

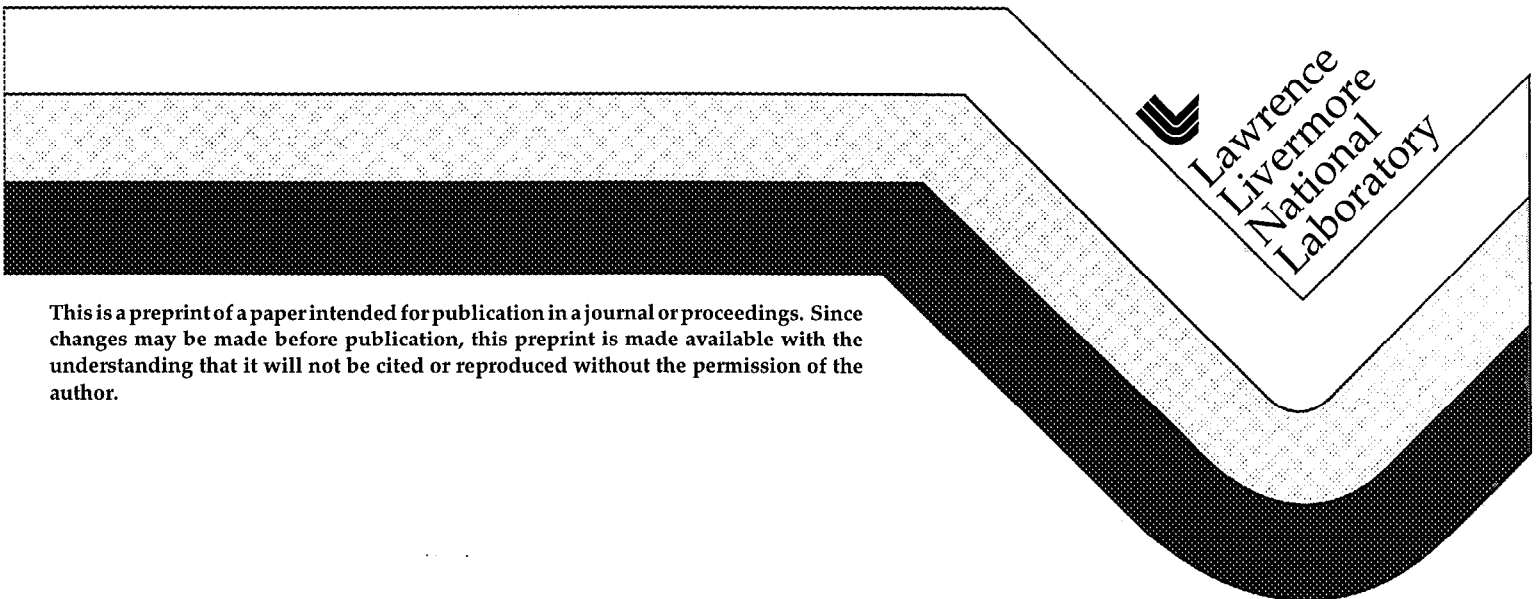
Wall-Confined High Beta Spheromak

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Wall-Confined High Beta Spheromak*

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Abstract

The spheromak could be extended into the high beta regime by supporting the pressure on flux-conserving walls, allowing the plasma to be in a Taylor state with zero pressure gradient and thus stable to ideal and resistive MHD. The concept yields a potentially attractive, pulsed reactor which would require no external magnets. The flux conserver would be shaped to be stable to the tilt and shift instabilities. We envision a plasma which is ohmically ignited at low beta, with the kinetic pressure growing to $\beta > 1$ by fueling from the edge. The flux conserver would be designed such that the magnetic decay time = the fusion burn time. The thermal capacity of the flux conserver and blanket would exceed the fusion yield per discharge, so that they can be cooled steadily. Ignition is estimated to require minimum technology: 30-100 MJ of pulsed power applied at a 0.5 GW rate generates an estimated burn yield > 1 GJ. The concept thus provides an alternate route to a fusion plasma that is MHD stable at high beta, yielding a reactor that is simple and cheap. The major confinement issue is transport due to $\text{grad}(T)$, e.g. driven by high beta modes related to the ITG instability.

1. Motivation

This is a progress report on a developing idea for a high beta, pulsed reactor based on the spheromak plasma confinement configuration. A new spheromak experiment, called SSPX, now under construction at the Lawrence Livermore National Laboratory, will explore plasma confinement at low beta and the potential for ohmically igniting the spheromak as discussed in Ref. [1]. If successful, the SSPX would point the way to a simple means of starting up the steady state spheromak reactor of Hagenson and Krakowski [2]. A spheromak reactor of this type would be much smaller and cheaper than the standard tokamak, comparable in size to a spherical tokamak with an unshielded copper central conductor [3] but superior to it by avoiding the need for the central conductor that consumes power and suffers neutron damage.

Here we consider a different two-phase approach, which leads to an even more compact, pulsed reactor, using only a flux conserver to confine the plasma and a liquid lithium wall to absorb the fusion energy during the high-power burn phase [4]. No magnets are required for equilibrium; the flux conserver stabilizes tilt/shift modes; the average power produced is much less constrained by wall load considerations than in steady state devices; and, protected by the liquid lithium, the device may have a longer life and superior waste disposal characteristics.

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2. Pulsed Reactor Scenario

The first phase of the pulsed reactor approach is a low beta spheromak obtained by helicity injection into a flux conserver shaped to prevent the tilt/shift instability. During this phase the plasma is ignited by ohmic heating as in the steady state approach. This is followed by a second phase in which rapid fueling causes beta and the power production to escalate to high levels, for a burn time of the order of the L/R time for the flux conserver. As beta increases, the plasma leans on the wall so that the pressure gradient relaxes to zero, and the field profile relaxes to the lowest energy Taylor state, resulting in a state stable to all MHD modes, both ideal and resistive. Also, at high beta, the system is relatively insensitive to heat losses since alpha heating, proportional to beta squared, is very large. However, the critical size for ignition does depend on drift-wave transport rates at low beta, accessible for study in near-term experiments. Theoretical studies of drift waves in the relevant regimes are in progress. Very high magnetic fields can be obtained in spheromaks, limited only by the strength of the flux conserver. The critical size decreases markedly as the field increases, allowing very small experimental devices to achieve ignition.

The high field capability of spheromaks also makes possible reactors of very small size which, in a pulsed mode, are limited only by the heat capacity of the flux conserver. The use of a sacrificial liquid lithium wall, which is effectively stationary during the rapid burn phase, permits very high yields and high gains relative to the stored magnetic energy required for ignition and confinement.

Finally, the system is relatively simple, the primary subsystems being the flux conserver and a low-tech, pulsed power system for helicity injection.

3. Ignition and Buildup

During helicity injection, the ohmic power increases as B increases and transport is dominated by magnetic turbulence caused by small departures from the Taylor marginal state, yielding approximately constant beta, around 4%, so T increases approximately as B^2 [5]. Magnetic turbulence should decrease as the temperature increases, so that, at higher temperatures (several keV), other processes, assumed to be the gyrobohm processes similar to those in tokamaks, begin to dominate transport, yielding an energy confinement time scaling as

$$\tau_E \propto R^3 B^2 / T^{3/2} \quad (1)$$

where R is the flux conserver radius. Ignition requires that alpha particle heating exceed these gyrobohm losses, giving as the ignition condition:

$$B^4 R^3 > X \quad (2)$$

where X depends on the value of beta and T at the ignition point. Nominally, $X = 17,000$ (in MKS units) for beta of 3%.

Following ignition at low beta, fuel is added at a rate limited by alpha heating in competition with heat losses. As beta exceeds MHD limits (around 10%), MHD activity relaxes $\text{grad}(p)$ to zero, giving density and temperature profiles like those shown in Figure 1. Continuing to fuel at the edge causes fuel to move inward by MHD relaxation, and beta continues to rise. The maximum allowed fueling rate can be estimated by neglecting heat losses (proportional to n) compared to alpha heating (proportional to n^2) and requiring that the temperature remain constant, to avoid fueling more rapidly than fusion reactions can heat the added fuel. Then

$$\frac{d}{dt}(3nT) = \frac{1}{4}n^2\langle\sigma v\rangle E_\alpha \quad (3)$$

which yields at constant T :

$$n = n_c(1 - t/t_\alpha)^{-1} \quad (4)$$

where n_c is the initial core density and $t_\alpha = (12T/E_\alpha)/(n\langle\sigma v\rangle)$. The transport model in Ref. [5] is being modified to calculate this high beta buildup scenario.

4. Flux Conserver with a Liquid Lithium Wall

A conceptual design for the flux conserver is shown in Figure 2, which indicates the main features including the liquid lithium layer, a vanadium structural wall and the location of the gun and fuel injector. One idea for fueling, indicated in the figure, is injection of fuel-filled capsules into the liquid lithium stream, which would sweep the capsules into the flux chamber. Nominally, the vanadium shell might be 2 - 3 m in diameter, though actual dimensions require further study and optimization.

Though lithium is a fairly good conductor at zero frequency, Alfvén wave propagation in lithium may negate its value as a flux conserver [6], requiring a metallic flux conserver buried within the lithium layer (not shown). Despite the high pressures attained at high beta, inertia prevents extrusion out the ends or expansion of the fluid during the brief high beta burn even at temperatures well above the nominal boiling point. Finally there is the

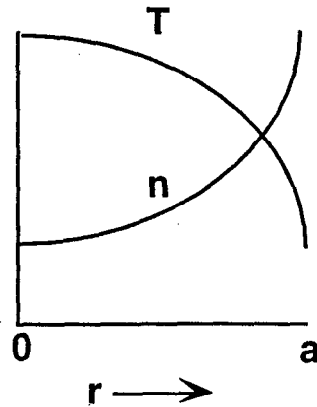


Fig. 1. Density and temperature profiles adjust to give constant pressure, with a density profile maximum at the edge and a temperature profile maximum in the core.

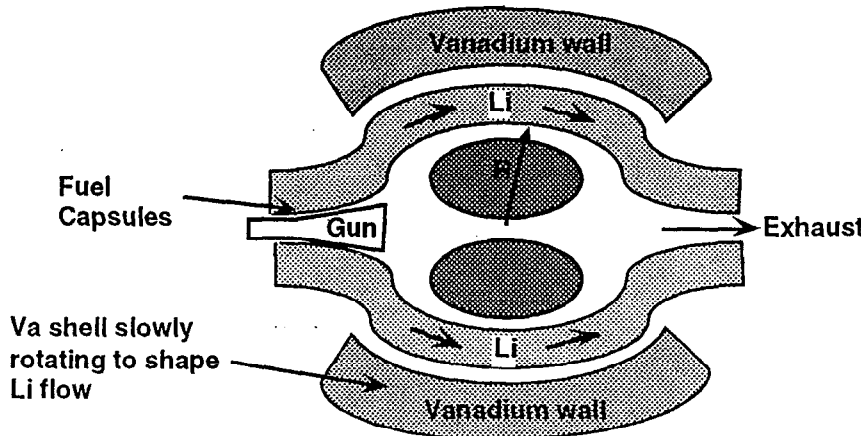


Fig. 2. Conceptual design of the high beta reactor

issue of plasma contamination by lithium evaporation from the surface [4]. Because lithium is low-Z, some contamination is acceptable, and in our scheme we fuel at a rate that outruns evaporation. We can quantify this using the energy balance for evaporation, given by:

$$(E_{Li} + 1.5T_{Edge})\Gamma_{Li} < P_{Loss} \quad (5)$$

and the energy balance for fueling at the edge:

$$1.5\langle T \rangle(\Gamma_{Li} + \Gamma_{DT}) = P_{\alpha} - P_{Loss} \quad (6)$$

where, taking into account the high density, low temperature gaseous boundary, the mean temperature $\langle T \rangle = gT_{Edge}$ and g is a geometric factor depending on the thickness of the gas layer. Combining Eqs. (5) and (6) gives

$$\Gamma_{Li}/\Gamma_{DT} = (\langle T \rangle/E_{Li})(P_{Loss}/P_{\alpha}) < g(T_{Edge}/E_{Li}) \quad (7)$$

where the Γ s are particle fluxes for lithium evaporation and fueling at the edge. Since the edge temperature T_{Edge} (the wall temperature) is much less the lithium evaporation energy $E_{Li} = 1.8$ eV, by Eq. (7) the lithium evaporation flux is generally much less than the fueling flux.

5. Scaling to a Reactor

To be interesting as a fusion reactor, our scheme must produce a high energy yield Y in ratio to the stored magnetic energy required to ignite and confine the plasma. Since the yield would continue to increase as fuel is added, the actual limitation on the yield is the thermal capacity of the liquid lithium layer and flux conserver. Since some vaporization of the lithium is acceptable, the lithium heat capacity is quite large since very large temperature excursions are allowed. Here we consider temperature excursions due to penetrating radiation, mainly the neutrons since even the Bremsstrahlung radiation penetrates several centimeters and is much weaker than the neutron power. Then the yield limit is:

$$Y = V \int P_{fusion} dt < \frac{17.6}{14.1} \lambda \rho_m c_p \langle \Delta T \rangle = 13R^2 \langle \Delta T \rangle \quad (8)$$

where λ is the neutron mean free path and $\langle \Delta T \rangle$ is the temperature rise averaged over λ . The gain G , in ratio to the magnetic energy, is:

$$G = \frac{Y}{E_{mag}} < 13 \frac{\langle \Delta T \rangle R^2}{1.7B^2 R^3} = 0.3 \frac{\langle \Delta T \rangle}{B^{2/3}} \quad (9)$$

where we have estimated $E_{mag} = 1.7B^2 R^3$ MJ and we have used Eq. (2) to express R in terms of B with the nominal value $X = 17,000$. The burn time and the maximum beta reached to obtain this yield and gain depend on the fueling rate. For the fastest possible fueling rate, given by Eq. (4), the burn time is t_{α} and the maximum beta is given by:

$$G = V \int_0^t dt \frac{1}{4} \langle \sigma v \rangle E_{DT} \left(\frac{n_c}{1-t/t_{\alpha}} \right)^2 \approx 4\beta_{max} \quad (10)$$

Using these crude formulas, some example parameters (very preliminary) are given in the table below.

B (T)	15.26	20	30	40
R (m)	0.68	0.474	0.276	0.188
E_{max} (MJ)	124	72	323	18
Y (MJ) *	3000	1494	506	235
G *	24.2	20.7	15.8	13.1
t_{α} (sec)	0.43	0.25	0.11	0.06

* For $\langle \Delta T \rangle = 500$ C.

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