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Stellarator-Spheromak

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Abstract.

A novel concept for magnetic plasma confinement, Stellarator-Spheromak (SSP), is proposed. Numerical analysis with the classical-stellarator-type outboard stellarator windings demonstrates a number of potential advantages of SSP for controlled nuclear fusion. Among the main ones are: simple and compact magnet coil configuration, absence of material structures (e.g. magnet coils or conducting walls) in the center of the torus, high rotational transform, and a possibility of MHD equilibria with very high β (pressure / magnetic pressure) of the confined plasma.

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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, [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 attractiveness of spheromaks as a base concept for a fusion reactor, there were a number of reactor-relevant studies (see, for example, [4, 12-13]) stressing various advantages of spheromaks. Among them are compact and simple magnetic field geometry with a natural divertor, supporting the high energy density plasma (in the Compact Torus Experiment (CTX) at magnetic field of $B_0 \approx 0.25$ T, the line average plasma density $n_e > 10^{20}$ m^{-3} and volume average $\langle\beta\rangle \approx 8$-10% have been reported [5] , while the experiments on 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 ($\mathbf{J} \times \mathbf{B} \approx 0$) minimizing stresses, and a simply connected fusion blanket. Because of 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 a tokamak, a stellarators, or an RFP.

However, the experimentally obtained spheromak plasmas are short-living, even when they are confined in flux conservers. Without continuous helicity injection [5], the plasma density decay time and the global energy confinement time are 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 are presenting 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) recently discussed in [14-15]. Below we present initial results of calculations carried out via the field-line tracing code, UBFIELD (see, for example, [16]), and the MHD equilibrium code, VMEC [17], running in its free-boundary mode.

In searching for the suitable SSP configuration, we took the following approach. First, we have found an efficient coil configuration utilizing OSW and capable of producing the strong stellarator effects, such as 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 [14], the poloidal field (PF) rings, and a few TF coils. The last closed vacuum flux surface is shown as well. The poloidal cross-section, showing all coil projections and the dimensions chosen, is presented in Fig. 2. In this case, the current in OSW is a factor of two higher than the current in each TF coil. The total vacuum rotational transform produced is $\iota = 1/q \approx 0.08$, with q being the safety factor.

The system of Fig. 1 represents the configuration that we classify as the Spherical Stellarator (SS) type [18] but with utilization of 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 [16, 18]. Transition from this SS to the corresponding SSP is made by removing the TF coils.

When the plasma with finite current and pressure is present then the set of closed flux surfaces can be obtained without the TF coils. Gradually decreasing the current in TF coils to zero and adjusting the plasma current magnitude and profile, plasma pressure, and the enclosed toroidal magnetic flux at each step we have been 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.

The system of closed flux surfaces, presented in Fig. 3(a-c), 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, $<\beta> = 21\%$, 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 a normalized enclosed toroidal flux, $s = \Phi/\Phi_{max}$. Three cross-sections in Fig. 3(a-c) 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 plasma current profile, rotational transform, and toroidal and poloidal magnetic fluxes are given, respectively, in Fig. 4(a-c). During the calculations, different toroidal current density profiles have been checked which satisfy to 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 being between 0 and 1. 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. 4b. It is important to mention that the local ι-values in SSP vary significantly on a flux surface - they are high outboard and low inboard, similar to that in SS [18]. Fig. 4c shows that both the toroidal, Φ, and poloidal, Ψ, magnetic flux components are present in SSP. Similar to the other spheromak configurations, Φ is produced by the plasma current.

One more peculiar characteristics of the SSP considered is the $|B|$ distribution within the plasma, which is demonstrated in Fig. 5. As one can see, the saddle point of $|B|$, a typical characteristics of a stellarator with the strong helical harmonic amplitude [19], 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.

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

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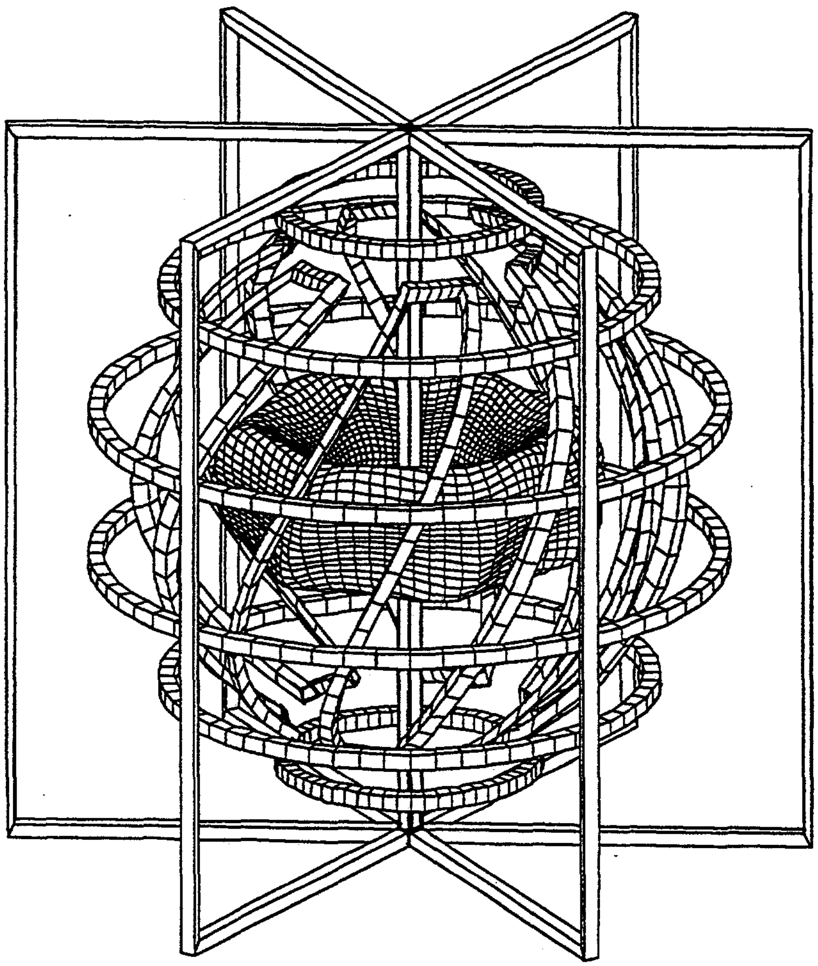

Fig. 1. Side view of the device considered and the last closed vacuum flux surface. The corresponding SSP is obtained by removing the rectangular TF coils.

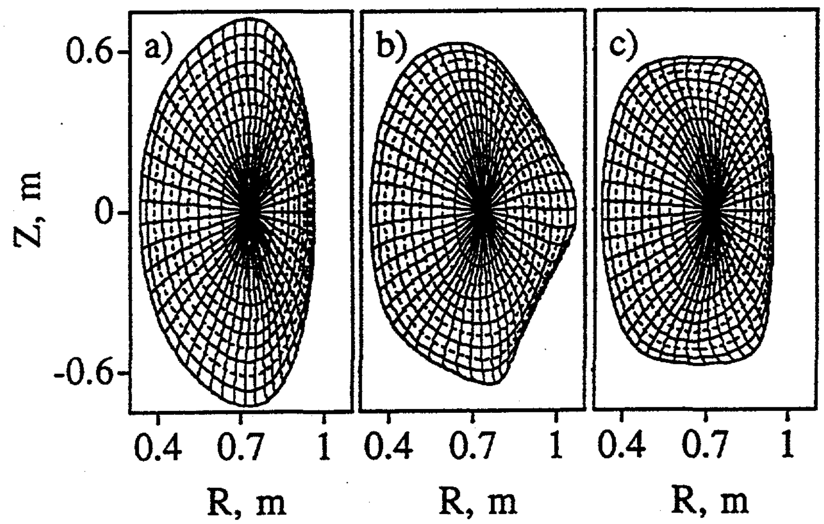

Fig. 3. High-β equilibrium in SSP; a) $\varphi = 0$, b) $\varphi = \pi/(2N)$, c) $\varphi = \pi/N$.

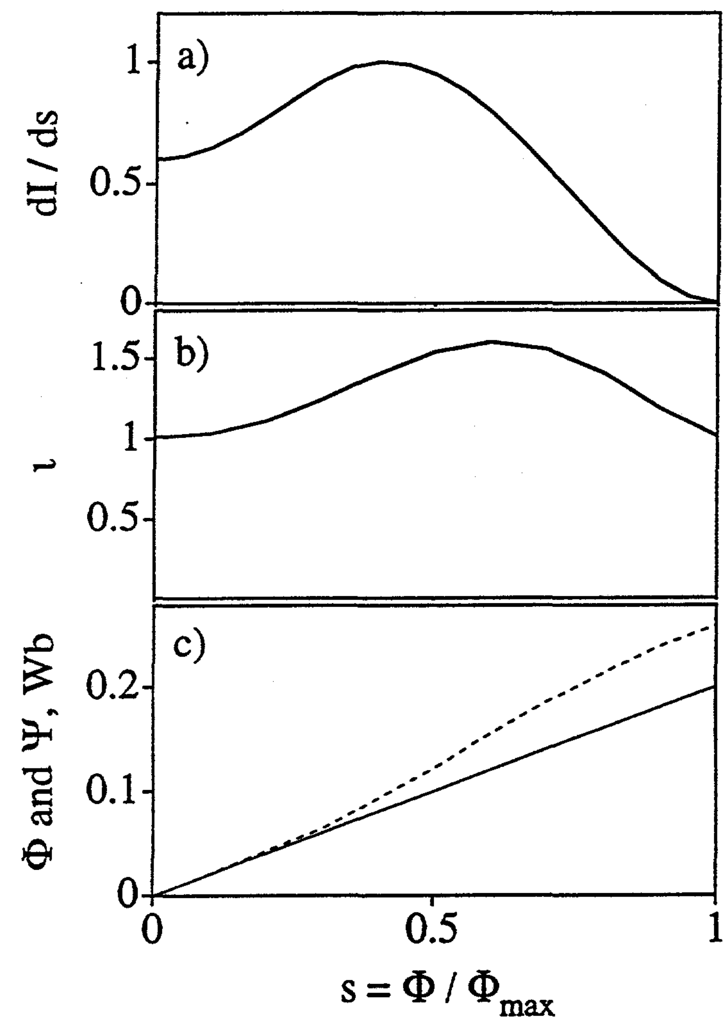

Fig. 4. Radial profiles in SSP of (a) normalized toroidal current density, (b) rotational transform, (c) toroidal (solid line) and poloidal (dashed line) magnetic fluxes.