UCRL-JC-132914
Preprint

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This paper was prepared for submittal to
Workshop on Cost-Effective Steps to Fusion Power,
By Fusion Power Associates and the University of California, Los Angeles
January 25-27, 1999
Los Angeles, CA

January 5, 1999

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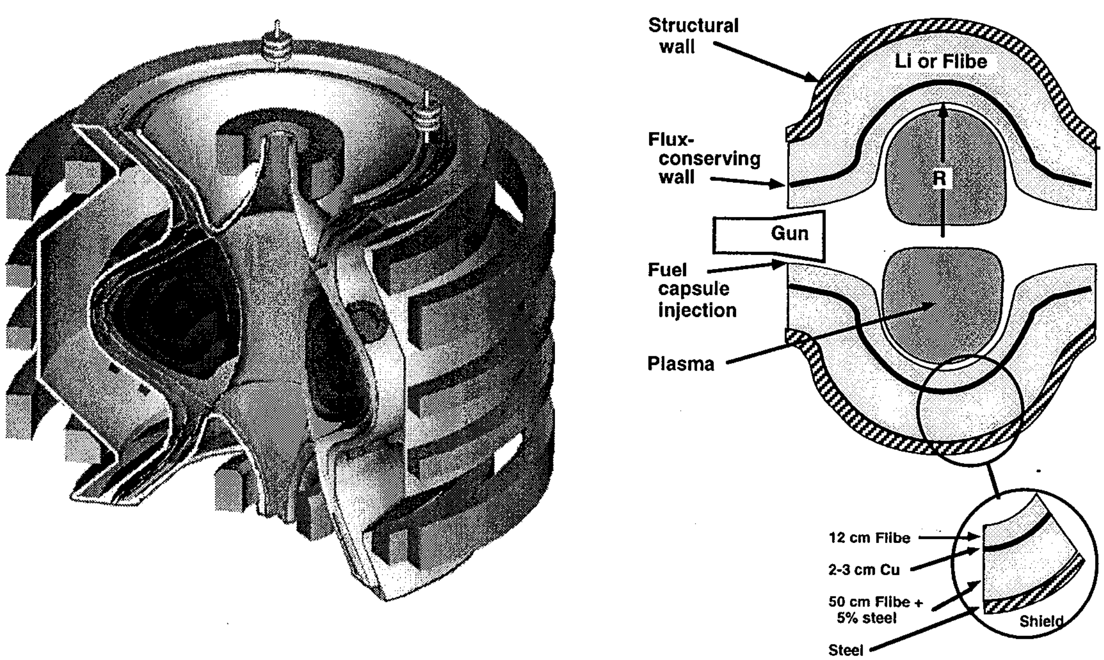
The spheromak path

The spheromak attributes[1] – internally generated toroidal magnetic field without linked coils, dynamo-driven plasma current resulting from helicity injection, and compactness – lead to attractive reactor options ranging from "conventional" steady-state designs, to high beta pulsed configurations, and to the core of a Magnetized Target Fusion (MTF) device. The resolution of the physics issues associated with these attributes, discussed in later sections, will determine the size and viability of the reactors. Preliminary designs, however, have been made and illustrate the opportunities.

Figure 1a shows a "conventional" reactor concept similar to that originally analyzed by Hagenson and Krakowski.[2] The plasma hoop force and shaping are generated by external coils, and the current drive is generated by helicity injection from a coaxial "gun." Stabilization of the m=1, n=1 tilt and shift modes is provided on the short time scale by a conducting shell ("flux conserver") and for long times by a set of feedback coils. Estimates of plasma confinement lead to flux conserver radii of 4-5 m (plasma major radius = 2-2.5 m)[2,3] for plasma betas ≥ 10%, well within the experimental data and theoretical modeling. Because of the absence of a strong, externally applied magnetic field the effective engineering beta is higher by a factor of 2 or more. The plasma is predicted[4] to ignite by ohmic heating, so no auxiliary heating or current drive source is needed. The simple geometry is also suitable for innovations such as liquid walls[5] which may alleviate difficulties with heat and radiation damage to the first wall of the reactor.



(a) (b)

Fig. 1. (a) "Conventional" spheromak reactor designed for steady-state operation. (b) Pulsed, high beta spheromak reactor with the fusion energy absorbed by the liquid lithium or Flibe which is replaced by flow between pulses.

The high-beta, pulsed reactor[6] shown in Fig. 1b takes advantage of the internal current drive associated with helicity. There are no external magnets except those that provide bias flux to the injector ("gun"). The plasma is built-up in the conventional way, with the equilibrium and shaping fields provided by currents in the flux conserver. As the plasma ignites by ohmic heating, the density is ramped up; together with the heating by the fusion reaction the beta is predicted to flatten the pressure in the plasma core, expelling magnetic field to form a boundary layer with large magnetic shear which stabilizes the current and pressure-driven MHD modes. Initial estimates indicate that the plasma should be stable up to beta-poloidal ~ 0.6-1, resulting in a very high burnup of the fuel before the discharge terminates and the liquid, acting as a heat-exchange fluid, is recirculated.

In an even higher density regime, the spheromak is an ideal core for MTF.[7] The potential high-beta operation and internally generated fields are a natural fit to a reactor based on fast compression by a liner, and the resulting heating by the compression will alleviate the need for achieving high initial temperatures in the plasma. In addition, confinement of order of Bohm is sufficient for fusion power, reducing concerns about losses due to magnetic turbulence in the spheromak plasma.

From complexity towards simplicity

In the spectrum of toroidal confinement geometries the means for creating the confining fields varies significantly. At one end of this spectrum, stellarators and large tokamaks will require superconducting magnet sets whose cost is typically half that of the machines themselves and contribute significantly to their complexity. The complexity of a stellarator set owes to its 3-dimensional character, but the introduction of current into the tokamak eases that technology by requiring only planar coils. But as a set, the nested toroidal and poloidal coils of the tokamak bring their own system complexity, for example to maintenance and replacement.

Magnetic fields can also be created by dynamo action (creation of a mean field through $\delta v \times \delta B$ terms in the equation for $\frac{\partial B}{\partial t}$ in moving media). The necessary ingredient is access to unstable modes whose fluctuations are responsible for this field generation. In the RFP the dynamo is invoked both to reverse, internally, the weak external field and to assist the ohmic currents produced by the central transformer. This reduces requirements on the toroidal and poloidal vacuum field coils. Complexity here could be further reduced if inductive drive of the current was eliminated, say with a form of ac helicity injection called "F-θ pumping", an old idea yet to be fully demonstrated. The spheromak completes the attempt to avoid reliance on external coils, using dynamo action to eliminate both the toroidal coils and the central solenoid. Only ring coils, as needed for all toroidal plasmas to counteract the expansion forces on the torus, are required. The FRC takes the process further by requiring no internal toroidal field, but the external confining field must be reversed internally by a toroidal current driven externally, or by reversing the external field after "freezing-in" the internal poloidal field.

From order towards disorder

Each reduction in cost and engineering complexity in this progression is generally attended by an increased complexity in the physics. The introduction of current in the tokamak opens the way for current driven modes that can degrade confinement or disrupt the plasma. The self-organized-field devices purposefully operate in linearly unstable regimes so that the dynamo drive mechanism is accessed. Clearly, to avoid the engineering complexity, capital cost, and impact on plant availability from magnet systems, one must relinquish some or all of the plasma control that externally imposed magnet fields provide. The plasma science for this direction is of great interest for astrophysical problems related to magnetic field generation and relaxation.

A critical issue is whether the consequences of allowing the plasma a freedom to self-organize is acceptable or intolerable. Of immediate concern is how the confinement of the plasma scales with the level of the fluctuations essential to the dynamo. While preliminary scaling laws are suggested for the RFP, the understanding of spheromak confinement is less mature, and its scaling at higher temperature and with device parameters must be discovered.

For all toroidal systems in equilibrium one attempts to create a set of closed surfaces of constant pressure, or flux surfaces. Constant flux (ψ) surfaces for the spheromak are shown here, derived from the Grad-Shafranov equation (azimuthal current equation resulting from the force balance $\nabla p = \mathbf{j} \times \mathbf{B}$) for a particular choice of the pressure and current driving terms. A coupled set of open and closed surfaces are created. Plasma cross sections are created in an (R,z) plane, in cylindrical geometry, axisymmetric in the toroidal or ϕ–direction. Between $R = 0$ and R_{min}, and between R_{max} and the wall of the flux conserver, there is open flux tied to a coaxial gun, but for $R_{min} < R < R_{max}$, the surfaces are closed. It thus has a topology similar to the spherical torus (ST), but unlike the ST the poloidal and toroidal fields are of comparable magnitude in the spheromak, the field line pitch is quite high (low safety factor q), and there are no coils in the hole of the torus.

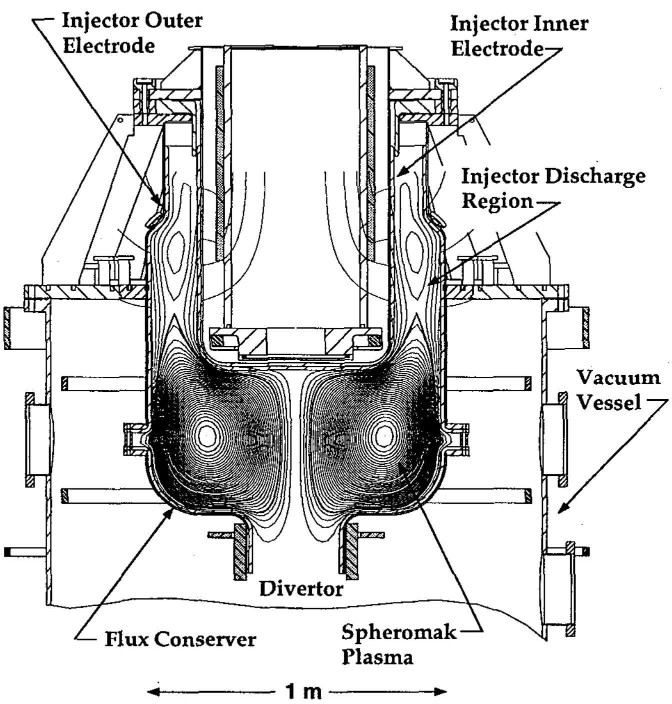


Fig. 2. Equilibrium magnetic flux surfaces in the sustained spheromak. The fields are calculated for the Sustained Spheromak Physics Experiment at LLNL.

Transport from disorder

These idealized flux surfaces, on which both the field and current vectors lie, are in reality perturbed by magnetic fluctuations to a degree that depends on the resistive stability of the device. For stellarators and tokamaks, they are generally operated where that stability is robust. But, it takes very little fluctuation energy for magnetic islands to form on surfaces where the field lines close on themselves after a few transits around the torus. So islands do form in these devices, but the radial extent $\Delta\psi$ of these islands is controlled through design, operating restrictions, or profile control to the extent possible. Thus, the influence of magnetic fluctuations on confinement in the externally controlled field toroids is kept in check; the overall confinement is still a process of transport across relatively well-ordered closed flux surfaces.

In contrast, in self-organized plasmas these surfaces are broken down to a much greater extent – by the magnetic turbulence creating the configuration. For example, Rechester and Rosenbluth[8] described a fully stochastic process in which there was so much disorder that field lines are braided in their toroidal transits of the plasma, and their radial excursions in time can be quite large. Then, the escape path for heat and particles is primarily parallel to the field. This transition from perpendicular to parallel escape processes requires a sufficient level of fluctuations. So the question becomes "how much turbulence is necessary to sustain the fields, and how does the level scale with device size, field, and temperature." This is a very complex issue and its study is the primary rationale for current experiments. But if the turbulent levels scale favorably with the Lundquist number (S), the ratio of resistive to Alfvén times, the transport will be acceptable. There is some evidence that $(\delta B_\perp / B_o)^2 \sim S^{-\alpha}$, with $\alpha \approx 1$, which would yield sufficiently low amplitude magnitude fluctuations[9,10] that a reactor will probably be limited by electrostatic turbulence as in a tokamak. This optimistic scaling, however, is highly uncertain and experiments need to be done over a wide range of conditions to determine the actual scaling.

In the Rechester and Rosenbluth process, once the fluctuation level is known, thermal diffusivities from the braided fields can be estimated from simple random walk considerations. If $\delta B_\perp$ is the part of the fluctuating magnetic field perpendicular to B_o, the time averaged field, and we define $b = \delta B_\perp / B_o$, we can estimate $\chi_\perp$ as follows. First, the fluctuations are essentially static during the events described below. So picture a plane of straight, infinite field lines on which there is superimposed a random spatial pattern for b. Suppose that if one travels a distance $\ell_\parallel$ along the field or $\ell_\perp$ across the field, b is decorrelated from its starting point. For a given value of b the particle diverges at an angle $\tan^{-1} b \approx b$ from the direction of the unperturbed field. If it decorrelates first in the parallel direction, the perpendicular step size is $\Delta r = b\,\ell_\parallel$ and we find $\chi_\perp \equiv \frac{\Delta r^2}{t} = b^2 \ell_\parallel v$ (with v a few times the electron thermal velocity). We assumed Δr was less than the perpendicular correlation length, so if instead the fluctuations are strong enough ($b\,\ell_\parallel > \ell_\perp$) then we have instead (as noted by Kadomtsev and Pogutse) that $\Delta r = \ell_\perp$. Now the distance traveled along the field is ℓ^*, where $b\,\ell^* = \ell_\perp$ (see diagram below), so $vt = \ell^*$ and then $\chi_\perp = b\,\ell_\perp v$. This is a more favorable scaling with b, and is somewhat annealing as the field increases.

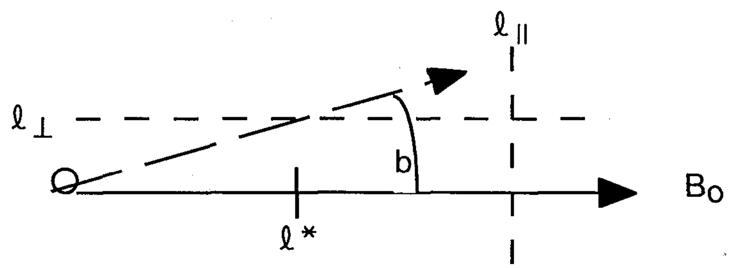


Fig. 3. Geometry illustrating correlation lengths.

The confinement challenge

These diffusivity estimates are for collisionless regimes (the modification for collisional regimes was given by Rechester and Rosenbluth,[8] and summarized by Kadomtsev[11]). They depend on the decorrelation lengths (roughly $k_{\|}^{-1}$ and $k_{\perp}^{-1}$ for whatever mode is responsible) along and across the field. If we simply assume that they apply, and want to achieve a confinement time of 1 sec (for levels such that $b\ell_{\|} < \ell_{\perp}$) we require $\chi_{\perp}\tau = a^2$ or $\frac{a^2}{b^2 \ell_{\|} v} = 1$. Then, taking $v = 3v_e$ (heat is conducted by electrons along the field), with "a" the plasma radius, and for a toroidal mode number m = 10 ($m\ell_{\|} = a$), the allowed fluctuation level is found from $b = 0.4\text{x}10^{-3}\sqrt{a}\ T^{-1/4}$ with T in keV. At 10 keV and "a" = 2 m, fluctuations of only 0.03% are allowed. In the strong fluctuation limit, assuming modes with $k_{\perp}\rho_i \approx 1$ and a field of 5 T, we find $\ell_{\perp} = \rho_i = 2$ mm and $\ell_{\|} = a/10 = 200$ mm, so this limit is for b > 1%. One could also take $k_{\perp} \approx \omega_{pe}/c$, which would correspond to $\ell_{\perp} = 0.6$ mm at $n = 10^{20}\ m^{-3}$.

Fortunately, these pessimistic times from planar theory may not apply. A condition sometimes overlooked is that, on perturbing the field, the closed nested flux surfaces in a torus first break into magnetic islands that do not overlap, and this braided field pattern does not first occur. Assuming perturbations in b of the form $\exp\{im\theta - in\phi\}$ islands form around surfaces $nq(\psi) = m$ with a radial width Δ_{mn} depending on the magnetic shear and fluctuation level. If we define $\zeta = \frac{d}{dr}\ q^{-1}$ at the rational surface in question, then $(\Delta_{mn})^2 = \frac{Rb}{m\zeta}$. Unless these islands overlap, the Rechester/Rosenbluth transport does not apply. For $m \approx n \approx N$ and q of order unity, the field amplitude must then be $b > N^{-1}$ if the mode spacing is given by the simple estimate $r_{mn} - r_{m'n'} \approx N^{-1}r_{mn}$. For N = 30, 3% fluctuations are required. In estimating the island width, we assumed that $\ell_{\perp} >> \Delta_{mn} >> N^{-1}R$. Thus, the island will not attain the above width if the modes decorrelate the particle motion radially in a distance equal or less than Δ_{mn}.

Spheromak creation

Since these self-organized toroids tend towards so-called Taylor states, with currents and fields everywhere aligned, and since these are minimum energy states for the plasma, there is hope for an operating point sufficiently near a minimum energy state that the fluctuations are low. But force-free configurations (**j** || **B**) hold no pressure, so one must be sufficiently far from this state that the plasma pressure is a good fraction (β) of the magnetic pressure. Encouragingly, high-β regimes have been found in spheromak plasmas, e.g. up to 20% electron beta (T_e = 100-150 eV) on the magnetic axis,[12] but consistency with low fluctuation levels has yet to be demonstrated.

In driving the plasma towards force-free configurations the local helicity (**A•B**, where **B** = ∇ x **A**) is altered on a fast local time scale, but the overall helicity K, its volume integral, is conserved on that time scale and lost more slowly by resistive decay on the time scale $T_{hel} \approx 0.03\eta^{-1}\mu_o(R_{max})^2$. The resistivity η has been found experimentally to exceed the Spitzer value by factors of a few.

The total helicity K is proportional to the stored magnetic energy W, viz., $2\mu_o W = \lambda K$, where the eigenvalue λ comes from the force free field solutions to $\nabla \times \mathbf{B} = \mu_o \mathbf{j} = \lambda \mathbf{B}$. The helicity loss rate $K/(T_{hel})$ must be balanced by the injection of helicity, and in experiments at LLNL and LANL a magnetized coaxial gun is used for that purpose. In Fig. 2, flux that initially crosses the coaxial barrel of the gun in its throat is stretched into the flux conserver and in equilibrium these flux tubes that begin in, say, the outer barrel, surround the spheromak and return through the center of the torus to the inner barrel of the gun. A current I_g from the gun flows through the flux channel whose net flux is Φ_g, and these are related by $\mu_o I_g = \lambda_g \Phi_g$, which when dividing by the cross sectional area of this flux channel gives $\mu_o j_g = \lambda_g B_g$. A necessary condition for the coupling of the gun region to the spheromak in the flux conserver is that $\lambda_g > \lambda$.

Power balance

The flow of helicity from the gun is at the rate $V_g I_g$, with some fraction going to the plasma in the closed flux volume. If that fraction of the power exceeds the helicity loss rate of that plasma the toroidal field and current will increase. As the temperature increases the loss of helicity by resistive decay is slowed, and the required power $\int \eta J^2 \, dV$ decreases. A simple power balance between this ohmic input and all losses will determine the possible operating points (n,T). Line radiation from impurities and charge exchange losses can be important, and profiles of neutral and impurity density near the edge in particular are required to estimate the power losses.

One significant difference between spheromaks and tokamaks is the equilibrium profile of the plasma current. The Taylor state solution for spheromaks has significant current at the edge of the plasma, on both the open field lines starting and ending in the gun and on the closed flux surfaces close to the separatrix surface. In this edge region temperatures of around 30 eV, relatively insensitive to other edge parameters, are determined from conduction losses on the open lines. Thus a dominant feature of spheromaks is that edge power densities are high, including both the ohmic drive and (potentially) the radiation and charge exchange losses. Core loss densities however, can be low if fluctuation levels are modest, and if temperatures are high so that the required ohmic drive is low. In a successful spheromak power plant the edge processes must not dominate the power balance, which fact will presumably give rise to a set of minimum constraints on parameters.

Key issues

With this description of the spheromak the key issues are quite clear, and progress towards their resolution can be assessed from the 20 years of experiments (carried out sporadically in time and space!) that have been reported.[13] Confinement is the dominant issue, with its scaling critical to a favorable power balance. Formation has not been an issue, and in the earliest experiments of coaxial gun formation of spheromaks the Taylor state was robustly generated. However, sustaining the configuration, particularly on times beyond those for wall stability, must be demonstrated. Stability to tilt and shift modes has been studied, and means for their avoidance on short time scales, through geometric choices and with conducting walls, were found.

Control of surface processes is critical. Extremely high edge losses were eventually reduced through understanding the role of impurities, wall conditioning, field errors, and applying kitchen physics learned elsewhere in the fusion program. This progress through the 1980's culminated with experiments on CTX at Los Alamos in which megamp currents, peak fields of 2-3 T, densities mid-10^{20} m^{-3}, and an electron temperature of 400 eV during the decay phase (gun off) of the experiment was observed. Analysis of these results led Fowler[9] to speculate that core confinement was much better than indicated by the total losses (edge plus core), and that if the two regions were treated separately one could "scale away" the edge losses as the device evolves to higher temperatures and sizes.

With these results in hand, the Sustained Spheromak Experiment, SSPX, was constructed at LLNL to study the turbulence and confinement properties of spheromaks while sustained by helicity injection from the gun. Expected parameter regimes are similar to those of CTX, and one goal is to achieve "decent" temperatures and confinement times with an active dynamo and in quasi-steady state. Care has been taken on surface preparation, avoiding field errors, and designing the poloidal field system and gun with modern equilibrium codes. Special features of this device include bias flux coils and a divertor that add flexibility in controlling particles and flux in the open field region. Experiments are scheduled for January 1999.

Acknowledgements

Work performed for the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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