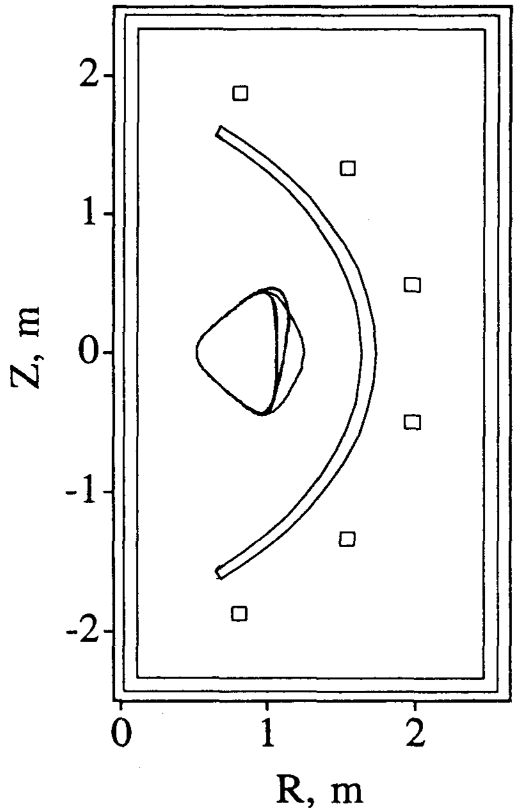

Fig. 2. Coil projections on the poloidal cross section for the device of Fig. 1. Three main plasma cross sections at $\varphi = 0$, $\pi/2N$, π/N are shown as well.

from this SS to the corresponding SSP is made by removing the TF coils (reducing I_{cp} to zero), and is discussed below.

Modification of the main parameters of the configuration with changing I_{cp}/I_{osw} is demonstrated in Fig. 3, which includes R and ρ, the average major and minor radii of the last closed vacuum flux surface, and ι_0, the rotational transform on the axis. One can see that with decreasing of I_{cp}/I_{osw} the vacuum configuration is shrinking but the rotational transform increases. When the plasma with finite current is present, the set of closed flux surfaces can be obtained even without the TF coils ($I_{cp} = 0$). Gradually decreasing I_{cp} to zero and adjusting the plasma current magnitude and profile, plasma pressure, and the enclosed toroidal magnetic flux at each step we were able to come to the high-β SSP configuration described below. The poloidal magnetic flux has been calculated self-consistently by the MHD equilibrium code.

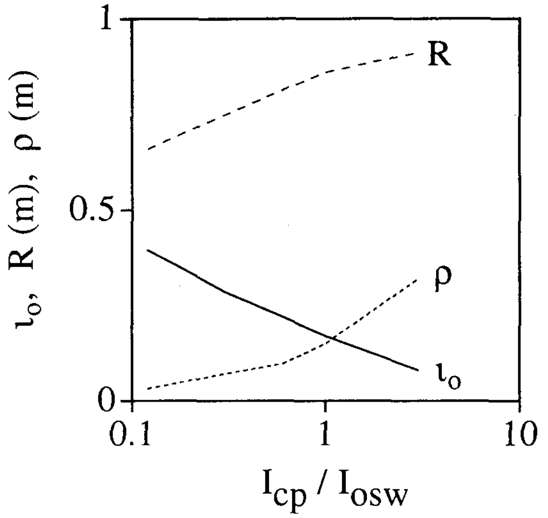

Fig. 3. Variation of the main parameters of closed vacuum flux surfaces, R, ρ, and ι_0, with I_{cp}/I_{osw}.

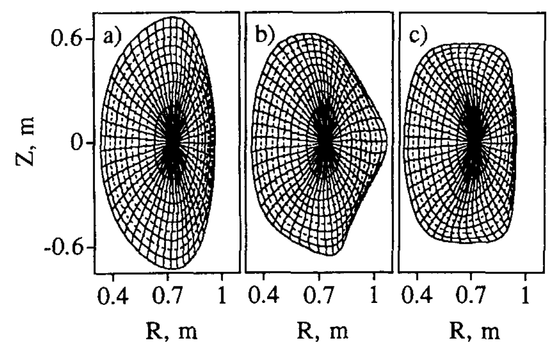

Fig. 4. High-β equilibrium in the SSP; (a) $\varphi = 0$, (b) $\varphi = \pi/2N$, (c) $\varphi = \pi/N$.

The system of closed flux surfaces, presented in Figs. 4a–4c, corresponds to the hollow plasma current profile and has the following parameters: aspect ratio $A \approx 1.5$, total plasma current $I_p = 630$ kA, total enclosed toroidal magnetic flux, $\Phi = 0.2$ Wb, central β, $\beta(0) = 90\%$, volume average β, $\langle\beta\rangle = 21\%$, and the total rotational transform $\iota > 1$ everywhere in the plasma. The plasma pressure profile has been chosen in the form, $p(s)/p(0) = (1-s)^2$, where s is the normalized enclosed toroidal flux, $s = \Phi/\Phi_{max}$. Three cross sections in Figs. 4a–4c correspond, respectively, to $\varphi = 0$, $\pi/2N$, π/N, φ being the toroidal angle, and $N = 6$ is the number of field periods.

More details on the plasma current profile, rotational transform, and toroidal and poloidal magnetic fluxes are given, respectively, in Figs. 5a–5c. During the calculations, different toroidal current density profiles have been checked which satisfy the chosen analytical form, $dI/ds = 1 - s_m^*[1-(s/s_m)^2]^2$ for $s < s_m$, and $dI/ds = \{1-[(s-s_m)/(1-s_m)]^2\}^2$ for $s > s_m$, with the parameter s_m between 0 and 1. The current profile in Fig. 4a is for $s_m = 0.4$, and corresponds to the highest β values obtained in our calculations. The total rotational transform, ι, is shown in Fig. 5b. It is important to mention that the local ι-values in an SSP vary significantly on a flux surface; they are high outboard and low inboard, similar to that in an SS [20]. Fig. 5c shows that both the toroidal, Φ, and poloidal, Ψ, magnetic flux components are present in an SSP. Similar to the other spheromak configurations, Φ is produced by the plasma current.

One more peculiar characteristic of the SSP considered is the $|B|$ distribution within the plasma, which is demonstrated in Fig. 6. As one can see, the saddle point of $|B|$, a typical characteristic of a stellarator with a strong helical harmonic amplitude [21], is present in all cross sections, at the major radius $R_s \approx 0.75$ m. The increase of $|B|$ for $R > R_s$ is because of the external currents in the coils which are located outboard. The $|B|$ increase for $R < R_s$ is solely because of the plasma current, and the effect of toroidicity.

The SSP configurations might have significant advantages in comparison with traditional spheromaks in a few areas where spheromaks normally have severe problems: plasma start-up, tilt/shift instability, and long-time operation. These advantages will be clearer in a large device with a high-β plasma. The new technique for plasma start-up can be used in an SSP reactor: the plasma can be initiated (via rf power, for example) while the small center-post current is present and the vacuum flux surfaces exist. At the later stage, when the plasma current is induced, the center post can be removed. Alternatively, the axial Z-pinch current can probably be used for start-up instead of the center post. The problem with the tilt/shift instability will likely be absent in an SSP. Normally, an SSP has a larger plasma aspect ratio than a traditional spheromak. In this situation [22], the tilt instability is suppressed while the shift instability is fast growing in spheromaks. However, in the SSP the strong magnetic field outboard the plasma, produced by OSWs, causes the field index, $n_i = -(r/B)\partial B/dr$, to be negative. This stabilizes the shift instability [22]. These arguments about stability, however, might not be valid for the three-dimensional configuration, such as an SSP, and should be considered only as an indication of possible good results.

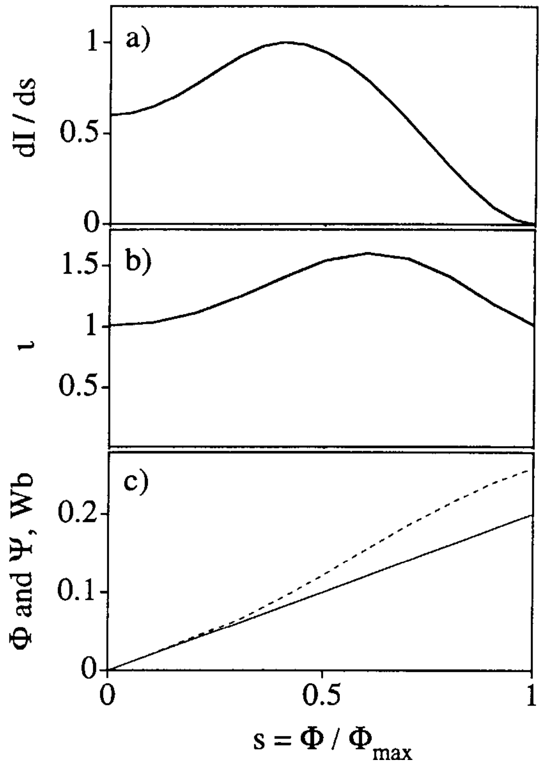

Fig. 5. Radial profiles in the SSP of (a) toroidal current density, (b) rotational transform, (c) toroidal (solid line) and poloidal (dashed line) magnetic flux.

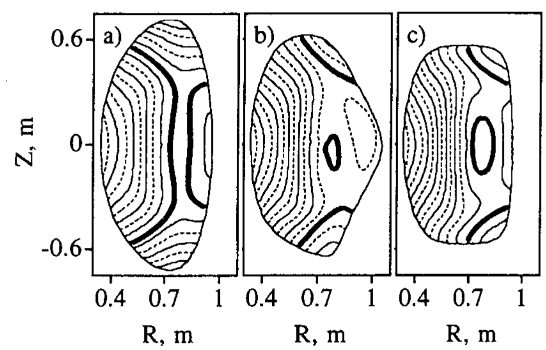

Fig. 6. Contours of $|B|$ distribution in the SSP; (a) $\varphi = 0$, $B_s = 0.317$ T, $\Delta B = 0.035$ T; (b) $\varphi = \pi/2N$, $B_s = 0.305$ T, $\Delta B = 0.027$ T; (c) $\varphi = \pi/N$, $B_s = 0.321$ T, $\Delta B = 0.024$ T, where B_s corresponds to the bold contour lines and ΔB is the difference between neighboring contours.

The long-time (or even steady-state) operation of an SSP can come from the strong bootstrap current at high β, which does not require any seed current. This feature is typical for stellarators and does not exist in the toroidally symmetrical devices such as a traditional spheromak. Calculations demonstrating the strong bootstrap current in an SS have been presented in Refs. [23,24].

The loss of toroidal symmetry caused by OSWs might, in principle, enhance the particle transport in an SSP in the low collisionality regime, as compared with that in a corresponding spheromak. To minimize particle losses, the OSW has to be optimized carefully, which might be a topic of a separate publication. This is a general problem for stellarators, and as is well known, the optimized stellarators, although being the three-dimensional configurations, feature particle transport characteristics almost as good as that for tokamaks.

In conclusion, a novel stellarator-spheromak hybrid concept, SSP, is described for the first time. As important elements, an SSP includes OSWs and the plasma current. The high-β MHD equilibrium in an SSP is demonstrated and the main parameters, peculiarities, and possible advantages are briefly discussed. In principle, different types of OSWs can be used and different regimes of SSP operation can be considered. The present Letter intends to bring the new possibilities revealed by the SSP concept to attention of the wide scientific community. More detailed calculations are in progress.

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References

[1] M.N. Rosenbluth, M.N. Bussac, Nucl. Fusion 19 (1979) 489.
[2] H. Bruhns, Y.P. Chong, G.C. Goldenbaum, G.W. Hart, R.A. Hess, Proc. 3rd Symp. on Physics and Technology of Comp. Toroids in the MFE Program, Los Alamos, New Mexico, 1980, p. 97.
[3] M. Yamada, H.P. Furth, W. Hsu, A. Janos, S. Jardin, M. Okabayashi, J. Sinnis, T.H. Stix, K. Yamazaki, Phys. Rev. Lett. 46 (1981) 188.
[4] R.L. Hagenson, R.A. Krakowski, Fusion Techn. 8 (1985) 1606.
[5] T.R. Jarboe, C.W. Barnes, I. Henins et al., Proc. 10th Int. Conf. on Plasma Phys. and Contr. Nucl. Fus. Res., London 1984, Vienna 1985, Vol. 2, p. 501.
[6] M. Yamada, R. Ellis, H.P. Furth, G. Hart, A. Janos et al., see Ref. [5], p. 535.
[7] A. Janos, Phys. Fluids 29 (1986) 3342.
[8] J.C. Fernandez, C.W. Barnes, T.R. Jarboe et al., Nucl. Fusion 28 (1988) 1555.
[9] T.R. Jarboe, F.J. Wysocki, J.C. Fernandez et al., Phys. Fluids B 2 (1990) 1342.
[10] F.J. Wysocki, J.C. Fernandez, I. Henins et al., Phys. Rev. Lett. 65 (1990) 40.
[11] R.M. Mayo, D.J. Hurlburt, J.C. Fernandez, Phys. Fluids B 5 (1993) 4002.
[12] K.A. Fowler, J.S. Hardwick, T.R. Jarboe, Com. Pl. Phys. Contr. Fus. 16 (1994) 91.
[13] R.M. Mayo, Fusion Technology 30 (1996) 1326.
[14] H.P. Furth, C.W. Hartman, Phys. Fluids 11 (1968) 408.
[15] P.E. Moroz, Nucl. Fusion 37 (1997) 8.
[16] P.E. Moroz, in: NSTX Research Forum, PPPL, Princeton, February 5–7, 1997.
[17] P.E. Moroz, Phys. Plasmas 2 (1995) 4269.
[18] S.P. Hirshman, W.I. Van Rij, P. Merkel, Comp. Phys. Comm. 43 (1986) 143.
[19] Y.-K.M. Peng et al., Proc. 15th Int. Conf. of Plasma Phys. and Contr. Fus. Res., Seville 1994 (IAEA, Vienna 1995) Vol. 2, p. 643.
[20] P.E. Moroz, Phys. Rev. Let. 77 (1996) 651.
[21] P.E. Moroz, in: RF Power in Plasmas, ed. R. McWilliams, AIP, New York, 190 (1989) 302.
[22] S.C. Jardin et al., Nucl. Fusion 21 (1981) 1203.
[23] P.E. Moroz, Phys. Plasmas 3 (1996) 3055.
[24] P.E. Moroz, D.B. Batchelor, B.A. Carreras, S.P. Hirshman, D.K. Lee, V.E. Lynch, D.A. Spong, J.S. Tolliver, A. Ware, J. Whitson, Fus. Techn. 30 (1996) 1347.
[25] P.E. Moroz, in: Innovative Confinement Concepts Workshop, March 3–6, Marina del Ray, CA, 1997.
[26] P.E. Moroz, in: Sherwood Int. Fusion Theory Conf., Madison, Paper 3C31 (1997).