Proposal for Research:
Spherical Microwave Confinement

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Abstract: Spherical Microwave Confinement (SMC) uses the motion of circularly polarized microwaves at the electron gyrofrequency (Ω_e) in two different mechanisms to create an isolated plasmoid that can reach thermonuclear conditions. The confinement will occur wherever the **B** field magnitude is near gyroresonance (B_c) with the microwave frequency and electrons. Spherical magnet coils outside the pressure wall generate cylindrically symmetrical cusps with B_c only at a spheroidal shell, thus defining the position of the electron cyclotron resonance (ECR) and the plasma surface. Where **B** is tangent to the plasma surface, away from cusps, radiation pressure couples strongly only at B_c and confines the plasma; near cusps, the external **B** is more radial, and rotating currents generate large tangential $\mathbf{B}_{rot}$ fields just outside the plasmoid. Pulsing **B** results in spheroidal implosion from the pressure wall to near the center, with efficient adiabatic heating and compression. The proposed test chamber microwaves will be 2.45 GHz with pulsed B_c of 875 gauss and several milliseconds, demonstrating SMC; the next reactor will be capable of high vacuum, thus testing fusion conditions. ECR heats the electrons; fusion reactors may need extra methods to heat the ions. The negative-curvature configuration is stable against MHD instabilities and can confine high-β plasmas. Extra experiments will explore atmospheric-pressure fireballs with aerosols in hopes of finding the energy source for ball lightning.

Note on terminology: a *plasmoid* is a self-contained bundle of electromagnetic and material energy, and is frequently used as a synonym for a spheromak. In this paper, "plasmoid" describes the organized and contained plasma object. Also I call the prospective device a *reactor* in anticipation of using it for interesting reactions. All units are SI except temperature in eV, and also where engineering realities in the US require inches.

I. INTRODUCTION

The first ideas for fusion reactors half a century ago used open magnetic confinement. There were several intrinsic advantages, chief among them the MHD stability of negative curvature fields; the curvature drift and "**B** drift are in opposite directions, vital in suppressing microinstabilities. Also, open fields allow beams of fusion products for direct energy conversion or space propulsion. However, the appeal of favorable curvature found in cusps has been tempered by the inability to plug the open ends to particle loss in fusion regimes. As a result the bulk of fusion research goes to closed magnetic geometries like tokamaks. These suffer from intrinsic instabilities and large areas of unfavorable curvature, and cannot operate without extreme expense and complexity. It is unlikely that an economic reactor can ever result from an engineering tour de force of such magnitude.

Spherical Magnetic Confinement blocks particle loss in an axial cusp arrangement by using currents formed by the surface of a spheroidal plasma responding to circularly polarized microwaves at the ECR frequency. In addition, the ponderomotive force presses inwards on the same surface away from cusps. By ensuring the **B** field is at

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gyroresonance on that shell and nowhere else, SMC defines stable plasma location and size. Thus stability problems that have frustrated fusion designs could be overcome; if SMC is valid, it could make possible an economical, relatively simple fusion reactor with modest magnets and strong, easily built and maintained, simply-connected geometry.

In the initial test device, a spherical metal chamber holds 20 inward-directed helical antennas that radiate circularly polarized 2.45 GHz microwaves. A slightly larger concentric sphere holds magnetic coils that run along latitudes; on one hemisphere they rotate in one direction, and counter-rotate on the other. Carefully adjusting the current density tunes the **B** field so that the microwave frequency is $\Omega_e = eB/m_e$ at the intended plasma surface. This magnitude is called B_c. To initiate plasma (except in ball lightning experiments), the microwaves cause breakdown at the resonant surface.[1] On that surface SMC causes stable confinement within a spheroidal shell, and effectively plugs the cusps.

Steady-state operation requires very large or superconducting magnets and is not the focus of this research. For pulsed operation, rapidly increasing **B** causes an imploding plasma shell, which can result in hot dense conditions on reaching a small radius. Using a single current for the magnet coil, the B_c surface can only be spherical at one radius, which is best chosen at the pressure wall. Further in, the isometric surfaces will be oblate spheroids. To have spherical B_c surfaces during the entire implosion would require multiple coils with intricate current controls, and is probably not worth the expense and complication.

The plasmoid is opaque to the microwaves and so there is reverberation between the plasmoid surface and the metal pressure wall. Anticipated Q is no more than 50 due to efficient coupling with the plasma.

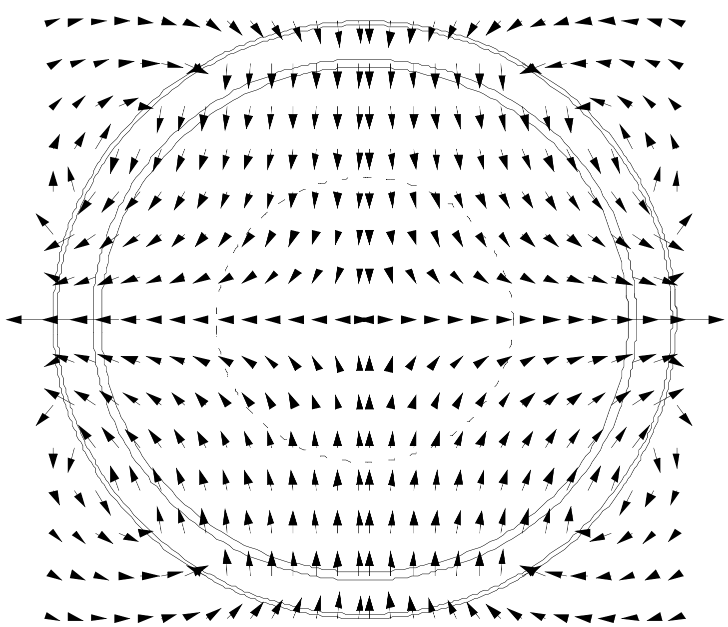


FIG. 1. Section along polar axis showing the outer sphere holding the magnet coils, the ground sphere (pressure wall, double circle), distance of the antennas' tips and inner edge of baffles from the center (dotted circle), **B** field cusp section (in vacuum). Rotation around the vertical axis gives 3-D.

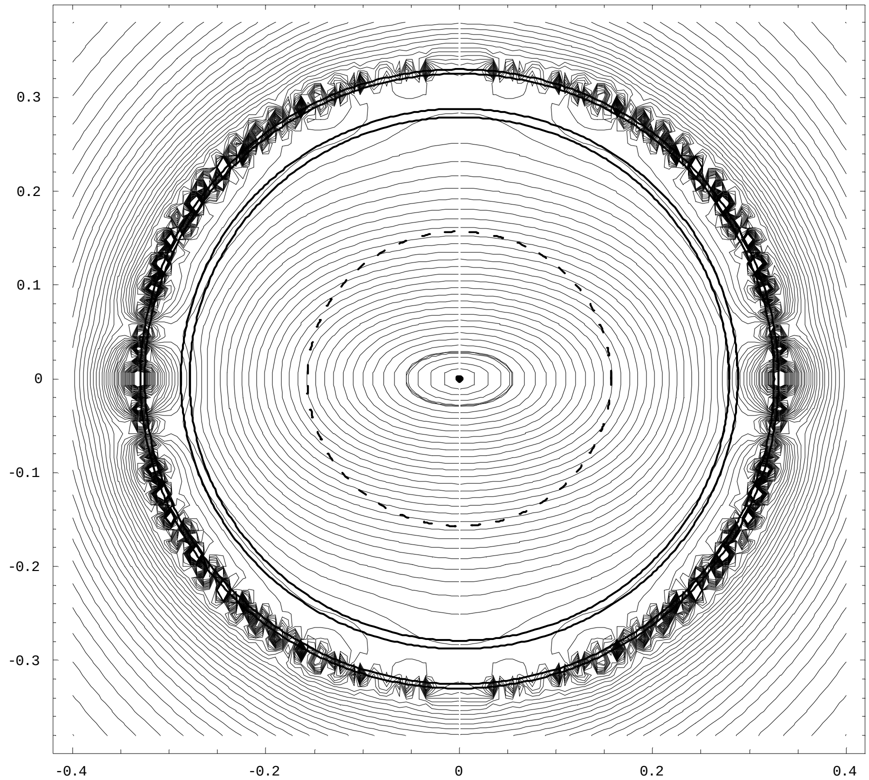


FIG. 2. Contours show B magnitudes. Superimposed sections are the outer coil sphere (upper hemisphere current in one direction and lower hemisphere the other); pressure wall, and antenna tip and baffle distance as before.. (See Green et. al.[2] for an analytic method for finding fields and current densities in spherical geometries.) Rotation around the vertical axis gives 3-D. Axis ticks in meters.

Figure 2 displays much that is critical to SMC. Each of the contour lines is an isometric surface for the **B** field magnitude. The outer sphere on which the coil rests is the outer two solid circles. Openings at the poles (above and below) and a missing coil on either side of the equator allow access to the pressure vessel, shown by the next two circles. The gap between the two spheres gives room for coax cables, air cooling, and for the magnetic field to smooth out irregularities before entering the chamber. Helical antennas point inwards mounted on the pressure wall; their inner tips reach as far as the dotted circle. Radial baffles of sheet metal coated with ceramic also reach in this far and separate the antennas to prevent cross-talk, allowing one magnetron per antenna.

Pulsed power to the coil causes the **B** field magnitude to increase rapidly, so that each contour line will indicate a progressively larger value while the shape of all lines remains constant. The contour that equals B_c travels inwards from the pressure wall in towards the center faster than the cold gas sound speed, changing shape from spherical to oblate spheroid and carrying the plasmoid surface with it. The extra-thick contour near the center is the target for the first experiment for the minimum B_c surface, and is the basis for the amp-turn calculations and **B** field cross-section plots (Figs. 3, 4 and 5). The center is indicated by a dot.

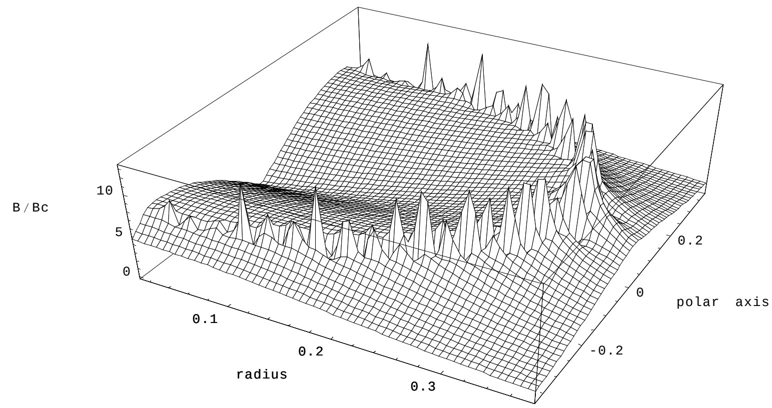


FIG. 3. Sample B magnitude in vacuum in units of B_c for test reactor, half-section along polar axis (left edge)

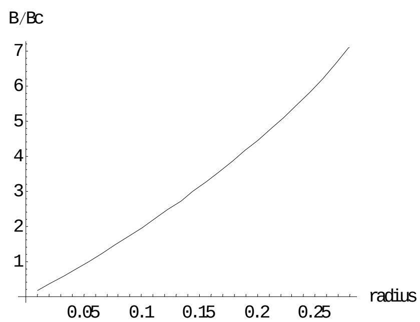


FIG. 4. Sample B magnitude in vacuum from center to pressure wall along equatorial radius

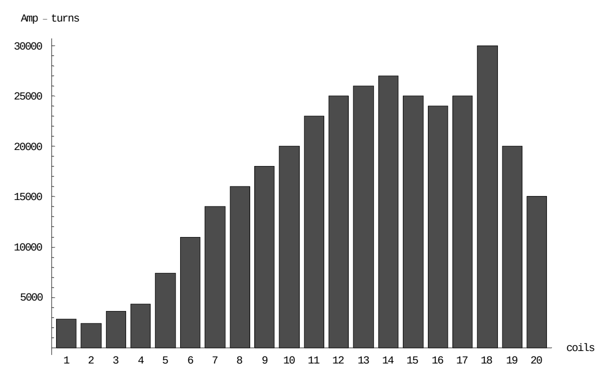


FIG. 5. Coil windings in amp-turns for test reactor, one hemisphere (other hemisphere is negative of this)

The magnetrons will be pulsed at about the same time as the magnet, which allows for high power radiation to be applied only when needed with small duty cycles (~ 10^{-3}). Also, breakdown should be limited to the B_c surface, without plasma forming in the central region before the magnetic field gains sufficient strength. Thus the microwave energy density must reach high enough levels for plasma initiation at the pressure wall when, but not much before, the B_c surface gets there. ECR heating will increase as the microwave power goes up, as well as the SMC confinement, so that the temperature and pressure increase greatly exceed pure adiabatic compression. Inward shocks can continue after the plasma surface stops imploding (although oblate symmetry will not make a very small focus). As a result, extreme conditions can result at maximum compression.

II. CONFINEMENT MECHANISMS

There are two methods for confining electrons in SMC; ions are confined secondarily by attraction to the electrons. Each method depends on the angle that the external **B** makes with the plasmoid surface. B_{rot} works with the radial component of **B,** and the ponderomotive force works with the tangential component of **B**. Combined, the entire surface is contained at pressures that can far exceed the magnetic pressure from **B**.

A. $\mathbf{B_{rot}}$ confinement

The circularly polarized microwaves rotate in two different directions, matching the gyrorotation of electrons in each cusp. For the inward-flowing cusp, the rotation is counterclockwise looking out (using the sense of rotation looking into the source of radiation); for the outward cusp, it will be clockwise. The electrons drift in response to the **E** field in two different ways. Without gyroresonance, when $B \neq B_c$, the orbital radius and velocity are inertia-limited and small. [3] As a result, both heating and current effects are negligible. In gyroresonance, the **E** field and velocity are in the same direction for about a third of the electrons at any given time, so the electrons accelerate until disturbed by a collision. This cyclotron behavior results in considerable current and heating. (The SMC confinement will apply to the large majority of the electron population even with only 1/3 in actual full gyrorotation.)

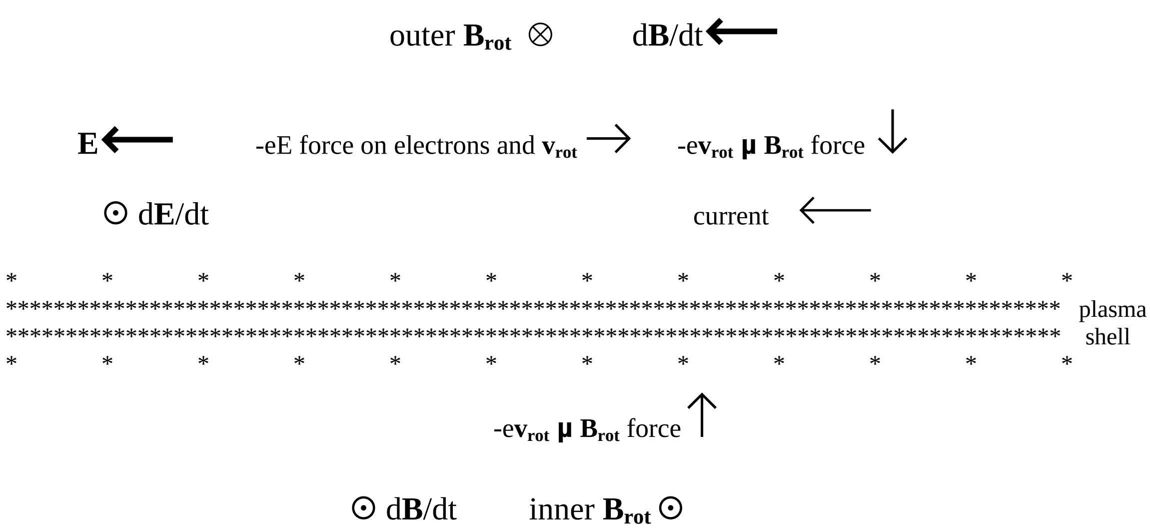


FIG. 6. **E** fields from microwaves, $\mathbf{B_{rot}}$ rotating fields, electron drift and current both inside and outside the plasma shell rotate clockwise seen from below. (This is for near the magnetic poles where B_c is close to perpendicular and pointing into the plasmoid; rotation is clockwise looking out for B_c going out of the plasmoid, always in same direction as electron circulation.) The inner fields and drifts will not occur for a plasmoid of near constant density within the shell, such as at high temperatures.

The antennas are isolated by baffles, so that the **E** fields each generate are approximately in the same direction within the scales appropriate (distances larger than instabilities) near the surface. The resulting current is in the form of a sheet; the **E** fields have negligible curl, so the electrons in any fairly small area move in unison at any given time in one direction and do *not* generate a radial **B.** The $\mathbf{B_{rot}}$ field generated by such motion is what would be generated by a thin sheet of current; tangential to the current, and in one perpendicular direction inside and the other direction outside. The sense of the $\mathbf{B_{rot}}$ field is such that the Lorentz force from the drift velocity is always into the sheet (current pinch effect). As long as the collision rate is sufficiently less than the microwave frequency, the B_{rot} thus generated can grow until its magnitude far exceeds B_c. Electrons will circulate rapidly and tightly around the strong $\mathbf{B_{rot}}$ lines which move quickly; they also will retain their slower orbit around the external, stable **B** lines. The following section leads up to a calculation of B_{rot} to ensure that it can become strong enough for confinement under the desired conditions.

The circularly polarized microwaves have a tangential electric field both outside the shell and exponentially decaying within the shell. To find the fields, we start with an idealized vacuum with strictly spherical symmetry and then modify for the actual condition. The baffles surrounding each antenna, the multiplicity of magnetrons, and the variability of the geometry due to the plasmoid ensure that distinct resonant modes will not form in any dominant manner. To a first approximation, the microwave energy will distribute evenly through the central portion of the sphere where it is not obstructed by baffles and absorbed by antennas.[4]

The quality factor Q is defined as 2π (energy in the system) / (energy lost per cycle). Q for this geometry is very difficult to calculate in detail, but a minimum, not counting losses to the antennas, is $Q_{\min} \simeq \frac{2\pi V}{\lambda S}$ with λ as the microwave wavelength, V the volume of the chamber, and S the plasma surface area. For the first reactor this is about 50, but the antennas and cancellation will lessen this quite a bit. (As a result it is not clear what the optimal number of antennas is, but the initial design has 20. There are some experiments somewhat like this indicating of about 10, despite theory predicting 100[5].) The total microwave power input, times the conversion to radiation efficiency (~90%) and Q, divided by ω and the chamber volume equals the energy density;

$$\frac{\varepsilon_o}{2} E_{\max}^2 = \frac{(0.9)\, Q\, Power}{\omega\, Volume} \tag{3}$$

From this can come an estimate of the electric field magnitude $E_{\max}$. For the test reactor it will be about $4.3\sqrt{Q\, Power}$. (The actual magnitude at the plasma surface and into the skin depth, E_o , is difficult to estimate due to unknown reflections and resulting interferences. The two confinement mechanisms use radial E_r (B_{rot}) and tangential E_t (ponderomotive), which will probably differ somewhat. For this first approximation, I will use $E_{\max}$ and adjust the theory after further research.) The flux from 4 kW should be more than sufficient for proof of concept, both for keeping the plasma hot and also for confinement. The first reactor will have at least 20 kW; more advanced reactors could have much more powerful microwave sources. The frequency might be lower, suited to larger reactors, but would be unlikely to be above about 8 GHz, the approximate limit for helical antennas. In addition, higher frequencies require proportionally higher B_c , which is a disadvantage; and there are always advantages to size in fusion reactors when such is possible.

To calculate the skin depth for reflective plasmoid densities we need the plasma frequency. Plasmas have an index of refraction that goes down from 1 as the density goes up, for a given frequency. The index reaches zero at the critical density (n_c) at which transmission into the plasma stops, when the plasma frequency ω_p equals the microwave frequency ω :

$$\omega_p = (n_c e^2 / \varepsilon_o m_e)^{1/2} \approx 18 \pi n_c^{1/2} = \omega \quad (4)$$

which for $\omega = 15.4 \times 10^9$ (2.45 GHz) means $n_c = 7.4 \times 10^{16}$, a practical level easily exceeded in the test reactor. All densities for reflective SMC must be substantially above the critical density so that the microwaves will bounce in a skin depth corresponding to the region of B_c. In reality there will be a complicated density gradient, but for this initial approximation the plasmoid has a hard edge and a skin depth of

$$\delta = \frac{c_o}{\sqrt{\omega_p^2 - \omega^2}} \quad (5)$$

As long as $\omega_p >> \omega$, δ is taken as c_o / ω_p . With this approximation, $\delta \approx 5.3 \times 10^6 n_e^{-1/2}$. Even when this is inaccurate, for the purposes of computing B_{rot} it is sufficient for estimating the total number of electrons or ions rotating in the sheet current; approximately the same number of charged particles will respond to the radiation, found by multiplying n_e by the volume of the skin.

The test reactor will start by using argon, as there is a lower collision frequency at moderate vacuums and temperatures due to the Ramsauer-Townsend minimum. The only collision rate of consequence in the conditions first investigated is between electrons and neutrals ν_{en} . For ν_{en} at temperatures less than 14,000 K, with n_n the neutral density and T_e in Kelvin:[6]

$$\nu_{en} = n_n (2.58 \times 10^{-6} T_e^{-0.96} + 2.25 \times 10^{-17} T_e^{2.29} \quad (6)$$

For higher temperatures this matches the slope for an argon cross-section of 1.52 x 10^{-19} m, so for the high temperature case with T in eV,[7]

$$\nu_{en} = (4.2 \times 10^5)\, n_n\, (1.52 \times 10^{-19})\, T^{1/2} \quad (7)$$

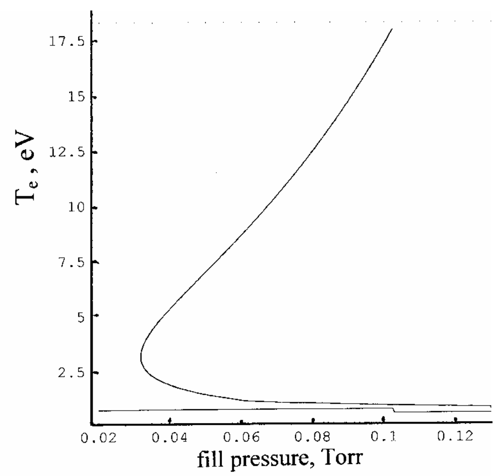
The other type of gases of interest are hydrogenic, which can use well-known formulas for finding ν_e . Now we can estimate B_{rot}. In gyroresonance, the electron velocity is in the direction of the electric field and continues to increase until stopped by collision. For a third of the electrons, with ν_e being the total electron collision frequency (sum of all species in the general case),

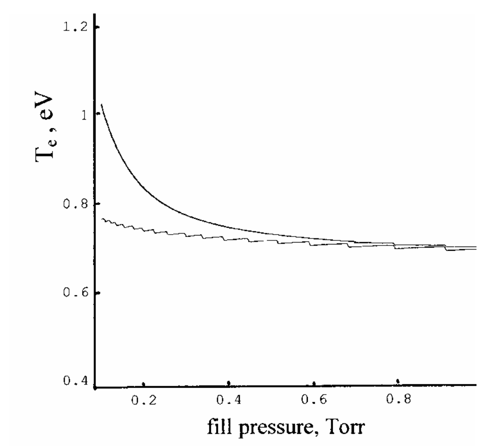
$$\mathbf{v_{rot}} = -\frac{e}{m\nu_e}\mathbf{E} \tag{8}$$

Deriving B_{rot} from the sheet current density requires a factor of cos ψ with ψ the angle between **B** and **r**, since the mechanism depends on alignment. With $\rho = e\ \delta\, n_e / 3$,

$$B_{rot} = \frac{\mu}{2}\rho\delta\left|\mathbf{v_{rot}}\right|\cos\psi = \frac{\mu e^2 \delta E_o n_e}{6 m_e \nu_e}\cos\psi \tag{9}$$

Considering that opaque plasmas have a minimal n_e , and given achievable and practical E_{max} and E_o levels, B_{rot} easily exceeds B_c in low-collision plasmas. This would be especially appropriate in fusion reactors where B_{rot} can reach a few hundred Teslas, tightly restricted to the region around the skin. Higher temperatures and lower densities work in favor of increased field strength. In the test reactor, using argon, B_{rot} can reach B_c at 4000 W anywhere below about 200 mTorr. (Note that the limited spatial extent of B_{rot} and the small magnitude of **B** might allow advanced fuels such as p-^{11}B without excessive cyclotron losses.)





FIGS. 7 & 8. (All figures assume 4 kW power in test reactor, Q = 50, β = 0.7 and use E_{max} instead of an attenuated E_o.) Argon confined by B_{rot} below and to left of the upper contour. Single ionization.

The maximum temperature and density confined at a given β (the ratio of magnetic to plasma pressure) comes simply enough from equating the magnetic pressure times β to the plasma pressure and assuming Maxwellian electron distribution. The figures show results for modest conditions in argon anticipated for the test reactor. Confinement improves without intrinsic upper limit as T increases, as these equations do not include factors that come into play at high temperatures.

B. Radiation pressure

The ponderomotive force per particle $\mathbf{f_{nl}}$ (*nl* from "non-linear") applies to both electrons and ions, but here we consider only its effect on the mobile electrons, and approximate for the moment no charge separation. This force is a result of the gradient in the spatial part of the microwave electric field, which is only appreciable in the radial direction at the surface of the plasmoid. Due to grazing incidence of some microwaves moving along the longitudinal direction of the **B** field, there is a radial component to **E** causing cyclotron motion and thus enlarged orbits of electrons just as for B_{rot} . The ponderomotive force is against the gradient of **E**, and thus always inwards towards the center since **E** attenuates exponentially into the plasma. For regions away from B_c , and thus out of cyclotron resonance (and away from appreciable $\nabla\mathbf{E_s}$),[8]

$$\mathbf{f_{NL}} = -\frac{e^2 \left|\nabla \mathbf{E_s}^2\right|}{4 m_e (\omega^2 + \nu_e^2)} \tag{10}$$

where $\mathbf{E_s}$ is the spatial part of the electric field, ω is the microwave frequency, and ν_e is the sum of electron collision frequencies. For anticipated reactor conditions, this force is negligible without ECR.

In the early 1970's, Donald Ensley[9] proposed two reactors using extremely intense microwaves (without ECR) for fusion reactors. One was spherical and heated a cryogenic fuel pellet in the manner of ICF; this could not work due to pre-heating of the pellet center as a result of the long wavelength and migrating electrons. The other was a low pressure, toroidal reactor relying entirely on radiation pressure without any external magnetic field applied. This was possible only with a Q of 10^{11}, which required all reflecting surfaces to be cryogenic and superconducting, something not possible in a fusion reactor. The interest in his voluminous labors lies in the sophisticated mathematical treatment of the interaction between microwaves and plasmas in spherical geometries, some of which can be applied to SMC; he showed how plasmas confined by radiation pressure in spherical symmetry would be stable due to plasma instability waves having shorter wavelengths than the confining microwave radiation.

In SMC, the ponderomotive force is greatly enhanced at the plasmoid surface where there is both cyclotron resonance and maximum $\nabla\mathbf{E_s}$. The gradient is radial and inwards at the skin. If the **B** field is tangential, with a re-derivation, ω disappears after much algebra and only the total collision frequency remains. Taking the decay of $\mathbf{E_s}$ to be exponential into the plasmoid in a hard-edge approximation, with ψ the angle between **B** and **r**, δ the skin depth, E_o the magnitude of the radial component of $\mathbf{E_s}$ at the plasmoid edge, and z the radial distance into the shell,

$$\mathbf{f_{NL}} = -\frac{e^2 E_o^2 \exp(-2z/\delta)}{2 m_e \nu_e^2 \delta} \sin\psi \ \hat{\mathbf{r}} \tag{11}$$

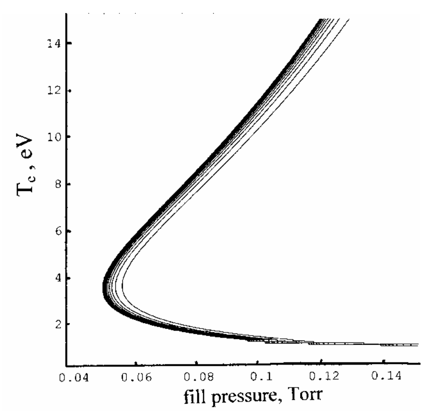
Note that $\omega > \nu_e$ when the fill pressure drops below a few Torr; high temperatures and lower densities dramatically decrease ν_e , and thus increase $\mathbf{f_{nl}}$. Even in this approximate form, it is evident that cyclotron resonance can enhance the ponderomotive force greatly as the collision rate decreases. In fusion conditions, which have very low collision rates and high E_o , the force would be extremely effective at confinement of electrons exactly in those regions where B_{rot} confinement is weakest.

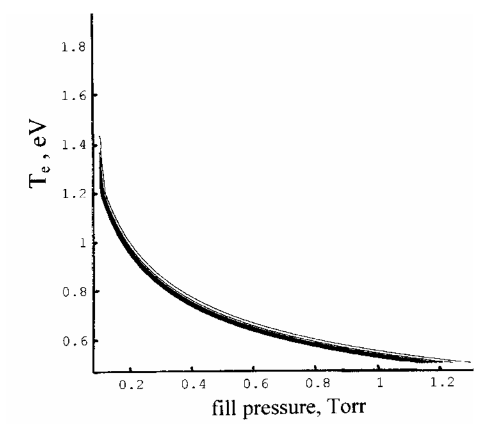
There is a typical density profile from ponderomotive pressure against a plasma surface ("profile modification", usually in the context of high-power lasers)[10] which is derived using techniques of statistical mechanics. The microwave wavelength λ_o is much greater than λ_D, the Debye shielding distance; if extreme conditions result in $\lambda_o \sim \lambda_D$, then the reactor can use longer wavelengths. As a result, charge separation will probably be negligible until the generation of fusion reaction products, which have much higher energies and will cause complications which will alter the equation below. These products must be confined enough to transfer energy to the plasma and cause ignition, so this is an important matter for future research.

In the simpler quasi-neutral case, taking z to be the radial distance inwards from the plasmoid edge, E_o the magnitude of the radial **E** component at the surface, n_{eo} the electron density inside the plasmoid beyond the skin, T the electron temperature in eV, and $\sin\psi = 1$,[11]

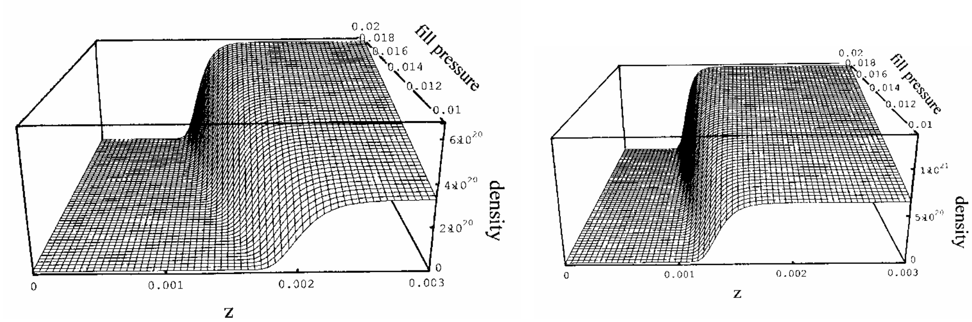
$$n_e(z) = n_{eo} \exp\left(-\frac{e E_o^2 \exp(-2z/\delta)}{2 m_e \nu_e^2 T} \right) \tag{12}$$

Note that if $n_{eo} < n_c = \omega^2 \varepsilon_o m_e / e^2$, the critical density, then $\mathbf{f_{nl}}$ will cause the surface to go a small distance inwards until **B** drops enough below B_c to weaken the force to equilibrium. If $n_{eo} > n_c$, then the radiation is reflected before $z = 0$ and the surface moves outwards and is not confined. Thus, the limits of confinement for a given T and n_{eo} are derived by setting $n_e(0) = n_c$. As the figures show, the confinement defined by this equation improves dramatically with increased T, without an upper limit intrinsic to the equation. This is due to decreasing ν_e and δ as T goes up.

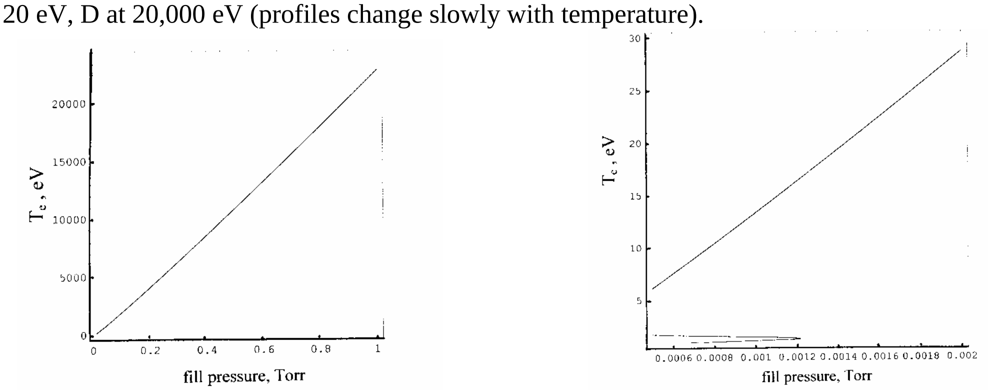




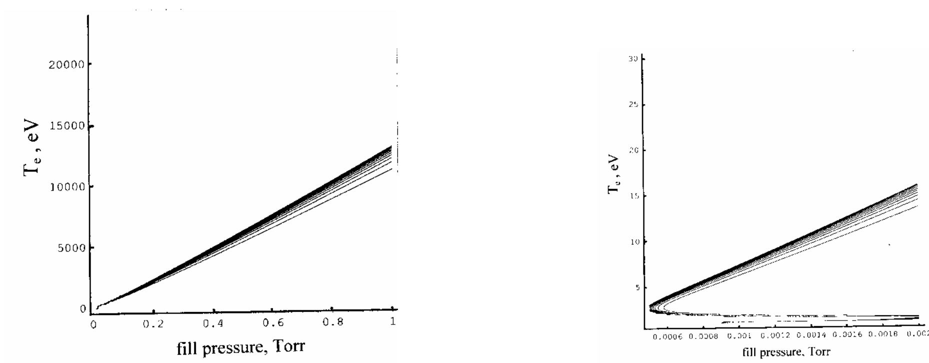
FIGS. 9 & 10. Argon confined by ponderomotive force. Contours are density confined, from 10^{21} to 10^{17} from left to right. Area to left of lines is confined for densities above 10^{21}; area to right and above lines is below the critical density required to reflect microwaves at 2.45 GHz. Vertical axes, T in eV; horizontal, fill pressure in Torr.



FIGS. 11 & 12. Argon and deuterium density profile due to ponderomotive force (**B** tangent to surface) well within confined T and n_e, with plasmoid surface at z = 0 (at least for mathematical purposes!). Argon at 20 eV, D at 20,000 eV (profiles change slowly with temperature).



FIGS. 13 & 14. Deuterium confined by B_{rot} to left of line. Note very high temperatures required compared to argon.



FIGS. 15 & 16. Deuterium confined by ponderomotive force, to same scale as Figs. 5 and 6. Densities above 10^{21} are left of lines as with argon; densities sub-critical are right of lines. Note the similarities in shape to the B_{rot} curves.

III. EXISTING EXPERIMENTAL EVIDENCE

There was an experiment by Komori et al[12] in 1990 that was far from ideal for SMC but which showed the effects of $\mathbf{B_{rot}}$ and $\mathbf{f_{nl}}$ confinement, although this was unrecognized. They used a Lisitano coil, which is an antenna made from slots cut in a pipe and was originally designed to create a plasma within the coil. Lisitano coils are not helical antennas as used in SMC as the turns are much too close together for an end-fire axial antenna. Their Lisitano coil was transverse to a cylindrical vacuum chamber with a 0.46 m diameter and 1.70 m length that was surrounded by a magnetic coil as shown in the schematic. The magnetic field was a simple mirror with the antenna inside the pinches and which could apply the 875 gauss B_c in large volumes of the cylinder. They used the same frequency and power as for the SMC test reactor (2.54 GHz and 1.2 kW) and made their plasmas in argon. Their gas pressure was between 3 x 10^{-5} and 3 x 10^{-4} Torr.

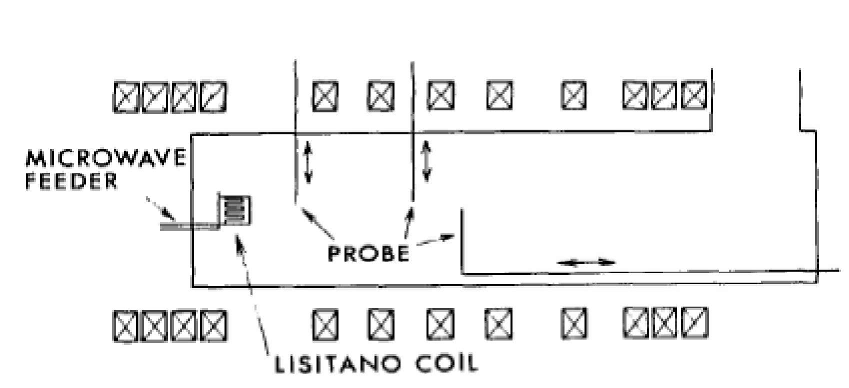


FIG. 17. (from Komori et al.) Schematic of experimental apparatus.

The resulting **E** field was not circularly polarized but was azimuthal in TE_{0j} modes, which was sufficient for ECR interactions. (Coupling would be much better with circular polarization in the correct handedness to match the **B** field, and without the radial nodes and antinodes of the cylindrical modes.) The area of ECR varied and was of most interest to SMC when it was more than 8 cm. away from the Lisitano coil. In those cases, the plasma was well beyond critical density at ECR, and the space between the coil and the plasma was transparent. There was no tendency for the confined plasma to diffuse towards the region of low density near the coil, which since the coil was between the mirror pinch and the plasma, certainly appears favorable for $\mathbf{B_{rot}}$ confinement at the open field lines.

Along the axis of the plasma they measured the profile modification and E_ϕ attenuation characteristic of either $\mathbf{B_{rot}}$ or $\mathbf{f_{nl}}$ confinement at the coil end of the plasma. They realized the characteristics of ponderomotive profile modification, but when they applied the conventional equation (10), the force was insufficient to explain the density profile. As a result they assumed that the confinement was due to the magnetic field, despite the data indicating otherwise. Had they applied eq. (11), which is appropriate in ECR conditions, they would have found sufficient $\mathbf{f_{nl}}$ to account for the measurements. However the orientation of the **B** field along the axis is more appropriate for $\mathbf{B_{rot}}$. This is good news since that is more speculative than $\mathbf{f_{nl}}$.

The plasma was relatively uniform in density within its boundaries and T_e was about 10 eV, with temperature dropping with increased fill pressure. The absorption of the microwave energy occurred well before B_c in the region $0.85 \lesssim (B / B_c) \lesssim 1$, which is very favorable for SMC. Electrons escaping from the plasma surface will have ample opportunity to be confined before colliding with antennas or the wall, even though the B gradient is large enough for a well-defined B_c surface.

IV. TEST REACTOR DESIGN

The first goal of the test reactor is to find out if SMC is a valid concept. This can be done in moderate conditions as long as the density is low enough for magnetic confinement to work. O-rings, gaskets with hose clamps, a simple mechanical pump with a trap and possibly a diffusion pump, argon (a particularly easy gas to use), and the modest magnets shown above run in pulses should suffice. The test reactor design described below is intended only to meet the first proof-of-concept goal. If extreme conditions result, tests will include deuterium, and also boranes.

A. Antennas

The antennas are arrayed symmetrically inside, pointing inwards, tapered radially to present the smallest possible shadow on the ground sphere. The proportions of the coil depend on the frequency, number of turns, radius of the outer sphere, and the radiation directionality and gain desired.[13] The circumference of the helix at the center should be one wavelength. The coil length needs to be at least one wavelength long for sufficient gain. One-wavelength antennas will have 4 ½ turns evenly spaced. The thickness of the copper wire is 10 gauge (0.102 inch), which is thick enough for good structural integrity and below the 5% of wavelength limit. The wire is coated with ITC 296A ceramic[14]. This prevents direct interaction with the plasma shell as it implodes past the antennas.

The distribution of the antennas is nearly icosahedral, at the centers of each of the twenty triangular faces. However, if not modified this would give uneven coverage. Thus, the arrangement has five antennas around each pole at 37.4^o with handedness to match the polar cusps, and ten antennas in icosahedral positions except azimuthally rotated 36^o and with opposite handedness matching the equatorial cusp.

Each antenna has its own oven magnetron rated at 1000 W. The magnetrons feed into 75 Ohm cable which then leads to the 150 Ohm antennas. There will be reflections due to the impedance mismatch; baluns to match impedances will probably be impractical and not required due to the high frequency and efficient power absorption of the plasma. Also the very small duty cycle should alleviate any heating problems. Future designs aiming at higher efficiency will include more careful impedance matching.

The icosahedral symmetry allows easy placement of baffles along the edges of the twenty triangular faces. These will be aluminum coated with the same ceramic as the antennas and will reach inwards as far as the antenna tips, which is about halfway to the center. The baffles prevent interference that would cause unwelcome cancellations and would cause difficulties among the twenty magnetrons. Details of the microwave system are subject to ongoing research.

The antennas produce an end-fire radiation pattern; the circumference, number of turns, and turn spacing determine how tightly focused the energy is. For reactors using one magnetron and dividing its power, antennas of similar helicity will have a phase relationship to ensure as nearly a common direction for **E** at the plasmoid in polar and equatorial regions respectively as possible. Tangential radiation for $\mathbf{f_{nl}}$ prefers phase coordination between polar and equatorial antennas. However the first reactor will have 20 magnetrons and, most likely, no specific fixed phase between antennas.

The half-power beamwidth for a helical antenna is, approximately,

$$\text{HPBW} = 52 / [C_\lambda (N S_\lambda)^{1/2}] \quad \text{in degrees} \qquad (13)$$

with N = number of turns, C_λ = circumference in wavelengths, S_λ = turn spacing in wavelengths. This is for cylindrical and not conical antennas. For the proposed reactor, HPBW will be about 50^o, measured from the middle of the antenna. When the plasmoid becomes quite small, direct radiation will be a small fraction of what it receives, but will be a large fraction during most of the implosion.

All the antennas are center-feed with a short tangential stub from the center wire to the beginning of the coil.

B. Magnet

The magnets are wound on 3/16" acrylic hemispheres of 26 inch o.d. that are each cut in two sections and mounted on the inner hemispheres. The windings shown in figures above allow for a one inch gap two inches from the equator on each hemisphere. While a smoother winding would have slightly better performance, the gap is essential for access to the inner sphere, and the disturbance is small to the **B** field inside the pressure wall. In practice the windings will be smoother than that in the figures, which assume no width to the coils. The distance between the two spheres is the minimum required to allow organization of the B field into smooth isometric surfaces on entrance into the pressure chamber. The wire will have heat-resistant coatings up to 180^o or 200^o C. The coils may be air-cooled with compressed air introduced between the two spheres at each pole. Present rough estimates are for several coils powered in parallel at between 5 and 8 kV, but this is subject to considerable change before construction.

As this is a simple, single-current, single-wire coil, the isometric surfaces can only be spherical at one radius. This is chosen to be just within the pressure wall. If the spherical surface were further in, then isometric surfaces further out would be disrupted and not closed, and would be worthless for confinement during the beginning of the implosion. The oblate spheroids formed inside the spherical surface are acceptable for SMC confinement despite irregular reverberation.

Figure 2 shows the target size for the smallest B_c surface. Progressively smaller surfaces require much increased magnet strength since fields cancel more and more towards the center. This reactor relies on supersonic compression and heating to reach maximum density and temperatures; given the efficiency of the geometry, if loss mechanisms are moderate and the confinement is good, quite extreme conditions could be within reach.

The magnet must be far enough away from the magnetrons to not interfere with their operation.

Due to the cusp geometry and the shape of the B_c surface, it is important to have coil windings around the equatorial seal of the two hemispheres; thus, each hemisphere's four mountings are two inches away from the equator, made of four flat bars of 3/8" thick aluminum plate. This allows two counter-rotating coils each almost two inches wide over the equatorial seal.

The power supply is a capacitor bank supplying between 5 and 8 kV and about 11 kJ of energy with a time constant of a few milliseconds. The shape of the pulse current is critical for maximizing the heating and compression. The imploding plasmoid surface should have a velocity greater than the sound speed of the cold gas or cool plasma within, to form a shock wave; but the velocity must be less than the sound speed in the plasmoid itself. Thus the ramp-up time has to be adjusted to the proper implosion rate. (For hydrogen this would be shorter than 0.2 ms.) After reaching full strength, the current needs to decay slowly enough so that confinement mechanisms can be studied; also, should conditions become extreme enough, longer time constants result in detectable numbers of nuclear reactions. An actual thermonuclear device would almost certainly require superconducting magnets, which would be much smaller and cheaper than those required in standard magnetic confinement schemes.

C. Other Details

The pressure chamber is an aluminum sphere. Spheres and hemispheres in the U.S. are available in stock sizes graduated in inches; custom sizes require substantial cost for tooling. The nearest size to the 21.5 inch spherical resonance node for 2.45 GHz is 22 inches. This allows ample room for one-wavelength long antennas. For strength and to accommodate extra holes, fittings, and changes expected in a prototype, the first sphere has a wall thickness of 0.34 inches (3/8 nominal). The two hemispheres are side-by-side; each mount on strong steel shelving on large casters. Thus, the entire apparatus divides into two parts, allowing full access to the inside of the sphere. The hemispheres can be separated from each other and remain rigidly fixed to all attachments, such as pumps, power supplies, cables, grounds, etc. with minimal disruption to connections, and no lifting. Each half of the reactor measures 18” by 36” and is 64” tall, which will fit through standard doors. The aluminum inner surface is sandblasted for better vacuum characteristics, but not plated with copper or silver as the plasma will absorb microwaves efficiently leading to low Q. Each of the 20 coax cables provide grounding points for the sphere through the coax sheaths and help short-circuit eddy currents from the magnetic pulse. (To function as a ground plane for the antennas, the pressure sphere needs many grounding points.)

At each pole, a 1 ¼ inch nom. schedule 40 aluminum pipe welds onto the pressure chamber and passes through openings in the plastic magnet sphere. This allows ample room for probes as well as openings for gas entrance and exit ports. The plastic magnet hemispheres use this pipe as a support point allowing them to slide and giving access to the metal sphere.

There is a limited range of appropriate wavelengths for SMC in this configuration. Power transmission favors longer wavelengths, while reasonable reactor size and the extreme savings (a factor of up to a thousand) of using 2.45 GHz are major factors as well. With the upper frequency limit of about 5 or 6 GHz for the antennas and the power limits of semi-rigid coaxial cables, the practical range for ω in this type of reactor is from 2 to 5 GHz. In pulsed operation, helical antennas have the advantage of radiating inside an imploding plasma shell; note that SMC works from the inside as well.

The most economical microwave sources, by several orders of magnitude, are 2.45 GHz magnetrons, easily available in 1000 W rated power appropriate for the reactor. As a result this is the only practical option for the test reactor. As shown above, this ω results in a B_c of 875 gauss. Dividing power from one magnetron to the 20 antennas is prohibitively expensive and results in relatively low power levels if using a household oven magnetron; 20 oven magnetrons of 1000 W rating are far cheaper. However this does lead to potential problems and especially negates control of phases of the individual antennas.

The magnetron power supply is in two parts. The cathode filaments requires 3 V at 10 A, which can be AC from the center feed of oven transformers. On top of this comes a 4 to 5kV pulse from a capacitor bank. (If the magnet runs at 5kV, then the two can share the same bank.) The microwaves need to be strong enough to cause rapid breakdown when the B_c surface reaches the pressure wall. In addition, there cannot be breakdown in the center of the sphere before the desired plasmoid shell forms for two reasons. The first is that such a central plasma would absorb microwave energy in a disorganized, unconfined manner that would have substantial energy losses and disrupt energy deposition in the imploding plasma shell. The second is due to the mechanics of implosion heating, especially with shock waves: the inner region is more effectively heated and compressed if it is not pre-heated. The peak radiated power should be about 20 kW.

Air cooling will suffice due to low duty cycles ($< 10^{-3}$). If required, squirrel cage fans supply air through tubing entering at the equatorial gaps and terminating near the poles, causing an air current from there to the equator. It may help to have a black coating on the inner sphere. The magnetrons will be lined up in four groups of five, and each group has forced air cooling from a squirrel cage fan. There is little power loss in the helical antennas and they will not require cooling in the test reactor even though the ceramic coating and vacuum environment will make heat transfer difficult. Higher-power reactors will require active antenna cooling, probably with an appropriate oil.

The polar pipes allow for easy access to the interior and include mountings for a fiber optic borescope probe with a video camera; a fiberoptic lead for a spectrograph; instrumentation for pressure, temperature, ionizing and microwave radiation; and a plasma probe.

For initial plasma formation and introduction of experimental aerosols (vaporized organic materials) in ball lightning research, there is a very small coaxial railgun of ¼ " diameter. The inner electrode is a 5 inch 1/16 inch diameter tungsten welding rod, with the cavity at the last half inch, the rest sealed with glass. It attaches to the inner sphere near the bottom through a valve that allows reloading of the railgun with minimal pumping. It will have a capacitor bank pulsed power supply of no more than 1500 or 2000 V. The railgun pipe reaches into the chamber as far as the tips of the antennas.

The main variations will be in gas composition, pressure, coil geometry, and power supply. Other variations require quite a bit of hardware adjustment, mostly unpredictable, and so the design must be modular and variable.

V. HIGH PRESSURE EXPERIMENTS AND BALL LIGHTNING

There are several websites[15,16] and some journal articles[17] describing fireballs in 2.45 GHz microwave chambers (usually ovens) formed with aerosols. These are frequently described as ball lightning (BL), although there are many differences between natural BL and the fireballs. The most obvious is that nature does not require an external power source or reflective chamber. All the fireballs extinguish within microseconds of turning off the microwaves, and some only last milliseconds even with continuous external power. Also, the fireballs are buoyant, while BL does not typically float up. (Recently there are reports of underwater discharges forming non-microwave related fireballs, which have anomalous durations of up to half a second instead of the anticipated millisecond. However these are buoyant in air, unlike BL, and do not have the same shape, power density, or other characteristics usually found in natural BL. Thus there is progress and demonstrated anomaly, but not yet synthesis.)

SMC theory depends on low densities. The chamber, power levels, and microwave frequency designed for SMC are also suited to fireball experiments at and near atmospheric pressures in a variety of gases and aerosols. BL was the inspiration for the development of SMC, even though the theory and conventional fusion applications require very different conditions. It is impossible to design a BL reactor directly as nothing is known of BL physics—not its confinement mechanism, temperature, formation, or even its constituents—or optimal conditions. There is no reason to suppose that atmospheric conditions are best for BL. All proposed theories are fatally flawed when matched to the full list of reliable observations; the list of theories and their problems is long and beyond the scope of this paper. It is known that high-energy BL, and probably all BL, broadcasts microwaves at wavelengths roughly corresponding to its size. High-energy BL produces energy at densities far beyond the range of chemical reactions or thermal energy storage, although no known nuclear reactions seem possible.[18] (Only one observation recorded radiation effects, which devastated a village in Venezuela in the ‘30s.)

There are many unsolved mysteries with BL. One is that neutrals are confined as well as charged particles. This is evident from several factors repeated in observations; BL doesn't cool, at least over several seconds, but if hot neutral gas could convect out it would do so in less than a second. BL can fizzle, but also typically pops or even explodes violently on its demise, implying internal neutral pressure (since the ionization is parts per million the partial pressure of charged particles is insufficient to explode at all). Also, BL doesn't rise, so it's as dense as the surrounding air, despite its temperature—requiring at least 15 atmospheres of pressure if it's several thousand K, as the color suggests. Even if there was a way to confine the charged particles with electric or magnetic fields, there is no known way to confine neutral gas molecules or atoms except by solid or liquid surfaces.

Here's another; the only known confinement mechanisms for non-transient plasmas require external magnets, as the thermal plasma pressure transfers to the magnet mounts (equal and opposite forces). Since that's not possible here, there's a basic Newtonian problem of force balancing in lieu of tension, which is only possible in solids. In addition, all magnetic confinement requires that the collision rate be lower than the gyrofrequency, so that the collisions don't bounce the particles out of the field lines. Otherwise there's little or no difference in diffusion rates parallel or cross field lines, as is the case in atmospheric cool plasmas like flames. So even if there's magnetic fields they would make no more difference than they do to a candle.

The inevitable conclusion from BL observations is that there must be a power source that sustains the plasmoid, especially as some BL doesn’t form in association with linear lightning. The upper bound for energy density is in the range of 10^9 J m^{-3}; the power output is in the form of microwaves and, sometimes, an explosive end. The goal for a BL-based reactor would not be necessarily to recreate natural BL, but rather to host the mysterious reaction that sustains the BL. This would make an ideal power reactor with no radioactivity, direct energy conversion from the microwave outputs, light weight, and (evidently) abundant fuel.

My experiments will include projecting a plasma formed from organic material into various gases, with hydrogen sulfide a prime candidate. This is because of soot and aerosol evident in many BL sightings, and from reports of acrid odor, typically of ozone or rotten eggs. The only available solids in the air to make soot are from living things; thus, I will take the novel approach of blowing up insects and other similar material in the miniature coaxial railgun sparker mentioned above. This deposits a plasmoid explosively to form a target for the microwave pulse. I do not anticipate using the spherical magnets for BL as the density is too high.

There are so many variables to explore and so little known of the physics that a suitable combination will probably result from a fortuitous blunder.

VI. SUMMARY

The potential advantages and utility of this novel plasma trap could be considerable. SMC promises the possibility of stable confinement of a variety of plasmas in a relatively cheap, simple, safe reactor. The inherent MHD stability of cusps, the efficiency of microwave power generation and its coupling to the plasma, the simply-connected geometry, modest magnets, the high energy efficiency of generating microwaves and their coupling to the plasma for both heating and confinement, the powerful heating and compression from implosion, and the convenience of direct energy conversion give great advantages for fusion applications. Breakeven might be achieved with a reactor large enough to confine fusion products. Once a test reactor demonstrates SMC for relatively cool plasmas, there is every justification to start serious research using advanced models in pursuit of a practical fusion reactor. In addition there will be explorations in up to atmospheric pressure fireballs in various gases with aerosols in hopes of finding the energy source of ball lightning.

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