The Polywell: A Spherically Convergent Ion Focus Concept

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Abstract

The Polywell spherically convergent ion focus concept for controlled thermonuclear fusion is described. The device magnetically confines electrons by a quasi-spherical-cusp magnetic field, forming a potential well. Ions are electrostatically confined by this well, converging to a dense focus in the center of the spherical potential, where the fusion rate is large because of the high local density of transient energetic ions. Power balance and critical physics issues are outlined, along with current experimental and theoretical work. The potential of the device for D-^{3}He operation is described by the derivation of scaling laws for energy gain.

I. Introduction

The Polywell concept, a magnetic version of a spherically convergent ion focus (SCIF) device, was invented and proposed by Bussard[1,2,3] as a significant variation of earlier studies on electrostatic confinement.[4,5,6,7,8] The idea of this device is to inject high-energy electrons into a quasi-spherical-cusp magnetic field; the electrons, confined by the cusplike magnetic field, create a potential well of sufficient depth to accelerate ions from low energy at the periphery to fusion energies within a focus at the center of the sphere. Injection of electrons keeps the system electrically non-neutral, so that the potential well, which accelerates the ions, is maintained at a constant value sufficient to confine the ions within the device, returning them again and again at high velocity to the central focus. Essential to the success of the scheme is that the cusp field needs to confine the electrons sufficiently long that the power required to maintain the cloud of energetic electrons is less than the fusion power produced by the convergent ion beams. Equally essential is that the ions maintain their non-thermal velocity distribution, with primarily radial flow, long enough to produce fusion in the dense focus at the center of the sphere. A schematic of the concept is shown in Figure 1.

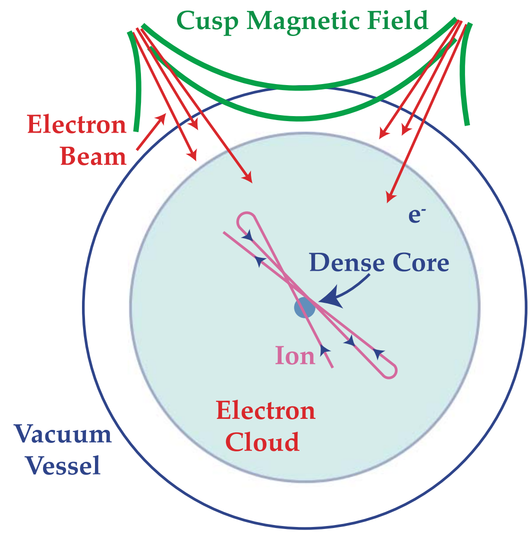

Figure 1 — Polywell SCIF Schematic

Fusion schemes that use electrostatic fields to accelerate and project ions onto a reacting region have a natural advantage for use with advanced fuels such as D-^{3}He compared with systems that confine a thermal plasma, because the need to heat the plasma to the increasingly high temperatures required for burning advanced fuels is replaced by a simple increase in the electrostatic accelerating voltage. Although we do not specifically emphasize a particular fuel in this paper, the Polywell SCIF concept falls into the general category of electrostatic acceleration devices and has the inherent applicability of that type of device for use with advanced fuels such as D-^{3}He. The scaling guides in Table 1 indicate the path to that application.

The power balance in the Polywell device includes the following:

1. Energy is lost by energetic electrons that leave the system; this loss depends on the confinement time of electrons by the cusps.
2. Energy is lost in the magnetic coils that confine the electrons; this loss depends on the strength of the magnetic field needed to confine the electrons.

3. Energy is produced by fusion in the dense center; this gain depends on the depth of the potential well and the degree of spherical focus in the ion flow in the device, which in turn determines the density of ions in the center of the sphere.

This description of the elements of power balance in the Polywell SCIF device highlights the physics behavior, which will determine whether or not the scheme is successful as a fusion reactor.

Implied in the above description is the fact that the plasma in this device is required to be far from thermal equilibrium and that at least the ion velocity distribution is far from Maxwellian. The electron orbits in the magnetic field are small compared with the size of the device, as they must be for magnetic confinement of electrons. The ion orbits, by contrast, are comparable to the size of the device, consistent with the idea that electrostatic effects dominate the ion orbits. The orbits of fusion products will be much larger than the size of the device since they are more energetic than the fuel ions, whose orbits are comparable to the size of the device. This makes ideas such as direct conversion of charged-particle energy to electricity an appealing possibility. Finally, the magnetic geometry is magnetohydrodynamically (MHD) stable by the nature of the cusp fields.

The non-Maxwellian nature of the ion distribution is in strong contrast with the requirements of more typical magnetic confinement fusion schemes,[9,10] which rely on magnetic fields to confine thermal plasmas of the energy and density required for fusion, with these parameters relatively constant over the device. In contrast, the Polywell device produces fusion in the dense core, where ions are not, in fact, confined but are passing through on orbits that intersect the core on each of a large number of passes. The magnetic confinement in the system is of a much lower density cloud of electrons.

In the next sections of this paper, we describe the physics of this concept in somewhat more detail. The reader is referred to Reference 3 for a definitive description of this novel fusion idea.

II. Electron Confinement in the Polywell SCIF

The basic magnetic geometry that confines electrons in the Polywell device is shown in Figure 2b, which shows the magnetic field lines in a plane through the center of the device. In the third dimension, the magnetic field continues to be a set of point cusps arranged in an alternating pattern in a generally spherical geometry. This field arrangement is the basis of the Polywell concept and can correspond to various orders of polyhedra. The lines shown correspond to an $m = 3$ configuration, called a *truncated cube*, with $B = B_o(r/R)^m$ fairly near the center of the configuration, where R is the radius of the device.

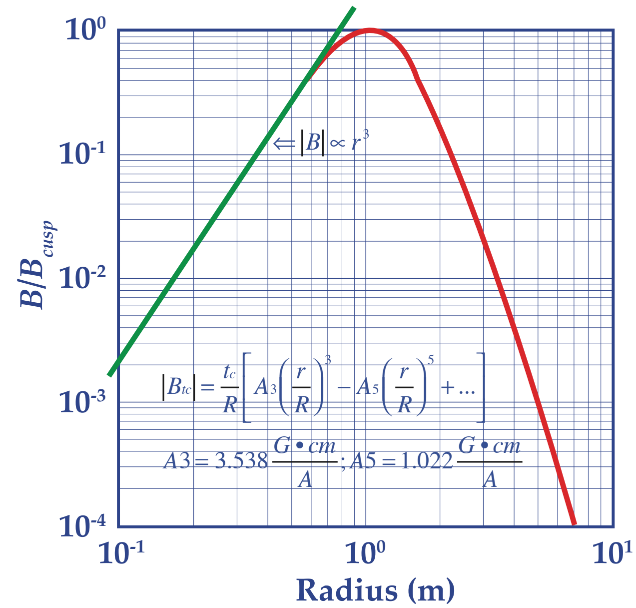

Figure 2a — Polywell Magnetic Geometry, Magnitude of B

Electrons are injected into this geometry from electron guns at high energy since it is to be expected that the maximum potential well that can be obtained will be approximately equal to the incoming electron energy. The current from the gun must be chosen so as to at least balance the electron losses.

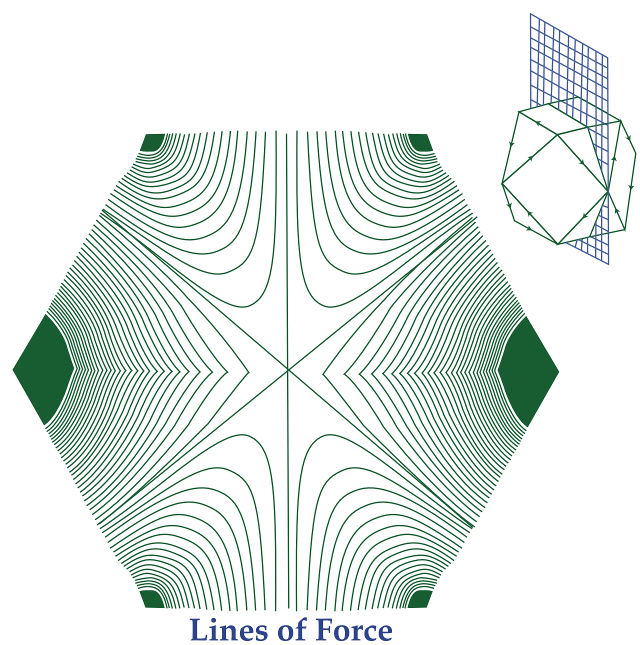

Figure 2b — Polywell Magnetic Geometry, Lines of Force

Electron losses are twofold. Losses directly through the cusp may be expected to be inversely proportional to the strength of the magnetic field. The "standard" expression for a single point cusp confinement time is:

$$t_c = t_{transit} \frac{R^2}{a_0^2} \quad (1)$$

where a_o is the gyroradius. A second loss mechanism would be from transport across the magnetic field, either due to collisions or to the fluctuating electric and magnetic fields from plasma instabilities. Although collisional cross-field diffusion is low, most confinement schemes with sharp gradients exhibit turbulence in the lower hybrid range of frequencies, $\omega_{LH} \sim eB/(m_e m_i)^{1/2}c$, generated by drift instabilities at that frequency. The diffusion due to that instability has been calculated, and the effect is to cause plasma expansion while simultaneously broadening the width of the plasma sheath until the interface between the electron cloud and the cusp field is many gyroradii. Thus, it is expected that hybrid frequency instabilities will affect the shape of the plasma more than the cross-field loss rate. Loss rates due to other instabilities have not yet been calculated.

Another energy loss associated with electrons is radiation, including synchrotron radiation and bremstrahlung, given by:[3]

$$q_{br} = 7x10^{-38} n_e(m^{-3})^2 T_e \sqrt{eV} r_e(m)^3 \ \ (W) \quad (2)$$

where r_e is the radius over which the electrons have density n_e. This loss will presumably be predominantly from the dense core.

It is not completely obvious what the effect of radiation and instabilities will be on the contribution of electron energy to power balance since the electron temperature must be determined consistently with the other physics of the system. These are among the problems currently under study. It is clear that the fact that the magnetic configuration is MHD stable is a necessary condition for power balance in the device. Numerical examples of the energetics of a typical device of this type are given below.

III. Ion Confinement in the Polywell SCIF

In the Polywell concept, the ions are electrostatically confined in the device as a whole but are not confined in the dense center of the device. That is, because of the excess of electrons in the plasma, enforced by injection of energetic electrons from the guns, a potential of the sort shown in Figure 3 will be produced. The ion orbits will consist of large-scale radial excursions from $+R$ to $-R$ passing through the center on each pass. Thus, the ions in the center of the device are transitory and highly non-Maxwellian. It is helpful at this point to demonstrate that:

(a) The ion orbits are indeed large scale, i.e., the ions do not gyrate in the cusp magnetic field but instead oscillate from boundary to boundary.

(b) This oscillation indeed produces a high-density region in the center of the device.

III.A. Ion Orbits in an Electrostatic and Magnetic Field

Assume that an ion is born with a low-energy E_o of a few electron-volts at a location r_o, and with comparable radial and azimuthal velocities v_r and $v_\perp$.

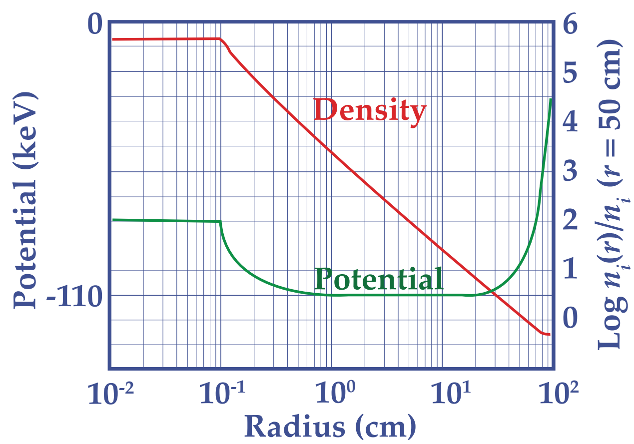

Figure 3a — Typical Potential Well Profile

Assume further that the ion sees an electrostatic potential $\phi(r)$ and magnetic field $B = B_o(r/R)^m$. To estimate whether the ion will reach $r = 0$ or instead be reflected by the magnetic field, consider a slablike abstraction of the problem, with

$$v_0 = v_{x0}\hat{x}, \ \phi = \phi(x), \ B = B_0(x/R)^m \hat{z} \quad (2b)$$

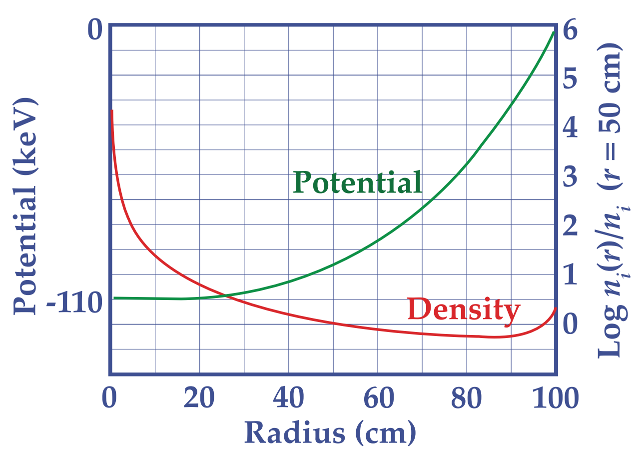

Figure 3b — Typical Ion Density Profile

Then the ion orbits can be written in terms of their ˆx velocity, integrating:

$$\frac{1}{2}\frac{dv_x^2}{dx} = -\frac{e}{M}\frac{d\phi}{dx} + \omega_{ci} v_y \left(\frac{x}{R}\right)^m \quad (2c)$$

and

$$\frac{dv_x}{dx} = -\omega_{ci}\left(\frac{x}{R}\right)^m \quad (2d)$$

from the ion birth-point x_o to an interior point x to obtain (setting $v_{yo} = 0$)

$$v_x^2 = v_{x0}^2 - 2e\left[\frac{\phi(x) - \phi(x_0)}{M}\right] - \frac{\omega_{ci}^2}{(m+1)^2 R^{2m}}(x^{m+1} - x_0^{m+1})^2 \quad (3)$$

where ϕ is presumed to decrease as x decreases, and $\omega_{ci} \equiv eB_o/Mc$. By examination of Eq. (3), the ions will reach $x = 0$ without reflection if:

$$\frac{eB_0}{Mc}\left(\frac{x_0}{R}\right)^m \frac{x_0}{m+1} < \sqrt{\frac{2e\phi_0}{M}} \quad (4)$$

where ϕ_o is the maximum depth of the potential well produced by the electron cloud. This means that the maximum birth velocity and local cyclotron frequency must satisfy:

$$\frac{v_{\max}}{\omega_{c,\max}} > \left(\frac{x_0}{R}\right)^{m+1} \frac{R}{m+1} \quad (4b)$$

if the ions are to have orbits as large as x_o.

This result shows that an ion born in a strong electrostatic potential will transit the entire geometry, of size R, even when the gyroradius calculated from the velocity and magnetic field at the ion birth is much smaller than R. It also allows an estimate of the perpendicular deflection of the ion by the magnetic field during its transit, namely,

$$\frac{\Delta V}{V} = \frac{\omega_{ci}^2}{(m+1)^2}\left(\frac{x_0}{R}\right)^{2m} \frac{x_0^2}{(2e\phi_0/M)} \quad (5)$$

where:

$$\Delta v_y \simeq \sqrt{v_x^2 - v_{x0}^2 + \frac{2e[\phi(x) - \phi(x_0)]}{M}} \quad (5b)$$

From this result, we can estimate the maximum magnetic field at the ion birth point in order for the ion to converge to a spot δr, $\delta r = R(\Delta V/V)$.

III.B. Ion Density from Spherical Convergence

Assume that at birth the ion distribution function is uniform in energy up to some small energy E_o, and uniform in angular momentum up to some small azimuthal velocity $v_\perp$ and take the potential at the birthpoint to be $\phi = 0$. This distribution is described in terms of the constants of the motion $[E = (1/2)\, M\, (v_r^2 + v_\perp^2) - e\phi,\ rv_\perp]$ by the function:

$$F = \begin{cases} 3\left(\frac{M}{E}\right)^{3/2} n_{edge}, & 0<E<E_0,\ 0< rv_\perp < r_0 v_{\perp 0} \\ 0, & otherwise \end{cases} \quad (6)$$

The Vlasov equation for steady state is $F(E, rv_\perp)$ = constant, so the density everywhere is determined by the potential and the value of F at the ion birth point. Integrating F over velocity determines the density. There are three regions. For a very small distance from the birthpoint, the potential is negligible, and the density is given by $n = n_{edge}$. Since the maximum well depth is in the kilo-electron-volt range, compared with ion birth energies in the few electron-volt range, a little way toward the center it will be true that $E_o \ll 2e\phi$ and $Mv_{\perp 0}^2(R/r)^2 < 2e\phi$. In that range, the density is given by integrating Eq. (6) over $v_\perp dv_\perp dv_r$ with the result:

$$n = \frac{3}{4}\sqrt{\frac{E_0}{e\phi}}\left(\frac{R^2}{r^2}\right) n_{edge} \quad (7)$$

Assuming that the potential reaches its full value at a moderately large distance from $r = 0$, we see that the electron density throughout the bulk of the device will be of the order [set $r = R/2$ in Eq. (7)]

$$n = n_0 = 3n_{edge}\sqrt{\frac{E_0}{e\phi_{\max}}} \quad (8)$$

Moving inward, the $(R/r)^2$ factor eventually becomes substantial, so that the density becomes much larger than n_o. Eventually, the radius is so small that $Mv_{\perp 0}^2(R/r)^2 > 2e\phi_{max}$. Inside that radius, the density is changing fairly slowly, on the scale of the changing potential. This defines the radius of the dense core r_c as the radius at which $2e\phi = Mv_{\perp 0}^2(R/r)^2$ because $n \sim 1/r^2$ outside that radius, while inside that radius n is nearly constant:

$$r_c \simeq \sqrt{\frac{mv_{\perp 0}^2}{2e\phi_{\max}}} R \quad (9)$$

Thus, the ion orbits are seen to be of the size of the device, and the ion density at the center is large, n ~(R^2/

$r_c^2)n_{\text{o}}$. The size of the core and the central density are seen to depend on the angular momentum at the outer turning points of the ion motion. This leads to the overall view of the Polywell SCIF shown in Figure 1.

IV. Advantages of the Polywell SCIF Configuration as a Fusion Reactor

The potential advantages of this approach to fusion are many:

1. The electrons are magnetically trapped in a high beta MHD stable configuration.
2. The magnetic fields are relatively small because the plasma density is low at the $\beta = 1$ point because of the $1/r^2$ density decrease away from the core. This allows the use of a low-technology magnet system.
3. There is no heating system as such. The electron guns provide the energy used to accelerate the ions to fusion velocities. These guns are external to the system and thus do not depend on interaction of a remote heating system with the plasma interior, as in current drive or electron cyclotron resonance heating (ECRH) and similar wave heating systems, which are an integral part of magnetically confined equilibrium fusion schemes.
4. The fusion products are not confined. This is clear since the orbit of an ion in the tens of kilo-electron-volts energy range is comparable with the device radius, so a more energetic fusion product will leave the device. Thus, there will be no ash buildup, and the escaping particles can be used in direct conversion schemes.
5. Application to $D\text{-}^3He$ and other advanced fuels can be achieved by increasing the energy of the electron guns.

In summary, the advantage of the Polywell SCIF approach is that it offers a high-beta geometry with no complex auxiliary heating or confinement systems; in practice, this means that the scheme can be tested with fairly modest budgets, with a fairly short development path. The trade-off, of course, is that the physics of the device is not simple at all, encompassing as it does a highly non-equilibrium system with widely varying parameters at different radial points in the device. In the next section, we list a few of the critical physics issues.

V. Critical Physics Issues

It seems quite reasonable that the Polywell SCIF will operate in a manner generally similar to the description in the previous sections. The injection of electrons from guns is straightforward and should lead to the creation of a substantial potential well. Production of ions by ionization of a source gas should be possible, leading to a source of low-energy ions near the periphery, as required. Convergence of large-orbit ions to the center should be an automatic consequence of the geometry, which should have a potential minimum near the center of the device. However, whether the details of the plasma state in this device will allow the production of more fusion energy than energy expended in operating the device will depend on a number of physics details rather than general behavior; some of these details are currently outside the scope of theory. In this section, we list some of the critical physics issues.

V.A. Electron Physics Issues

Electron losses will be a major energy drain on the system. Favorable energy balance will depend on the electron confinement time not being too much shorter than classical.

Cusp loss is not a particularly well-established concept. If the single-particle lifetime in a cusp field is calculated, the confinement time will resemble mirror confinement, with the effective collision time being comparable with a particle transit time. This is because in a single pass the particles lose track of their magnetic moment when they pass through the low-field region. Numerical calculations of single particle orbits in a cusp confirm this picture. Mirror losses with transit time collisions are not acceptable. When a plasma fills the cusp, magnetic field is excluded, and the $\beta = 1$ surface becomes a mod-B = constant surface. The transport picture is then expected to revert to the cusp picture, with much longer confinement than would be produced by mirror loss with transit time collisions as appropriate for a system with a non-adiabatic core. The ability to establish this high-beta plasma and reduce electron loss is a central issue for the Polywell scheme. Instabilities that broaden the plasma/field interface will increase cusp losses. Although it is expected that an increased B can reduce electron losses, this will also increase the energy loss if a normal-conducting magnet system is used.

Electron instability processes will undoubtedly be an issue in this device. As the density rises, the wavelengths for beam instabilities shrink and may play a role in the electron behavior. If these instabilities lead to electron thermalization, they may be unimportant to the gross energetics. If they lead to cavitons and the production of superthermal electrons, they can increase the electron loss rate. If they lead to turbulence, which decays by cascade into low-frequency turbulence, they can change the ion angular momentum, which we have noted will affect the ion convergence radius.

Radiation from the electrons will help determine the well depth necessary to increase the P_{fusion} until it exceeds $P_{radiation}$. This will depend to some extent on the electron temperature in steady state in the center of the device, which is currently not a known quantity. This should not be a major issue.

V.B. Ion Physics Issues

The requirement that the ions converge to the center and make sufficient passes before thermalizing so much that the focus is lost is a central requirement for exothermic operation of the Polywell device. Several issues are connected with the need to achieve and prolong ion convergence.

One effect already mentioned is the need to have the ions born at a location where the B field is weak enough that the ions are not deflected very much on their way to the center. Unfortunately, to use the electron energy efficiently it is clearly necessary for the ions to be born at a location where the potential well depth is still a large fraction of its maximum value; if they are not, most of the well is wasted. This depends on details of the radial and azimuthal profile of the well, which has not yet been calculated or measured in a three-dimensional configuration. The convergence, which will be achieved by an actual ion source in the potential well actually produced in the device, is a physics issue that is important to the success of this scheme.

If the ions converge to a high-density small-radius focus, collisional effects can destroy the configuration, even if they do not cause the ions to leave the device. Consider a collision that causes one ion to gain energy and the other ion to lose it. The ion that gains energy will make an excursion to a radius beyond its birth radius, with the possibility that the magnetic fields at the new turning point will be sufficient to deflect the ion in $v_\perp$ leading to a degradation of the focus. This effect has been calculated and may not be significant. Scattering in azimuthal velocity of ions outside the core will also degrade the focus. The effect of beam instabilities and instabilities driven by the anisotropic nature of the ion distribution in the core also offer potential sources of increased ion thermalization, which would result in a degraded focus. It is worth noting that loss of ions from the system does not in itself represent an energy loss to the system since the ions were born at very low energy, and replacing them costs little energy. Instead, thermalization of ions that remain confined is the effect that degrades the energy balance in the system.

VI. Power Balance and a Successful Polywell SCIF Equilibrium

It is instructive to combine the classical estimates of power loss and gain into a sample of the parameters that a successful proof-of-principle experiment or energy break-even experiment might have. Consider a device with a radius of R metres. The classical results of the previous sections can be used to calculate optimistically the power balance. Take the following estimates [σv = 4.4 x 10^{-16} cm^3/s has been used in estimating the fusion power appropriate for D-^{3}He at 100 keV or deuterium-tritium (D-T) at 20 keV]:

$$\textit{fusion power} \simeq n_c\,(m^{-3})^2\, E_F\,(\mathrm{eV})\, r_c\,(m)^3 \times 0.7 \times 10^{-41}\ \mathrm{W},$$

$$\textit{electron power loss} = \int n_e\, d^3\underline{r}\, E_e/\tau_e$$

$$\simeq n_o R^3 E_o/\tau_e\,(s) \times 1.6 \times 10^{-19}\ W$$

$$\textit{ion density} \simeq n_o (R/r_c)^2 = n_c E_e / M v_{\perp o}^2$$

and

$$\textit{radiation loss} \simeq n_c^2 T_{e,c}^{1/2} r_c^3 \times 7 \times 10^{-38}\ \mathrm{W}$$

where:

c = dense core

R = radius of the cusp field

E_p = fusion energy per reaction

n_o = bulk density of electrons or ions

Magnet losses are neglected in this estimate. They can be reduced by use of superconducting coils if this proves to be a crucial issue.

Table 1 summarizes these values for a set of parameters appropriate to reactor conditions, and for parameters appropriate to an experiment that provides a significant test of the concept. The fill density is clearly a critical parameter, and it has been chosen to give a net energy gain in the reactor. In Table 1, the first six entries are device parameters, and the rest are calculated quantities. The examples are clearly optimistic in that Eq. (1) is used for estimating the electron loss. The electron temperature in the core has been arbitrarily taken to be 4 keV. The potential well will ensure that $T_e(r_c) << e\phi$, but the actual value of $T_e(r_c)$ is questionable. Table 1 includes the scaling with electron confinement and other parameters, so it is straightforward to calculate degradation of performance with degraded values of electron confinement, as well as enhanced performance by increasing the size, field strength, or density in the device. Although the fuel in the example of Table 1 is D-T, extension to D-^{3}He is straightforward from the scaling guidelines indicated in the last column of Table 1.

We conclude from this set of estimates that if the Polywell behaves nearly classically, it will extrapolate to a very compact and attractive fusion reactor. This would allow the use of advanced fuels, such as D-^{3}He, and also lend itself to a variety of applications, such as space propulsion. An obviously attractive feature of the scheme is that so much of the physics can be tested in a device as small and economical as the Concept Test Experiment listed in the table, which is only a small factor more expensive than the experiment under construction (see Section VII).

VII. Work in Progress on the Polywell SCIF Concept

A modest program is currently being conducted to explore the feasibility of this approach to fusion, including both experimental and theoretical studies. The program includes the following:

1. Design, construction, and operation of a full size test device with a limited amount of electron beam power and magnetic field. This is being carried out by Directed Technologies, Inc. (DTI), which also acts as prime contractor in charge of managing the theoretical, numerical, and experimental support activities referred to below
2. Numerical modeling of the Polywell SCIF concept, which is being done by Mission Research Corporation at the DTI facility
3. Theoretical studies in support of the experimental and numerical programs as well as basic studies of device physics, which is being done by Krall Associates with substantial support by Energy/Matter Conversion Corporation (EMC2), also at the DTI facility
4. Phenomenological and exploratory studies of the physics of this device in reactor-relevant regimes and other applications, which is being done at EMC2.
5. An experimental study on the purely electrostatic version of electrostatic confinement that follows the pioneering work of Hirsch[5] and Farnsworth[4] and is being carried out at the University of Illinois
6. Additional experimental support of the DTI experiment. This program, using a smaller version of a SCIF-related device, is being carried out at Columbia University.

Table 1 — Polywell SCIF Parameters for D-T Fusion with Classical Loss Rates

	Fusion Reactor	Concept Test Experiment	Performance Scaling
Device radius, R(m)	2	1	—
Ion source radius (m)	1	0.5	—
Magnetic field, B_o (T)	1	0.2	—
Electron gun energy, E_e (keV)	50	20	—
Ion source energy, E_o (eV)	5	5	—
Bulk density, n_o (m^{-3})	2 x 10^{20}	1 x 10^{16}	—
Core density, n_c (m^{-3})	2 x 10^{24}	4 x 10^{19}	$n_o(E_e/E_o)$
Core radius, r_c (m)	1 x 10^{-2}	0.8 x 10^{-2}	$(E_o/E_e)^{1/2}R$
Electron confinement time, τ_e (ms)	120	2	Classical ~ $R^3B_o^2/E_e^{3/2}N_p$
Electron injection current	5 kA	5 A	n_oR^3/τ ~ $n_oE_e^{3/2}/B_o^2$
Fusion power (MW)	800	—	$n_o^2R^3E_F(E_e/E_o)^{1/2}\sigma_F$
Electron loss (MW)	40	—	$n_oR^3E_e/\tau_e$(cusp) $\rightarrow$ $n_oE_e^{5/2}/B_o^2$
Radiation loss (MW)	4	—	$n_o^2R^3T_{e,c}^{1/2}(E_e/E_o)^{1/2}$
E_{fusion} = 15 MeV	—	—	
Gain ≡ fusion power/electron loss	20	—	$n_oE_FB_o^2R^3\sigma_F/E_e^2E_o^{1/2}$

The primary experiment, which came online in March 1991, has the parameters listed in Table 2. The ability of a small program to make a significant contribution to the understanding of this concept follows directly from the relatively small size and low-technology nature of the approach. Note that an experiment with a 1-m radius has a volume of ~3 m^3, in contrast with a toroidal device with a 1-m minor radius and 3 m major radius, which has a volume of ~50 m^3. This difference in size, combined with the high-beta nature of the device, makes for an economical experimental study program and commercial development path if nature should prove not to be too harsh when the inevitable physics anomalies that plague all plasma devices begin to be uncovered and understood.

Table 2 — DTI Experimental Parameters

Radius	92 cm
Electron current	25 to 75 A
Cusp field	1 to 3 kG, $m = 3$
Pulse length	25 ms
Ion source	ECRH ionization
Diagnostics	Neutron measurements X-ray measurements Charged-particle measurements Fusion product analyzers Charge-exchange Microwave interferometer Langmuir probes Electron energy analyzer
Plasma parameters (planned)	$n_0=10^{11}$ cm^{-3} $n_c=10^{14}$ cm^{-3} $\Phi_0=10$ kV $r_c=1$ cm

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