Spherical Microwave Confinement: Current Status and Near-Future Developments

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Abstract: Spherical Microwave Confinement (SMC) is a proposed method for heating and confining plasmas by RF near-field radiation with a positive outer grid. The test chamber microwaves are 2.45 GHz, from 20 magnetrons of 1000 W, each powering a conical helical antenna coated with ceramic, then a metal shield, then more ceramic. By accelerating hot electrons to the center, especially if pulsed (Periodically Oscillating Plasma Sphere, or POPS), this could result in a form of gridless Inertial Electrostatic Confinement (IEC). If SMC avoids IEC losses and scales favorably in size and density, it could be a candidate for fusion reactors. The critical test is with deuterium to measure for neutrons.

Note on terminology: Units are SI except temperature in eV, and also where engineering realities in the US require inches. "IEC" refers to conventional systems with an inner grid.

I. INTRODUCTION

Construction started on the first Spherical Microwave Confinement reactor in August 2006 at Research II, Centennial Campus, NCSU, with first plasma about a year later. Now, after many refinements, it is almost time to start testing with hydrogen, in preparation for deuterium and the possible production of neutrons. Since this cannot happen at NCSU, I am looking for another safe location where fusion research is appropriate.

To explain the current experiment, I first review IEC, which was first invented in the 1950's by Philo Farnsworth; then comes a description of SMC, the reactor, what it can do, and what is required to test for neutrons. Finally is a short note about ball lightning, which is quite intriguing, while not the focus of research.

II. CONFINEMENT MECHANISM

A. Inertial Electrostatic Confinement

Here is a brief introduction to basic IEC ideas, especially those relevant to SMC. There is a large body of information now on the internet, especially due to amateur interest and experimentation, for those seeking more detail.

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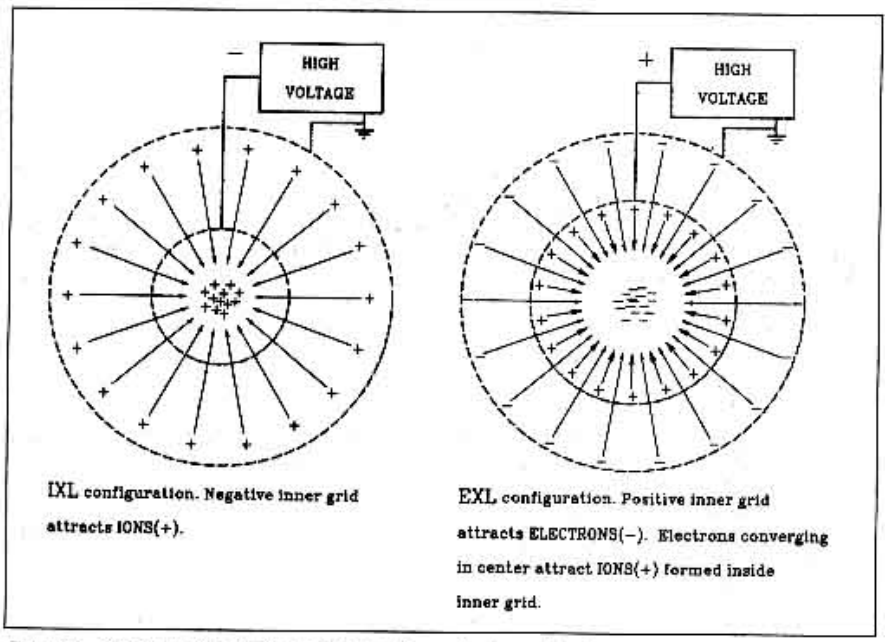

Figure 1. The two basic spherical convergent focus fusion methods.

Plasma confinement, as defined by keeping the plasma physically separated from material walls in a closed body, cannot be obtained by static electric fields alone. By use of a charged porous "wall", an inner grid, through which charged particles flow, a ballistic confinement can work, at the cost of losses to collisions on the grid and current losses from putting a potential across the conducting plasma. (This is still not true confinement since the plasma is not separated from the inner grid; I do not discuss here variants that try and protect the grid.)

As shown in Figure 1[1], there are two varieties of IEC. Ion accelerated (IXL) has the inner grid at negative voltage, causing a "virtual anode" at the center. Electron accelerated (EXL) has the inner grid at positive voltage and creates a virtual cathode at the center. This is a highly idealized view of a much more complex situation; angular momentum builds up inside the inner grid, especially among the electrons, leading to a double-well potential instead of a single focus.

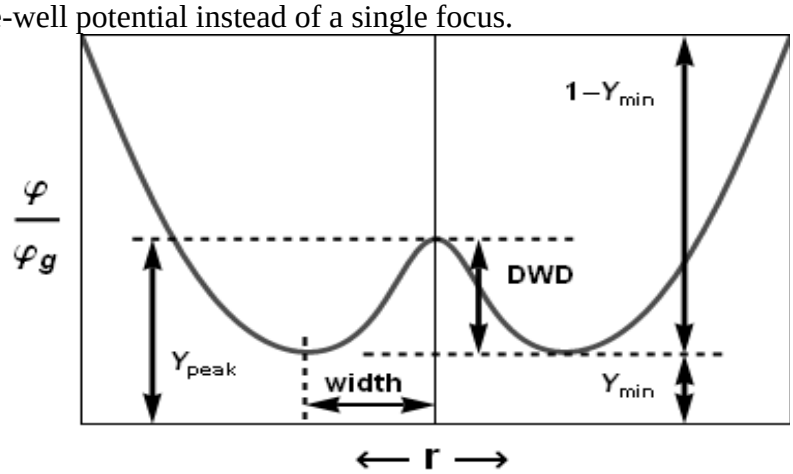

Figure 2:[2] Double well potential structure. The double well depth (DWD) is $Y_{peak} - Y_{min}$. Here, Y_{peak} coincides with Y_{core}. A double well is much more likely than a single well.

There are remarkable advantages of IEC over other fusion techniques. There are no magnets, which simplifies, shrinks, lightens, and cheapens the reactor by orders of magnitude, as well as avoiding synchrotron and magnet power losses. Very high temperatures are easy to obtain, and the geometry is simply-connected and convenient to build and maintain, unlike toroids.

However there are fatal disadvantages that are intrinsic to the design. The net reaction rate for any fuel in IEC is inversely proportional to both pressure and volume, which means that peak power is at densities far too low for power generation even if everything else worked perfectly. IEC reaction zones are typically about a cubic centimeter at the center, far too small for a reactor where plasmas are typically measured in cubic meters. (The upper limit for power in a thermal cycle is 100 W cm^{-3}.) The best power gain so far (Q) is about 10^{-5}. This can result in a good neutron source when using either D-D or D-T fuel (2×10^{10} at best so far) but this is about 10^{7} too low for a power reactor.

Collisions with grids are also prohibitive for power production; in terms of power loss, $P_{gridloss}/P_{fusion} > 3000$.[3] Ion upscatter and energetic tail loss time is about 1/1000 of the fusion rate; for both ions and electrons, the loss times are much less than the fusion time. There are substantial losses from ion-neutral charge-exchange collisions, where a hot ion takes an electron from a neutral atom and then, having no charge, is not confined. The plasma cannot ignite, in the sense of fusion products heating the fuel plasma, since the energy of the products is far greater than the potential well and they escape quickly with few collisions. The potential is created by a non-maxwellian, non-equilibrium plasma; but this requires Coulomb collision losses far outstripping energy gained by fusion to sustain. Bremsstrahlung is the same or worse as in other reactors, which makes advanced non-neutronic fuels impractical, despite the attractiveness of the easily achieved extreme temperatures required (several hundred keV).

One interesting attempt to improve the situation is by means of the Periodically Oscillating Plasma Sphere (POPS), now being investigated at Los Alamos by R. A. Nebel and his team.[4] The ion cloud oscillates collectively due to the virtual cathode with this frequency;

$$\omega_{POPS} = \sqrt{\frac{2 e \phi_o}{r_{VC}^2 m_i}}$$

Here, f_0 = potential well depth, and r_{vc} = virtual cathode radius. POPS uses RF modulation of the grid voltage matching the ion oscillation frequency to preferentially heat the hottest ions, as well as greatly compress then expand the plasma, leading to adiabatic heating and fusion-relevant densities. Thus some ions are expelled, deepening and prolonging the potential well. Also, beneficially, POPS appears to aid in thermalization, thus minimizing Coulomb losses, while still allowing the small charge imbalance required for the virtual cathode or anode. (This space charge can limit the central density.) While the existing experiments show the concept is valid, the experimental RF voltage swing is on the order of hundreds of volts at pressures of (0.1-10) x 10^{-6} torr, three orders of magnitude below practical fusion plasmas. The swing must be of kV in order to achieve volume compression ratios of about 50 for D-T, and 2000 for D-D fusion, for break-even in IEC reactors (other factors being optimized).

B. Spherical Microwave Confinement

A spherical chamber holds at least 20 inward-directed conical, helical antennas that radiate near-field 2 to 5 GHz microwaves into opaque plasma. Each antenna is designed to distribute energy evenly along its surface into the plasma by means of an inner coil surrounded by a metal shield gradually opening from base to tip. The variation in shielding provides impedance matching over a wide range of loads. All the metal is embedded in ceramic except for the inner tip of the shield. At the base of each antenna is a grid, a small distance from the insulated wall, charged to -6 kV or more. This external grid causes initial breakdown in the plasma and facilitates microwave-induced plasma formation up to opaque densities ($n > 7.45 \times 10^{16}$ m^{-3} for 2.45 GHz microwaves). The opacity of the plasma lessens cross-talk between antennas and assists in protecting the microwave circuit from damage.

There is a current between the grid and small patches of exposed metal shield near the inner tips of the antennas. This electron flow is accelerated and forms waves of electrons flowing towards the center. Negative space charge just beyond the tips of the antennas prevents outward electrons from hitting the antennas, and the grid-to-antenna-tip potential confines the electrons all other places.

With electron confinement, ions rush in periodically to neutralize the plasma. However due to the rapidly changing environment, due either to phase and frequency differences between the microwave antennas, or RF frequency voltage modulation to the grids or to the microwave generator(s), the plasma never reaches neutrality. Ions, which are too massive to directly respond to the microwave fields, oscillate at MHz frequencies, and heat due to Landau damping.[5] The most energetic are expelled which leads to a net negative potential well. In case of fusion reactions, the well is insufficient to confine reaction product ions, leaving electrons behind to deepen the well as they and cause fresh fuel ions to rush in. SMC should have no problems refueling the reaction zone.

When using a single generator for the microwaves, it could be possible to detect the ion oscillation frequency, and by using amplifiers, use this signal to generate the RF modulation on the grid. This could create POPS in the SMC reactor without the limitations faced in IEC, and with higher ambient densities, could require much less compression for break-even.

Work done by Donald Ensley[6] in the early ‘70s showed that when a confinement mechanism depends on EM radiation, instability waves with wavelengths on the order of the driving radiation are damped. Thus by using RF frequencies for SMC that are roughly the size of the confined plasma, or at least on the order of the distance between antennas, instabilities should smooth out in a favorable manner.

IEC can also work in cylindrical geometries, with less efficiency. SMC might also extend to cylinders with hemispherical ends, although this would probably be in large chambers in applications where spheres are not possible. Spheres appear to be advantageous and so are the focus of initial research in SMC.

III. FIRST REACTOR DESIGN

The goal of the test reactor is to find out if SMC is a valid concept. The density must be low enough (about 1 to 10 mtorr) for a mean free path of one to ten cm. Since in a power reactor this is the desired range, experiments should start and concentrate on this regime. The test reactor design described below is intended only to meet the first proof-of-concept goal. The critical test is with deuterium, measuring the resulting neutrons. If no neutrons result with the current device, this does not disprove SMC, since the microwave circuit is very simple and largely hand-made, and may not be sufficient for fusion reactions. If neutrons are detected, it will show that the technique is relatively robust, can work in marginal conditions, will very likely greatly improve with more elaborate and efficient engineering, and can result in a reactor that is economically viable. No actual power reactor can afford to be a technological tour-de-force when competing with a coal fire in a boiler.

A. Antennas

The 20 antennas point inwards, arrayed with icosahedral symmetry. The coil length is at least one wavelength long for sufficient gain. One-wavelength antennas have 5 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. Also, wire this thick will not heat appreciably with pulsed operation.

Initial tests were with a helical wire coil coated with a couple of millimeters of ceramic, designed similar to customary microwave antennas that give end-fire circularly polarized far-field radiation in atmospheric air. However these antennas ionize the low-pressure gas immediately and most intensely inside the coil; most of the radiated energy went to the plasma inside the antenna. This is highly undesirable; also the gentle, radial taper of the first antennas is not suited to the near-field operation and electron acceleration. When modified by filling the inside of the coils with plastic, the result was that intense plasma formed at the base of the antenna and little or none anywhere else. This also is useless for SMC.

The Mark II antenna solves all these problems and functions well in the current reactor setup. First, the coil is conical, one wavelength long and 3 inches in diameter at the base. By casting the coil in solid epoxy, there is no chance of internal plasma formation. Over this plastic cone is an eighth-inch ceramic composite layer, followed by a copper sheet metal sheath. This sheath protects against leakage of all the power at the base, and gradually tapers to fully open at the inner tip. By a long transition from coaxial geometry to bare wire (under ceramic), a full range of impedances occur along the antenna length, matching whatever external conditions apply. Ceramic coats the shield except for a short bit at the tip, which can function to allow a current between the grid and the antenna tip.

The net result of this design, when tested as low as 200 mtorr, is a plasma that forms evenly over the surface of the antenna and extends out a few centimeters. As of now only one antenna has undergone tests, and the other 19 are under construction. Once all are completed and installed, then the chamber can reach target pressures of 1 to 10 mtorr, to test the full antenna ensemble.

There are small gas pockets between the epoxy core and first layer of ceramic, then the shield, then the final ceramic layer. This gas must drain to the vacuum by means of pores in the ceramic, which could take some time. Future antennas will be monolithic and without voids, which will require matching the thermal expansion of metal and ceramic.

B. Pressure Chamber

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, and so in the early days when I was considering resonance, this was a reasonable choice. It 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 casters running in two 8 foot long channel irons. 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 coated with ceramic, to avoid conduction from the grid. (Presently, I am using a relatively soft ceramic that appears to function well enough for now, but it is easily damaged and rather thin. I would like to replace it with a ceramic composite material, but this would cost several hundred dollars.) Each of the 20 coax cables provide grounding points for the sphere through the coax sheaths and help short-circuit eddy currents. To function as a ground plane for the antennas, the pressure sphere needs many grounding points.

The equator of each hemisphere, arranged vertically, has a flange and O-ring seal with bolts. While this does not allow for bake-out, it is well suited to the frequent disassemblies required at this stage of development, and gives maximal access to the interior.

At each pole, a 1 ¼ inch nom. schedule 40 aluminum pipe welds onto the pressure chamber. This allows ample room for probes as well as openings for gas entrance and exit ports. As a convenient result of earlier designs now discarded, which included two hemispherical magnets that fit over the chamber, it is possible to encase the reactor with a blanket for absorbing neutrons that leaves open only the polar pipes and space around the equator for the coax cables. Such a blanket would be cumbersome and costly, and would be difficult to make effective enough to obviate the need for a neutron-shielded room for tests with deuterium, and still allow for neutron measurements.

C. Microwave circuit

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 frequency range in this type of reactor is from 2 to 5 GHz. The frequency must be high enough to influence only the electrons, and leave the ions untouched due to their higher mass. The POPS frequency will be in the order of MHz in order to match the ion resonance.

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. This is the only practical option for the test reactor. Dividing power from one magnetron to the 20 antennas is prohibitively expensive in this initial reactor, and results in relatively low power levels if using a household oven magnetron; 20 oven magnetrons of 1000 W rating are far cheaper. Future research, detailed below, will have a far more sophisticated and expensive microwave circuit to maximize the reactor's efficiency. (It may be that this improvement is required to prove the concept and the initial attempt is not capable of reaching fusion conditions.)

For economic reasons, and also since several fittings are custom and not commercially available, I have made coax connectors and adapters by hand for each of the 20 antennas and magnetrons. The NCSU physics machine shop has also fabricated some parts for these connections. There are inevitable reflections and losses, not to mention leaks, in the circuit that would require several thousand dollars of equipment to avoid and correct. The reactor works reasonably well at the intended pulse duration, but it cannot be considered anywhere near to optimal in safety and efficiency, and cannot be run CW.

The most difficult aspect of the present reactor is the difficulty in even distribution of power to each antenna. It is not yet possible to test each individual circuit as I do not have a spectrum analyzer or signal generator, or tools to tune each coax cable to the proper impedance. Also, each magnetron requires a current source, and tends to take more current as it warms up. Thus even the 500 ohm current dividing resistors do not sufficiently keep the power evenly divided. This should be improved with the new Mark II antennas which match the load to the antenna impedance much better than earlier antenna designs. For now, coax adjustment is ad hoc and approximate.

While I was warned before construction by microwave engineers of dire consequences, in practice the opaque plasma provides ample separation between antennas, minimizing cross-talk and resulting arcs in the magnetrons. This is no longer true above about 200 mtorr, far above the pressure range of interest for SMC, but well within range for ball lightning experiments. I also tested CW operation for a few seconds at low pressure with one antenna powered by the usual microwave oven power supply it is designed for, and damaged the test antenna and magnetron severely, as well as the connector just outside the sphere. Thus the current setup is clearly adapted for pulsed operation only, which typically lasts about 0.2 s.

The magnetron power supply is in two parts. The cathode filaments requires a highly insulated floating 3 V at 10 A, which can be AC from the center feed of oven transformers. On top of this comes a -6kV pulsed bias from a capacitor bank that decays to -4kV, at which point the magnetrons stop functioning. The peak radiated power in this reactor is about 20 kW minus losses which are not yet measured; future reactors of this size will require much less microwave power.

D. Grid

The present grid, third to be built, is of 10 ga. solid stainless wire in 20 rings. 10 rings are spot-welded together in half-icosahedral symmetry to fit around each antenna in a hemisphere. Ceramic rods hold the ring assembly about an inch minimum distance from the chamber wall. To prevent conduction, there is a thin ceramic coating on the wall surface, which will be thickened with better material in the future. A feedthrough on each hemisphere connects the grid to its capacitor bank via a high-voltage relay; two water resistors help split the current and slow the discharge with a time constant of about 3 seconds.

Typically the grids handle -6 kV, and when fired at the same time as the magnetrons, there is about -5 kV charge on the grids when plasma peaks. I have a delay relay that can time the onset of grid charge to match the magnetron power, but for some reason the magnetrons fire with an unpredictable time lag between onset of its current supply and the peak plasma production. Usually the lag is a few tenths of a second. Future tests will have more advanced antennas (the Mark II design now under construction) and lower pressures, which may make results more repeatable.

Although the details remain difficult to decipher due to a paucity of meaningful measurements, the grid bias seems to be essential for proper functioning of the device. Whenever there is energy leaking from the microwave circuit, which typically occurs when reflections dominate, the video camera will not operate properly. This tends to happen when the grid has no charge, while little or no such interference occurs with both magnetrons and grid in use. The most severe such indication comes when the pressure in the chamber is relatively high, above 200 mtorr, in which case the magnetrons can be damaged and grid charge is no help.

Higher voltages on the grid would require more insulation on the inner wall, more sophisticated feedthroughs, and a whole new circuit for the capacitor bank and relay. This may be required for fusion conditions, but it is a hope for SMC that not much more than the present voltage is required. With plasmas in the right density for fusion to be practical ($n \sim 10^{19} - 10^{20}$), resistance is so low that trying to maintain a grid voltage on the order of 50 to 100 kV would require severe power loads and destroy any hope of break-even. This is one of the critical problems with IEC that cannot be avoided in gridded systems.

E. Other Details

I'm using surplus data acquisition equipment from undergraduate NCSU physics labs, which is relatively simple and quite adequate for the current use. When measurements become more sophisticated I will have to add more elaborate electronics.

There are two circular windows 2" in diameter, made of ¼ inch polycarbonate. On the inner side is a metal grid taken from the window of a microwave oven to help block microwave radiation. In addition, I have two coatings of 20 dB plastic film RF blocking material.

One window allows in light from an LED lamp, over which is abundant aluminum foil to block x-rays. The other window is for the video camera, which is surrounded by an aluminum Faraday cage. This is to avoid static from stray leaking

microwaves, which with some experience is now minimal. X-rays will not be able to leak through the camera and the cage, so this appears safe.

The magnetrons and grid are powered by two capacitor banks, made of series and parallel arrangements of 350 and 450 V, 5000 and 5100 microfarad electrolytic capacitors. Both banks are typically charged to -6kV, although the grid does have the option of alternate voltages from a -3kV DC power supply. The actual arrangements in the magnetron bank vary according to how many antennas are functioning; I am careful to have sufficient capacitance for roughly 0.2 s rise from -6kV to -4kV. There is sufficient capacitance in the grid bank, in series with two 15 kOhm water resistors to split the current between the two hemispheres, for the voltage to rise no higher than -4 kV by the time the plasma pulse has ended. Both cap banks dump charge through a 7 kOhm water resistor.

I have made my own water resistors, as well as high-voltage cable and other circuit components. Operation beyond -6kV on the grid would require substantial new construction and new connectors, no longer made by hand, and at considerable expense. Observations indicate that the present setup is sufficient for breakdown and microwave operation; indeed, without the grid there are difficulties getting the magnetrons to behave, as indicated by increased video interference. (It would be wonderful to be able to measure this process with some accuracy and detail but this requires equipment and resources not yet available.) IEC grids are typically at or above 50 kV when trying for D-D fusion, but SMC potential well depth might far outstrip the grid bias. This would be a great advantage in avoiding grid power losses and simplifying construction. Other experimenters have to go to extreme lengths to construct bulky HV feedthroughs and keep currents to a minimum in the sphere. Given the conductivity of the plasma, no reactor could possibly break even with grids running at 50 kV or more.

While I have an elderly Fluke 6 kV, 20 mA power supply set to negative bias, this is only to top off the capacitor banks to a well-defined voltage, when that is needed. A much more efficient, cheaper, and far faster charger is a microwave oven; I tap into the power supply via a diode and a resistor, which charges the capacitor banks to -6 kV from a cold start in just a few minutes. For most rapid operation, I leave the oven on and the capacitors recharge much quicker than I can recycle the test firings, due to data collection.

Air cooling for the magnetrons will suffice due to low duty cycles (< 10-3). The magnetrons will be lined up in four groups of five, and each group has forced air cooling from a squirrel cage fan; this is probably optional. There is little power loss in the antennas and they will not require cooling in the test reactor even though the ceramic coating and vacuum environment will make heat transfer difficult. Continuous wave operation is not possible in this first reactor but is a goal in future models. 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 probes measuring temperature, ionizing and microwave radiation; and plasma potential.

F. What this reactor can and cannot do

The present reactor has interesting capabilities, but also constraints due to the lack of funding, and the limits of one person's labor. The current setup, with various modifications over time, can do the following:

1) try various gases; so far I've used only air, but next comes hydrogen in preparation for deuterium. D-D fusion is the focus, but with pentaborane (the least toxic and safest borane to handle) it might be possible to try p-B11 reactions with an alpha detector, although the yield would be low
2) with D-D, and perhaps in time D-T, measure neutron production, which would be proof of SMC and determine if it is viable for more development
3) test different ceramic coatings on the inner wall, with regard to thermal expansion, particle impact erosion, plasma contamination and other first-wall issues
4) test alternative antenna and grid designs
5) measure x-ray production under various conditions; any x-rays hotter than the grid potential indicates exothermic reactions
6) measure the potential through the radius to the center
7) use a spectrometer to measure density and temperature, assuming a nearly-maxwellian plasma
8) apply RF modulation to the grid voltage to test POPS

The limitations are due to financial and engineering limitations that cannot be avoided. High vacuum systems are intrinsically expensive, and while this project has benefited greatly by borrowing equipment from past lab experiments in the current lab space, there are critical features that limit the lower pressures the chamber can achieve. For example, the two windows are entirely hand-made and would take hundreds of dollars each to replace with manufactured units.

Most critically, the antennas mount inside the hemispheres by screwing into pipe thread cut into the 3/8" aluminum wall. The connection must conduct, so I use copper-based conductive pipe dope, as well as vacuum sealant varnish on the outside. The connection to the external coax is hand-made. It would be much preferable for these 20 fittings to be more vacuum-tight and to have standard coax connectors, but this application has custom requirements and will take some serious engineering and machining to improve for higher vacuum and better microwave performance. The current equipment cannot operate with CW power.

The microwave circuit is simple and works as intended, but is dramatically inadequate for a comprehensive research program. Much more equipment, such as a spectrum analyzer and signal generator, would be required to improve and tune the circuit, change to a single generator, reduce power, protect against reflections, maximize the energy delivered to the plasma, and test CW operation. The existing system can only operate at 2.45 GHz, 1000 W pulsed power at each antenna, although I do have the option of running 10 antennas instead of 20 with half the capacitor bank. Successful

neutron production with SMC might be dependent on an improved microwave circuit, so there is the unfortunate possibility of a false negative with the current reactor.

The O-ring between the hemispheres as well as the windows and antenna feed-throughs make bake-out impossible, limiting the low pressure range. I am hoping to be able to reach 1 mtorr, and thus back-fill to 10 mtorr for D-D tests. However this is not fully adequate for good gas purity of the type required for accurate fusion tests. Since peak IEC neutron production is far below this density, it would be prudent to be able to test down to 10^{-6} torr to compare the two systems.

IV. LABORATORY REQUIREMENTS FOR NEUTRON TESTS

My current location in Research II at Centennial Campus, NCSU, has been a good one for the project so far. However it is not possible to adequately shield this lab from the 2.45 MeV neutrons anticipated from D-D fusion tests. As a result I am making a request to the Triangle Universities Nuclear Laboratory (TUNL) to use a shielded environment.

SMC is highly speculative and the neutron flux is not possible to closely estimate; there is a good chance that there won't be any at all. The first tests can be under marginal conditions, guaranteeing low yield. Existing IEC reactors producing 10^{10} neutrons/s have an active volume as small as 1/1000 the size of this reactor's anticipated plasma, and operate at significantly smaller input power. Thus, when conditions are optimized, the neutron flux from even this preliminary reactor could be comparable to these existing units, or even beyond. Thus it would be prudent to assume the possibility of 10^9 neutrons per pulse, with one pulse about every five minutes, during initial tests.

Other needs;

1) Shielded space for the reactor and walking space around it, about 11 feet long and 6 feet wide, about 7 feet tall
2) Room for the electronics rack (20 inches wide, 7 feet tall)
3) 110 AC power, about 2000 W; substantial central ground
4) Internet connection
5) Room for a desk, chair, and some shelves adjacent to the reactor
6) Tap water for cooling the turbomolecular pump, need 1.5 liters/minute, and drain
7) If possible, equipment for detecting and analyzing neutrons of up to 2.45 MeV. I can borrow a detector for short times from the NCSU NE department, but it would be far superior to have gear native to TUNL. I will need help learning how to use MCAs and other gear as this is outside my experience. The same consideration applies for a spectrometer. I am unsure about x-ray measurements and could use some advice.

V. HIGH PRESSURE EXPERIMENTS AND BALL LIGHTNING

Ball lightning is completely devoid of adequate theory and the natural version has not been made yet in the lab, despite many claims to the contrary. As a result any research in this direction by this investigator is simply based on guesses and a literal acceptance of the most reliable anecdotes.

There are several websites[7,8] and some journal articles[9] 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.10 (Only one observation recorded radiation effects, which devastated a village in Venezuela in the ‘30s.)

My excursions into BL experiments have lead me to the following conclusions:

1) SMC requires a clean reactor, and BL tends to make things very dirty due to test aerosols, so the two kinds of research are not simply interchangeable.
2) The first reactor depends on isolation of each antenna due to opaque plasma. At pressures above about 50 Torr, the plasma does not reach critical density quickly enough and the resulting cross-talk can damage the magnetrons.
3) It will require a more elaborate microwave circuit, and probably lower power, to operate anywhere near atmospheric pressure.

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. 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

This project is funded by student loans, as my status as a graduate student precludes grants. In addition, it is speculative and unproven until there is evidence of fusion reactions. As a result, the main challenge is to have proof of concept with my limited resources, which then would provide an attractive rationale for funding.

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. Considering the critical importance of learning how to use fusion as a power source, the argument in favor of researching diverse and speculative techniques is compelling—and will become more so over time. SMC research is practical applied physics of a type that can be achieved with modest resources when compared to other fusion methods, and is well-suited to a laboratory the size of TUNL.

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[1] Tom Ligon, Infinite Energy, **issue 30** (2000).
[2] Ryan Meyer, *IEC thesis, U. of Missouri-Columbia*, 2007
[3] Todd Ryder, A general critique of inertial-electrostatic confinement fusion systems, Phys. Plasmas 2 Vol. **6**, (1995).
[4] J. Park, R. A. Nebel, and S. Stange, Physics of Plasmas **12**, 056315 (2005).
[5] F. Chen, *Introduction to Plasma Physics and Controlled Fusion* (Plenum Press, 1984), Vol. **1**
[6] Donald L. Ensley, Shape stability for a plasma contained within a standing electromagnetic field, Phys. Fluids **22(12)**, 2359 (1979).
[7] Ball lightning Page, http://www.amasci.com/tesla/ballgtn.html (a major source of current information and archived eyewitness accounts)
[8] Ball lightning photographs,
http://www.ernmphotography.com/Pages/Ball_Lightning/Ball_Lightning_ErnM.html
[9] Vladimir Dikhtyar and Eli Jerby, Phys. Rev. Lett. **96**, 045002 (3 Feb. 2006).
[10] M. D. Altshuler, L. L. House, and E. Hildner, *Is Ball lightning a Nuclear Phenomenon?* Nature **228**, 545-546 (1970).