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Research Article

Model for Sonofusion

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Abstract

Experimental cavitation sonofusion results needed a mechanism to explain the measured ^{4}He and heat produced. A model is introduced based on high-density low-energy transient astrophysical behavior, creating an environment for fusion events by forming electron free clusters. The cluster's low temperature and high density are shown to be essential to the fusion environment.

Keywords: Bubble, Calorimetry, Cavitation, Cluster, Ejecta, Fusion, Fusion products, Jet, Picosecond, Transient high-density plasma

PACS: 47.55.df, 45.50.Tn, 47.15.Uv, 44.90.c

1. Introduction

The sonofusion model is based on the concept of producing very high-density relatively cool transient environments for BEC (Bose Einstein Condensate) fusion events and has some similarities to muon fusion [1]. Environments of black dwarf stars that are cooling have a similar density. The collapse of a transient cavitation bubble is followed by the control of a natural progression of events ending in sonofusion products. The bubbles are produced using ceramic piezo resonating ultrasound devices [2—5] that enable DD fusion events in nm and sub nm size clusters in target foils via a picosecond electromagnetic (EM) implosion pulse. Some advances in hot inertial confined fusion in the last several years support cavitation produced clusters [6] but of a scale more than a trillion times larger. The acoustic driven transient cavitation bubbles produce very high energy densities and D_2O dissociation is in an EM compressing high-density plasma that is found in the transient cavitation bubble jet and cluster (see Fig. 1). Sonofusion experiments have produced fusion products ^{4}He and heat measured by mass spectroscopy and calorimetry [7] as well as ejecta sites, and transmutation [8]. Scanning electron microscope (SEM) and inductively coupled plasma mass spectrometry, have measured ejecta sites and their transmutation. Some early work indicates ^{108}Pd $\rightarrow$ ^{112}Cd, alpha addition. The model is speculative but explains most experimental results and draws from advances in astrophysics, nano and atomic physics, pulsed laser physics, inertial confined fusion physics, and muon fusion physics.

Sonofusion requires a strong enough acoustic field to produce collapsing bubbles in D_2O. The temperature and pressure adjustments control the reactor. The process starts with a million-fold collapse of the cavitation bubble's

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Cluster Squeeze to Fusion

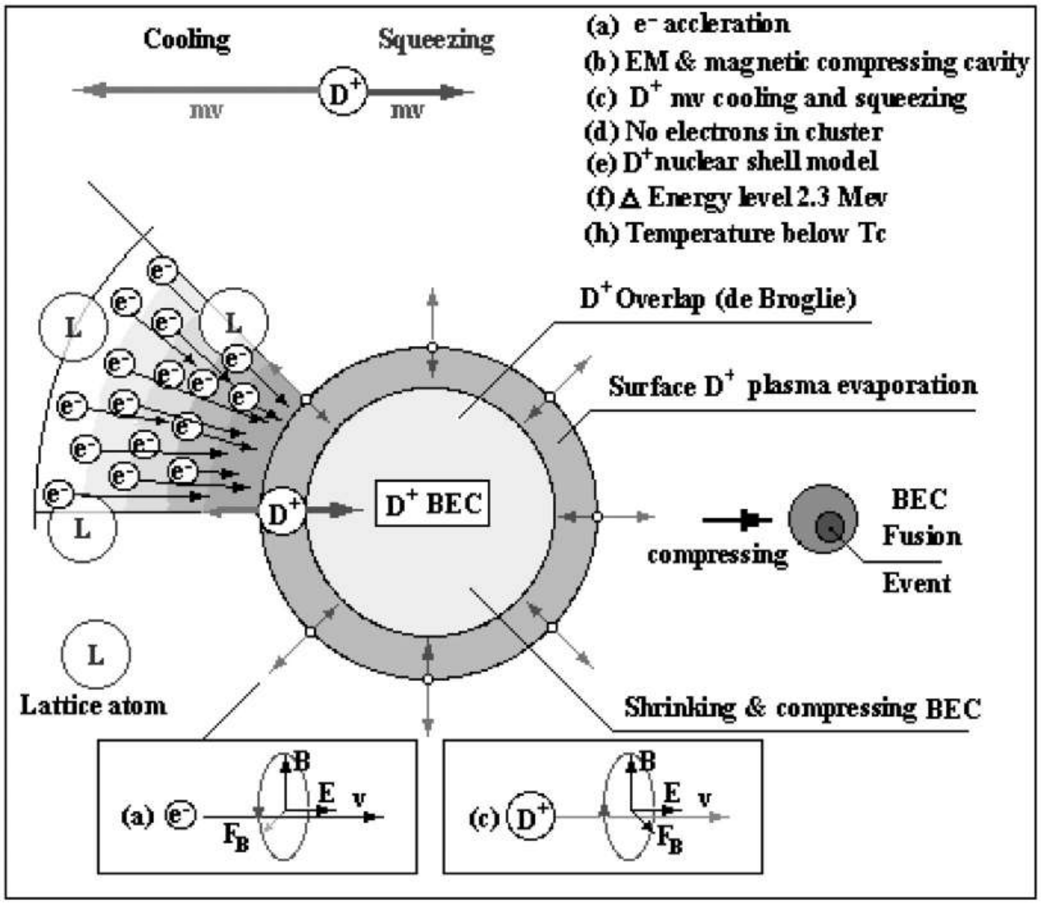

Figure 1. After the jet implants deuterons and electrons into the target lattice, a transient cluster cavity is formed. The scale for this 1,000,000 deuteron cluster shows a 1 nm diameter, at a high density, being squeezed by pressures that far exceed the coulombic escape pressure. As compression continues, the cluster contents are cooled well below their BEC critical temperature, T_c. The cluster is cooled by surface ablation and/or evaporation to form a BEC environment for DD fusion to products of ^{4}He and heat. Fusion occurs when the deuteron separation in the cluster approaches 10^{-12} m. There would be several random target foil atoms (L) in the surrounding EM field that donate some of their electrons to the free electron cloud surrounding the cluster.

volume, a few microseconds or less in duration. This produces the potential for a 1 millionfold increase in the energy density in the transient cavitation bubble's adiabatic collapse, and in its final stage it produces sonoluminescence and jet. Z-pinch compression of the bubble jet of dense D^+ and e^- plasma follows. The jet implants and there is a brief charge separation (Fig. 1). Accelerating electrons (a) facilitate the cluster's EM implosion pulse (b) create a dense cluster of electron free deuterons (d). The cluster is EM squeezed and evaporatively cooled to form a BEC (c). The population of local accelerating electrons towards the cluster center (a) creates a surrounding imploding EM cavity picosecond pulse (b) with the magnetic field parallel to the cluster surface. The electric field is parallel to the electron velocity with a compression pressure much greater than the coulomb escape pressure during the picosecond pulse duration. About half of the total cluster's population pops from the surface during this picosecond EM pulse. This occurs as the cluster's surface deuterons evaporate helped by positive charge repulsion. The evaporative cooling removes heat from the interior deuterons of the cluster and counters its compression heating. These escaping deuterons may be too hot to react with the incoming electrons and ultimately will become hydrides of the surrounding target foil lattice. The continued pressure produces an environment for fusion events not unlike muon fusion (a DDì BEC). The cluster's BEC nature gets help from the cooling evaporation of its contents of the remaining compressed deuterons in the cluster that produces significant de Broglie overlap and a much higher T_c (transition temperature) than the temperature of the cluster (h). The T_c is controlled by the 2.3 MeV (f) energy difference between the cluster's ground state and the next energy level supports the nuclear shell model (e).

The time line, Fig. 2, shows the sequence of events for one TCB cycle at the reactor's piezo acoustic resonance. The transient cavitation bubble's isothermal growth, its pseudo adiabatic violent collapse, its sonoluminescence emission and its high-density jet formation depend on this frequency (1–25 μs). The jet accelerates from the remnants of the collapsed transient cavitation bubble and implants into the target foil. A charge separation preserved by a small portion of the implanted deuterons is prevented from Coulombic disbursement by accelerating free electrons rushing to the cluster with a squeezing pressure much larger than the Coulombic escape pressure.

This implosion pressure, the EM pulse, squeezes the cluster to a density approaching that of muon fusion and white or black dwarf stars. If fuel is present these would be fusion producing densities. At the same time the surface of the cluster is eroding as plasma-evaporation of surface deuterons are expelled from the cluster. The momentum lost via deuteron evaporation is equal to and opposite to the compression gain of the remaining cluster contents. This helps keep the BEC cluster cool ($\lambda_{BEC} = k/T^{1/2}$). These deuterons interact with the flood of EM accelerating electrons directed to the center of the cluster. The evaporating deuterons may interact with an electron (14.7 eV producing a deuterium atom) or pass into the surrounding lattice as a hydride. The EM picosecond pulse compresses the cluster contents towards muon densities and fusion.

The cooling of the natural boson's interior deuterons keeps the cluster's electron free system at its extremely high ΔE of 2.3 Mev. The deuteron's nuclear shell model dissociation energy is the next energy level with respect to its ground state. This ΔE is more than a million times greater than that for a deuterium atom with its electron. This gives a broad temperature range for the BEC cluster to exist well below its million-degree (T_c) transition temperature. The BEC cluster's existence depends on its high transition temperature range. When the EM squeeze produces enough density, one or more fusion events occur in the cluster and are destroyed initiating a spherical heat pulse and ejecta, shown in Fig. 2. The heat pulse reaching the target lattice surface ejects useful heat, ^{4}He, and vaporous target foil into the D_2O. This occurs in the order of 10 ps and is acoustic frequency dependent [7].

2. Sonofusion Experimental

The velocity of the collapsing bubble surface interface is about Mach 6 where sonoluminescence emission occurs [9]. The velocity of the squeezed z-pinch jet as it implants into the foil at about 20 Mach is several times that of the collapsing transient cavitation bubble interface boundary in D_2O. A SEM photo of the target foil surface in an aborted run shows the 100 μm impact crater of an accelerating 1 μm particle caught by the surface tension at the interface of a collapsing transient cavitation bubble and jet. The impact crater fits the expectation of a micro impact of the 1ìm particle [10].

Some of the measured experimental data gathered over a 20 year period were calorimetry, mass spectrum analysis, MS, scanning electron microscope analysis, SEM, and inductively coupled plasma mass spectrum analysis. All devices used for sonofusion were devised for some sort of calorimetry measurements. Usually the technique used was a D_2O flow-through type with a variable resistance heater in the reactor flow that could be switched on and adjusted to continue the power input that maintains the steady-state temperature in the reactor. This matching of the input acoustic power

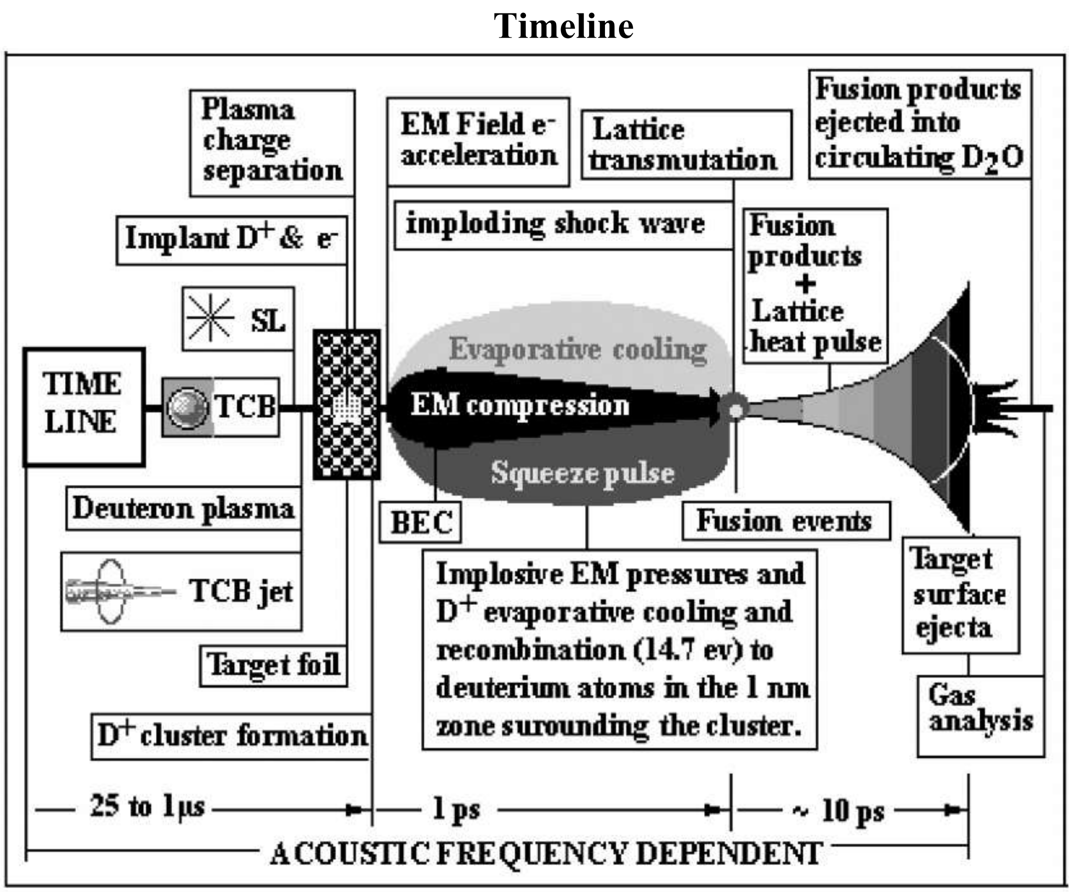

Figure 2. The time line above extends from the bubble initiation to the fusion ejection for a single cavitation bubble. There is a sequence of events that sets the time line for a fusion event and product ejecta. During the first microseconds, depending on frequency, the target foil lattice, black dots, is implanted with deuterons and electrons from a dense jet plasma that is produced by an acoustically driven collapsing, transient cavitation bubble, TCB. The deuteron jet that forms because of the bubble collapse is implanted into the target foil and the initial impact separation of free electrons produces EM forces to form clustered deuterons, with a high transition temperature. The cluster of deuterons is EM squeezed and cooled to a BEC where a fusion event occurs producing ^{4}He and heat. This implantation to fusion period is a picosecond event. The resulting ^{4}He and heat are ejected via a spherical heat pulse made up primarily of vaporized target lattice.

to the resistance power showed the imbalance of the input power to the output power and was the measurement of the excess heat produced. These were comparative power inputs with power errors of 1–3 W in input and output measurements that relied on acoustic power measurements and their efficiencies. The efficiencies of piezo inputs can be measured by comparing the run mode to the calibration mode. Thermocouples placed at various interior and exterior points of the reactor allowed for steady-state calibration temperature measurements with the reactor in the calibration and running mode.

Three reactors MII, MIII and MVI with frequencies of 20, 46, and 1600 kHz were used to produce data that fashioned the model. Figure 3a is the MII reactor showing the dual cavitation systems, the H_2O and the D_2O, the top system containing the target foil. Figure 3b is the open MII reactor with the $5 \times 5 \times 0.01$ cm in the 0.5 cm thick reaction cavity.

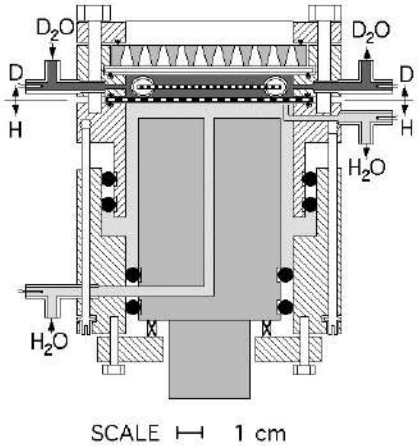

FIGURE 3 a. The M II reactor - top detail.

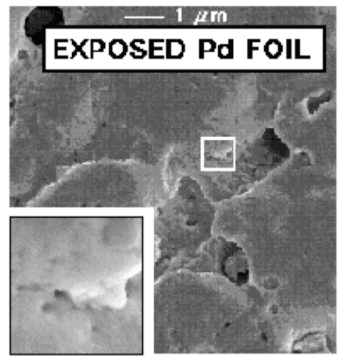

FIGURE 3 c. SEM of target foil.

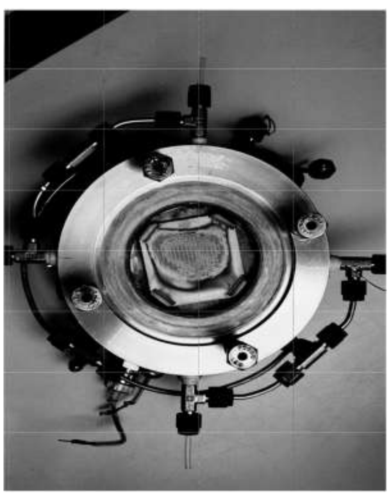

FIGURE 3b. The MIII reactor –Ti target foil.

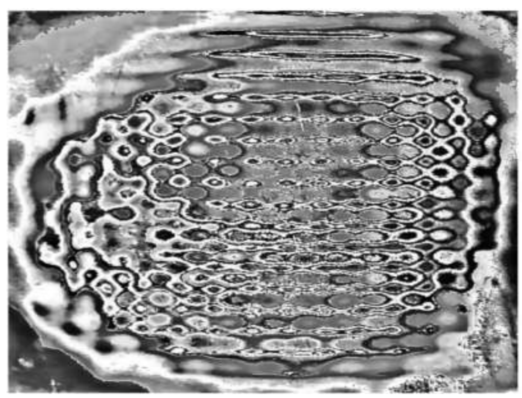

FIGURE 3d. Detail of Ti target foil.

Figure 3. Experimental apparatus and exposed target foils.

Figure 3c,d is exposed target foils from the 46 kHz systems. SEM, photo of a Pd foil and an optical photo of the TiO_x thin film surface of iridescent color of a Ti foil are shown [10].

SEM photos of exposed target foils showed the extreme temperature surface effects of localized melting and volcano like ejecta sites. Ejecta sites 50–10 000 nm in diameter, depend on the acoustic frequency, with the larger sites filled with recondensed 1 μm spheres of target foil metal. Some larger volcano-like vents showed vent linings of sub–micrometer hemispheres. Not many of the total number of foils were examined by SEM, but all exposed foils had visual changes that varied from slight to 80% destruction. John Dash of Portland State University took the first SEM photo of a Pd foil in 1993. Several foils were examined at the Scanning meeting in Monterey, CA in 1996. In the year 2000, Pd and Ti foils were examined by SEM and photographed by Jane Wheeler of Charles Evans Lab in Sunnyvale, CA 2000 and later in 2003 a 1.6 MHz foil was examined. Lorenza Moro of SRI examined some of the same foils in the year 2000 [11].

The mass spectrum measurements of reactor gases for ^{4}He were made at SRI by Dave Thomas and later by Fran Tanzella; at the Bureau of Mines in Amarillo, TX by Tom Davidson; and at the DOE in Canoga Pk., CA by Brian Oliver [12]. These measurements were made from 1990 to 1995 with varying degrees of success.

In 1990 Dr. S. Tam of Balazs Analytical Lab, in Sunnyvale CA, dissolved a small portion of an exposed Pd foil in nitric acid, and examined it by inductively coupled plasma mass spectroscopy [8]. The measurements showed the presence of ^{112}Cd not found in the non-exposed foil. This was explained as ^{108}Pd picking up an alpha and a couple of electrons to yield ^{112}Cd. Other Cd isotopes were not found.

In the fall of 1994, X-ray analysis at the Naval Research Lab in Washington, DC by George Chambers of exposed and unexposed Pd foils showed clearly the swelling and rearrangement of Pd lattice atoms. The gravimetric measurements by Ed Storms at his laboratory in Santa Fe, NM of cavitation exposed Pd foils at 46 kHz showed no change in weight. This was an unexpected result; no D loading of the Pd lattice. Pd foils were Au electroplated and non-plated $50 \times 50 \times 0.1$ mm foils and showed no measurable D loading from weight measurements before and after cavitation exposure. X-ray and the gravimetric measurements pointed to the fact that even if the Pd lattice was permanently expanded, the D was not present as shown by the gravimetric measurements. We know that D_2, ^{4}He, and DOOD were measured by MS in the gases collected from the reactor that were ejected into the circulating D_2O (see Table 1). Brian Oliver, DOE laboratory in 1994, also measured some ^{4}He via MS of selected milligram samples from exposed Pd target foils. Only small amounts of ^{4}He were found. It is this experimental data gathered over 20 years of experiments that strives for an explanation of the heat and ^{4}He and needs a model as a guide for the next critical experimental procedures that will help open the door to a useful device.

Table 1. *Table of MS Data From Gases Collected From Three Runs.* Brian Oliver at the DOE laboratory at the Rocketdyne facilities in California did a series of mass spectrum measurements of three 50 cm^3 stainless steel gas sample volumes labeled 4-1, 4-2, and 4-3. Sample 4-1 was a standard run – background ^{4}He. Sample 4-2, a Ti target foil run showed ^{3}He and ^{4}He [12]. Sample 4-3 was a Pd foil run showing ^{4}He. (^{3}He data not shown [10])

Sample volume (50 cm^3)	Measured ^{4}He (10^{14} atoms)	^{4}He in sample (10^{14} atoms)	^{4}He Concentration (ppm)	
4-1A	0.2506	4.623		0.471
4-1B	0.2436	4.760		0.484
4-1C	0.2237	4.621		0.470
			Mean	0.475
			($\pm 1\sigma$)	$\pm$0.008
4-2A	0.7696	31.31		2.548
4-2B	0.7521	31.37		2.552
4-2C	0.7357	31.46		2.560
			Mean	2.55
			($\pm 1\sigma$)	$\pm$ 0.01
4-3A	188.2	7483.0		553.5
4-3B	182.6	7447.0		550.9
4-3C	178.3	7460.0		553.5
			Mean	551.8
			($\pm 1\sigma$)	$\pm$1.0

3. Outside Experimental Support

The implanting jet initiated by the cavitation bubble collapse is very much like the imploding wire and the *z*-pinch. An example is the frozen deuterium thread in a vacuum where a bank of condensers discharges a powerful energy jolt producing a crushing magnetic field pressure to the thread. This thread implosion's transient environment approached that needed for fusion events. The high velocity transient cavitation bubble jets are similar to the imploding wires and frozen threads of deuterium atoms, but sonofusion has an advantage passing through the dielectric D_2O and not the vacuum of the wire and thread [13]. The sonofusion jets are on the order of 10^{16} times less in volume.

Back lighting inertial confined fusion experiments at Massachusetts Institute of Technology and the University of Rochester, measured the density, electric field, and magnetic field of an imploded 2.7 mm gold covered sphere of deuterium via focused lasers. The squeezed contents of the sphere measured 300 gm/cm^3, the electric field at 10^{9} V/m, and *B* field at 10^{2} T [6]. There is a tremendous advantage using the much smaller inertial confined sonofusion system and its nanometer scale that takes advantage of derived atomic forces. The sonofusion cluster is 10^{22} times smaller in volume than the 2.7 mm back lighting sphere.

Work in Sweden where Leif Holmlid's group used a femtosecond pulsed laser focused on liquid D produced transient densities equivalent to that of muon fusion [14]. The transient high densities 3 00,000 times those of water were produced with a deuteron separation similar to those of muon fusion. These densities were produced in his laboratory by passing the pulsed femtosecond laser beam into deuterium. This is the density that sonofusion needs to approach to be effective. Its advantage is that the number of transient cavitation bubbles formed in a microsecond can lead to millions of clusters in target foils.

Muon fusion represents extreme densities, deuteron separation, which we hope to approach with sonofusion experiments [15]. The densities or deuteron spacing are the same as those found in white and black dwarf stars due to their gravitational pressures. At these densities sonofusion needs just a picosecond or less to consummate a DD fusion event. The density or separation between deuterons in DD_{μ}^{+} is around 10^{36} D/cm^3 or a separation of 10–12 m.

The DOE funded much of the outside supporting research that also supports the sonofusion model. Some international laboratories and universities research support sonofusion's experimental data, but those results need to be scaled down to the nano dimensions of sonofusion's natural transient cavitation bubble collapse.

3.1. The transient cavitation bubble (TCB)

Start with the cavitation bubble that has enough acoustic energy to rapidly grow isothermally followed by a catastrophic pseudo adiabatic collapse producing very high energy densities. This bubble is known as a TCB (transient cavitation bubble). The final stage of the TCB collapse produces sonoluminescsnce and a jet of the bubble's contents. See Fig. 2 [7,16–18]. As the TCB collapses, the energy density is inversely related to the change in the bubble's radius cubed where a one hundred fold radius decrease is a million fold increase in energy density. For H_2O or D_2O liquid this effect is aided by high frequencies, surface tension, and smaller TCB. The symmetry of this process is not present as the TCB oscillates during its microsecond collapse. Also during the collapse process the collapsing TCB does lose some mass so it deviates from the ideal of a pure adiabatic nature. During the TCB collapse process, the formation at the bubble's interface of small proto jets form the resonant oscillation. During the bubble's collapse its surface is in continuous deformation [19]. When observed by Mie scattering, this process is smoothed out showing a curve of time vs. bubble radius change at an accelerating rate [9]. The single bubble sonoluminescence uses a much less intense acoustic field so the same bubble cycles through millions of growth and collapse cycles without a terminal collapse and is in a continuous cycle process using less acoustic energy than the TCB mode. If the TCB acoustic input is too intense, the TCB is lost to frothing. Acoustic power couples to the temperature and external pressure.

3.2. The jet

The jet contents are high-density dissociated deuterons and electrons from the transient cavitation bubble. Some high mass ions of Ar and O will be pinched off from the high velocity jet on its short journey to the target foil. D^+ and e^- have a small collision profile. The cavitation jets photographed by several bubble research programs [20,21] are the cause of much erosion damage. This jet damage arises from the increased energy density from the violent adiabatic collapse of a transient cavitation bubble. These bubbles that form a resonance population will grow isothermally to 10 times their initial radius. Those bubbles will be involved in a near adiabatic collapse process. This energy density is transferred as the high density partial plasma to an accelerating EM z-pinched jet originating from the last stage of the bubble shell or interface of the collapsing transient cavitation bubble. The velocity of the jet coming from the last stage from the bubbles interface at 6 Mach [9] is squeezed by the EM z-pinch and via the jet's sheath electrons just before its implantation into the target foil [5]. The jet gains more velocity by its release from its interface and the EM z-pinch squeeze in the water dielectric. This velocity was estimated to be in the neighborhood of 30 Mach with the squeeze on the jet [22]. It is ironic that the very phenomenon, the z-pinch, that hobbles the Tokomak type reactors is the one that makes sonofusion work.

3.3. Jet implantation

As the z-pinch, high density jet impacts the target foil lattice, the electrons enter first followed by the deuterons. The jet's impact lattice penetration carries the electrons deeper into the lattice than the deuterons but is influenced by deuteron Coulombic forces. Any entering deuterium atoms with loosely bound electrons will lose their electrons via lattice stripping. The deuterons are separated from the cloud of free electrons for a femtosecond or less creating a charge separation and the condensing into a proto-cluster. From this chaotic mixture an EM pulse focuses on the forming cluster. The EM implosion pulse is in place before the Coulombic repulsion can disperse many of the clustering deuterons. These clusters probably range in deuteron number from 1000 to a million with a limit placed on the smallest number by the absence of gamma radiation that is suppressed by the unique properties within the BEC of the cluster. A BEC mass is larger than that of μDD^+ muon ion that produces a gamma fusion product. A BEC size of a 1000 deuterons should be enough to disperse the heat of DD fusion events to the lattice heat pulse. The lattice is probably locally disordered where the sub surface cluster is formed, a volume of a cubic nm or less. See Fig. 2. Before coulomb forces disperse deuterons, a compression EM pulse larger than the coulomb repulsion squeezes the cluster contents to 1/10 its original radius (see Fig. 1).

3.4. The cluster and compression

The cluster is transient and free of electrons. This is very important to the formation of the high temperature BEC. The cluster is a transient entity having a low temperature probably below 100,000 K and a compressed volume of more than 10^{31} D^+/m^3. An imploding picosecond EM pulse pressure much greater than the Coulombic escape pressure surrounds the cluster cavity. A cluster, spin 1, of deuteron bosons and a cluster mass of a million deuterons has an energy difference of 2.3 Mev between its ground level and its next energy level. This is in accordance to the nuclear shell model of a deuteron. The properties of the cluster are those of a BEC. The presence of the BEC is made possible by the ablative or evaporative cooling and the inertial implosion pressures of the single escaping surface deuterons from the cluster. This evaporative loss of energy from the cluster, potentially millions of Kelvin from the mass loss evaporating deuterons from the cluster involves as many as one-half of the total of initial cluster deuterons. The cluster's cooling keeps the BEC well below its transient transition temperature increasing the deuteron overlap. Keeping the cluster in a BEC phase for the fusion event opens up new possibilities for fusion channels. The cluster's deuterons, although surrounded by other deuterons, do not individually feel their charge and tend to behave as neutral particles except at the cluster's surface (all being repulsed equally). As long as the EM pulse confines the cluster this will be true. The deuterons escaping from the cluster during the imploding EM spherical pulse are a cooling mechanism for the remaining interior deuterons of the cluster (see Fig. 1). The gray outer circle of the cluster represents surface deuterons that may be lost to evaporation.

The EM implosion pulse of one picosecond surrounds the cluster cavity in the lattice with an electric field moving in the direction of the center of the cavity and cluster. And the pulse's free electron acceleration generates magnetic field lines that are tangent to the cluster surface and perpendicular to the electric field as the EM pulse squeezes the cluster's contents. The magnetic field's lines accelerate perpendicularly towards the surface of the cluster with a spherical squeeze. The electric field pressure squeeze is much like the squeeze of the z-pinch of the jet but is a spherical compression. Added to compression of the cluster and opposed to evaporation inertia is the momentum of the lost deuterons directed to the cluster center following the direction of the electron electric field pressure [23]. These compressions are similar to the large laser inertial confined fusion systems using back lighting. If a 10-fold cluster radius compression occurs, it leads to a 10^{34} D^+/m^3 density in the cluster contents approaching that of muon fusion.

3.5. The fusion

At some point during the cluster compression the cluster density will be enough to initiate DD fusion events. The transient cluster dynamics within the EM pulse time frame of a picosecond will produce one or more DD fusion events. It may be initiated by a shockwave or by just the increasing density of the cluster via the imploding EM pulse and is enough to produce a DD fusion environment. The heat of fusion is distributed to the cluster's deuteron mass because of its boson BEC properties. This occurs before any gamma radiation can form. Experimentally sonofusion showed an absence of any measured gamma or other radiation from laboratory setups at EQuest Sciences, Los Alamos National Lab, or Stanford Research International. For example, our LANL experiments show in the sample Pd 4-3 in Table 1 that there were 452 ppm ^{4}He produced that were collected in the gas phase via a 50 cm^3 sample volume in a 20 h period in the laboratory's atmosphere air. The ^{4}He production of 10^{18} atoms would be a potential gamma source of 1.6×10^5 Gy/h dispersed spherically and 4.5 Gy/h (Gy = Gray) where this amount is fatal to one-half the population [24]. No gammas were measured and nobody has suffered adverse radiation effects working on these experiments.

3.6. The heat pulse and ejecta

The fusion destroyed cluster forms an intense heat pulse that makes its way through the lattice to its surface as a spherical lattice hot spot that ejects its contents. The vaporized target foil and the remnants of a vaporized cluster that includes the deuterons, the heat, and the ^{4}He are ejected into the circulating D_2O. The ejected heat pulse contents are ejected into the flowing D_2O surrounding the target foil with the gases distributed in the gas phase and throughout the D_2O. The formation of D_2 and D_2O and some DOOD were measured by mass spectrum analysis [7]. The heat carried by the ejecta was transferred into the flowing D_2O and also in contact with the target foil surface. The sonofusion heat as the product of ^{4}He fusion events was transferred to the circulating D^2O to be used for some designated utility. The advantages of sonofusion are its ease in the use of transient cavitation bubbles produced at a rate of billions per second, its lower cost, and its small size compared to a very complex inertial confined fusion systems. The comparison between the known inertial confined fusion and sonofusion systems shows heat removed from billions of clusters per second make up in quantity for what they lack in size. This is also true for the economics of the two systems.

3.7. The ejecta site

There are SEM photos of a number of the cavitation exposed target foils that show the extent of the damage and the frequency of ejecta sites and their population distribution [3,5,17]. There are maybe six of sixty target foils that have been examined by SEM. The population distribution of the various diameter sizes (diameters equals depth for the average heat pulse) of ejecta sites covering the surface of the target foils and plotted as the number vs. diameter shows a size cut off and also a maximum number for ejecta sites that are single fusion events. The energy of a single fusion event is about the energy of the smallest ejecta volume. The SEM of the target foil surface shows many ejecta sites, as many as thirty per one square μm (see Fig. 3c). There is a timeline of target foil ejecta activity and the instant the acoustic power is shut down, one sees the ever-changing ejecta site population frozen in the target foil at that instant, between acoustic cycles [25]. The next acoustic cycle the surface would have changed the target surface. Every acoustic cycle alters the target foil surface with a new generation of ejecta sites. The target foil damage at lower frequencies, 20 to 46 KHz, was substantial, but at 1.6 MHz the damage was difficult to measure with the SEM [11].

3.8. The target foils

The target foils exposed to the sonofusion environment have been varied. The surface areas were mostly $5 \times 5 \times 0.01$ cm thick for the 20 and 46 kHz systems or $1 \times 1 \times .01$ cm for the 1.6 MHz systems. The foils were of many elements and their alloys. The following is a partial list of sonofusion materials: Cu and CuB, C as Graphite, Ti and Ti alloys, V, Ni and Ni alloys, Pd and PdB, Ag, and stainless steel. Many of these target foils showed evidence of excess heat suggesting that more than one type of lattice could be used in the sonofusion process. The acoustic frequency changes produce different characteristics in surface damage to target foils [14]. The higher frequency of 1.6 MHz shows more SL, but less target foil damage, and just single fusion event per ejecta sites form smaller clusters. The target foils show other acoustic surface alteration via coloration, addition to surface as MD_x and MO_x [10], and concentrated cavitation damage related to standing waves induced into the foil from the propagating frequencies 20, 46 and 1600 kHz. The cavitation patterns etched acoustically into the foil surface were a function of mass, thickness, area shape, and composition (see Fig. 3d).

3.9. The D_2O

The advantage of using D_2O rather than other deuterium containing molecules is that when D_2O is dissociated it will cycle back as D_2O, DOOD, and D_2 and will remain at one low degraded steady-state mixture. But, for example, $(CD_3)_2CO$ will dissociate into many species including the above and continue to degrade into a mixture quite different than initial deuterated acetone (CO, CD_4, CD_3CD_3, CD_3OC, $(CD_3)_4C$, etc.). A better fluid than D_2O in this respect is liquid hydrogen, but it is difficult to work with. D_2O has the added advantage of hydrogen (deuterium) bonding and high surface tension. Another possibility is as a circulating fluid of HgD and other MD_x in a non-metallic system, perhaps a ceramic.

H_2O and D_2O systems of D bosons and H fermions have complexities and unknowns of mixed deuteron clusters. This introduces the addition of jet implanted protons and deuterons producing fermion and bosons and clusters. If protons are added to the cluster, it will maintain its boson character if the protons are added as pairs, H_2 bosons, maintaining the cluster's BEC character. If this is the case, it helps explain excess heat found in mixed system of D_2O and H_2O.

3.10. Many bubbles

The model discussed above involves the path of one bubble, one jet, and one cluster. However, sonofusion is a multi-bubble system. Billions of bubbles are produced each second and some of the bubble population will qualify as transient cavitation bubbles. These bubbles, if near to the target foil boundary will implant the foil with one or more deuteron clusters. These tillions of clusters implanted per second each producing ^{4}He and fusion heat from the sonofusion reactor is a source of useable heat. It is the sum of trillions of cluster events per second initiated by the transient cavitation bubbles that supplies a constant flow of heat that holds more promise as an alternate energy source for heating when compared to the complexities of a back-lighting inertial confined fusion event [6].

4. Discussion

The purpose of the model is to present a possible path to fusion derived from the various experimental results obtained over the last 21 years. Sonofusion starts with controlling the natural phenomenon of the cavitation of D_2O. The transient cavitation bubble is controlled by manipulation of the parameters temperature, pressure, and acoustic input. The adjusted parameters produce transient cavitation bubbles that adiabatically collapse producing high-density jets that implant into target foils [26]. With lattice stripping and impact range difference, the electrons and deuterons are separated with Coulombic attractive forces of a compressing nature overcoming the Coulombic repulsion forces of dispersion for a picosecond. During the ensuing picosecond EM imploding pulse generation compresses cluster density to the point of DD fusion. The very small clusters at the higher acoustic frequencies and clusters with 1000 to 1 million deuterons and volumes of 0.3–1 nm^3 with starting densities of 10^{31-33} deuterons m^{-3} are delivered by high velocity target foils implanting dense deuteron plasma jets. The clusters are squeezed by a picosecond EM pulse and a deuteron evaporative pressure that combines to compress these small clusters to 1/10 their original implant diameter. Densities that approach those of muon fusion are reached during the EM picosecond pulse. The muon fusion μDD molecule is separated by 10^{-12} m at a density of $10^{36}D^+m^{-3}$. This transient density has been produced in deuterium by Leif Holmlid of the University of Gothenburg in Sweden using a femtosecond pulsed laser to irradiate liquid deuterium [14]. His group has created transient densities of three hundred thousand times that of water and a deuteron separation distance of 2.3×10^{-12} m.

The heat pulse from the fusion event is produced in the BEC cluster. The cluster is a BEC with a very high transient temperature of more than 106 K due to its ΔE of 2.3 Mev, between the nearest energy levels. In the separation of the deuterium proton from its neutron, noting there are no electrons in the cluster, there are no other energy levels available other than dissociation for the shell model's proton and neutron of deuteron nucleus. Cooling the cluster via plasma evaporation of deuterons from the cluster surface at a rate will compensate for compression heating of the BEC cluster contents. The cluster compression is more complex as the individual electrons are also coupled to lattice atoms, other electrons, plasma of evaporated deuterons, as well as the cluster. Most of the accelerating electrons are probably within a nm of the cluster surface. The deuteron cluster being the focus of accelerating free electrons produce the electric field. What happens to these fermions in this electric field as this picosecond implosive pulse advances to the cluster? The cluster cavity surrounded by compressing magnetic field lines encapsulates the cluster of deuterons. The dense electrons in a shrinking phase space may form Cooper like fermion pairs, bosons, altering the amount of available space during the squeeze pulse.

Fusion in a BEC environment leads to a ^{4}He and heat product with no gamma radiation. The gamma radiation requires the time period one cycle of a 24 MeV gamma but the heat of fusion in the BEC cluster will be distributed immediately throughout the BEC mass of deuterons. Fusion must occur before the deuteron population disappears via plasma evaporation and coulomb repulsion becomes dominant. This should be something less than a picosecond. The BEC will accept the heat of fusion and is ready for transfer to the target lattice before the mechanism for gamma production can occur. The transfer occurs as the fusion event destroys the deuteron cluster. This heat of fusion is transferred to the lattice target as a spherical heat pulse erupting from the target surface as an ejecta site. The ^{4}He, heat, target foil, and other minor products are found in the circulating D_2O and can be collected from the gas phase for analysis.

Some of the damage to the foil looks like heavy clusters dropping through the target foil due to a cluster's transient million fold gravity and density increase. The bubble is such a good energy concentrator that it has been considered the underlying cause in other modes of fusion, particularly hot fusion producing neutrons and excess heat. This does not appear to be the case for sonofusion.

The sonofusion model been examined as a 1-D ray array of spherically focused accelerating free electrons directed towards the D^+ cluster surface.

5. Summary

Inertial confined fusion, hot fusion, has some similarities to sonofusion. Comparing their high densities, compression, and EM fields show that a lot is gained by sonofusion being smaller and faster. One must overcome the compression heating to maintain the properties of the BEC sonofusion clusters. Half of the total cluster deuterons, see Fig. 1, evaporate in a picosecond removing heat from the remaining cluster deuterons. The T_c for these clusters will be high because of the large energy between the electron free cluster's ground state and its next energy level of the deuteron's nuclear shell model. These conditions preserve the BEC cluster for a picosecond. The sonofusion energy density of a W/g is very high. In another direction, if the reactor's piezo geometry is altered, it may be a possible source for ambient superconductivity. The key to fusion and superconductivity is the transient nature and the staying power of the BEC cluster.

Sonofusion uses the leverage of natural processes to produce the high density implanting *z*-pinch jet and the picosecond BEC cluster. The initial chaotic electron deuteron implanting impact condenses this mixture via EM pressures organizing the clusters. These relatively cool, extremely high transient density BEC clusters (close to those of muon fusion) produce measured fusion products of heat and 4He. Sonofusion can be developed into a large utility or a portable hand held power system. It is an ideal space energy system with its low fuel-mass to energy ratio, and has the flexibility to be scaled up to megawatt or down to milliwatt outputs.

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