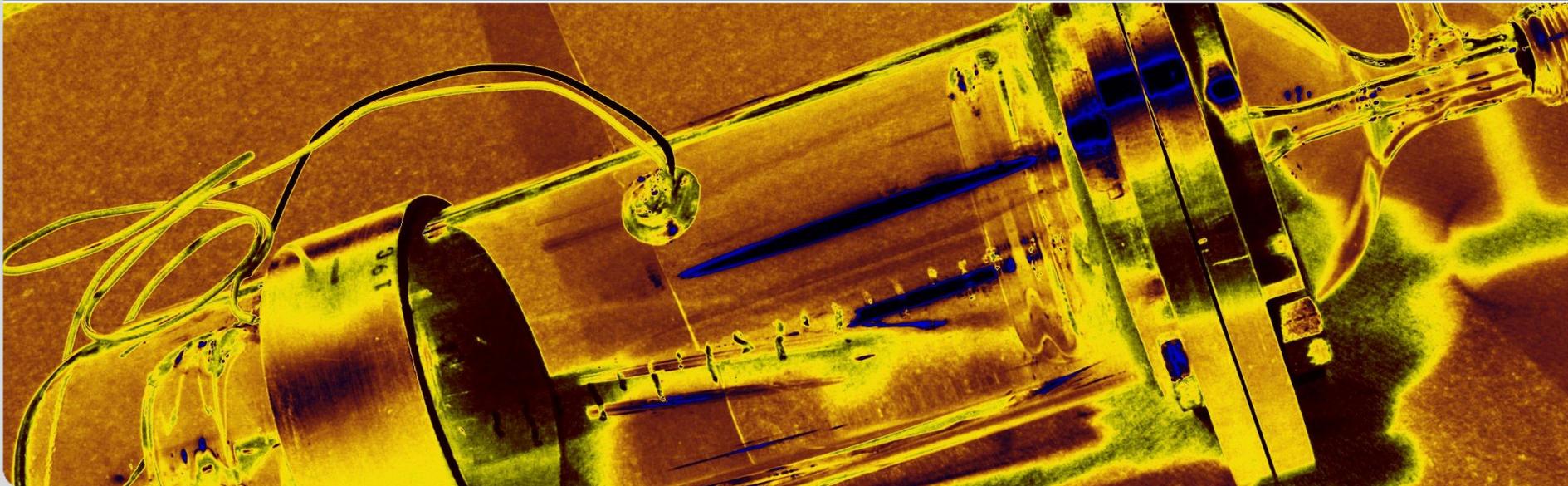


The Physics of Sonoluminescence, the Story of Sonofusion, and our Project of simulating the Vibration Modes of Sonofusion Test Sections

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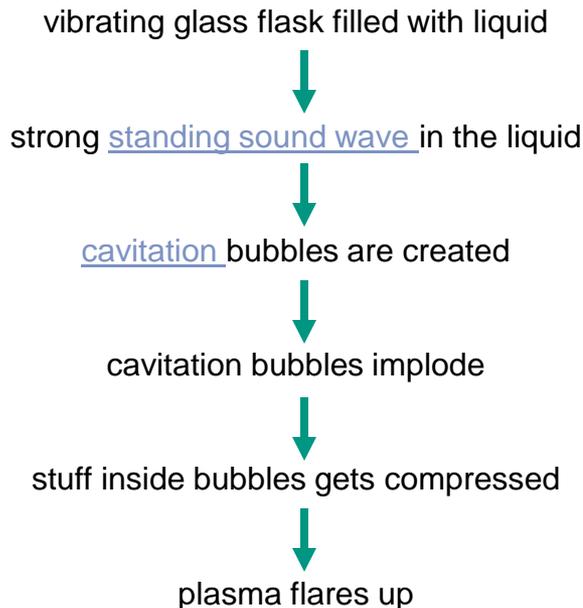


intro part 1

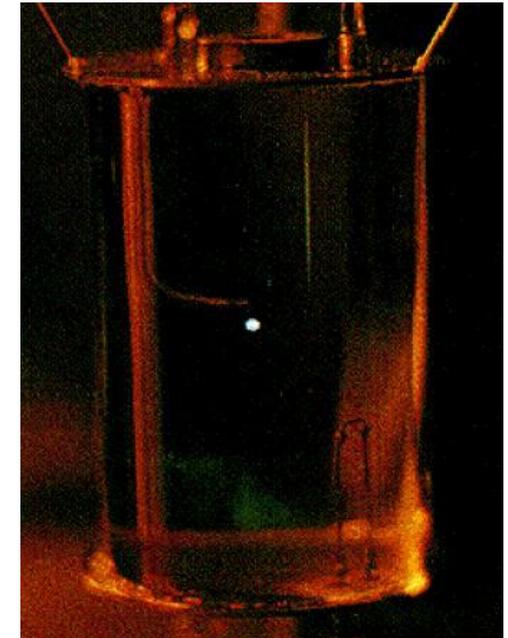
The bright spot in the middle of the picture on the right originates from multiple **sonoluminescence** flashes. The Greek geeks among you will know that this means as much as “light from sound”. Indeed, the photons having made their imprint in the middle of the photo plate, were most likely born in a cloud of plasma. And the only energy input the liquid-filled glass chamber receives is through ultrasound and coming from the ring shaped **piezoelectric** crystal glued to the chamber’s top.

The observation of sonoluminescence leads us to the question of how to get a relative high-energy phenomenon such as light emission fed by a sound field, a thing of much lower energy density.

The chain goes like this:



The big question:
When there is plasma: could energy densities reach the threshold for thermonuclear fusion?



picture source: Seth Putterman: Sound into Light; in: Scientific American, Feb. 1995, p. 33

Wikipedia links:

- [sonoluminescence](#)
- [piezoelectricity](#)
- [cavitation](#)
- [plasma](#)

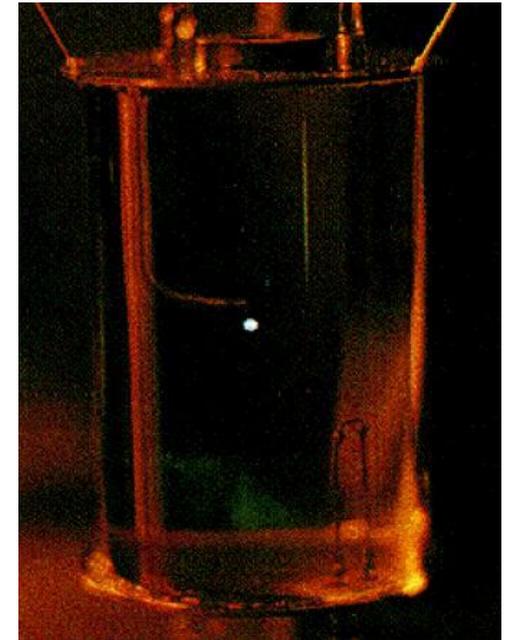
The big question: When there is plasma: could energy densities reach the threshold for thermonuclear fusion?

In case the answer was yes, it would be a very important finding, because it would mean that we could master thermonuclear fusion at tabletop scale with a very simple setup.

It would not mean we could get energy out of such a tabletop setup, but it would allow researchers to play with the phenomenon and conduct further experiments checking whether energy harvesting could become thinkable in the future. Apart from that, such a simple fusion neutron source as a cavitating bubble would be neat in any case.

So far the motivation. Now let us go more closely through the physical background and the description of our research:

- What is sonoluminescence?
- Could there be sonofusion?
- The literature controversy sparked in 2002
- What we identify as the main and still unapproached problem
- Sonofusion chamber optimisation



picture source: Seth Putterman: Sound into Light;
in: Scientific American, Feb. 1995, p. 33

Wikipedia links:

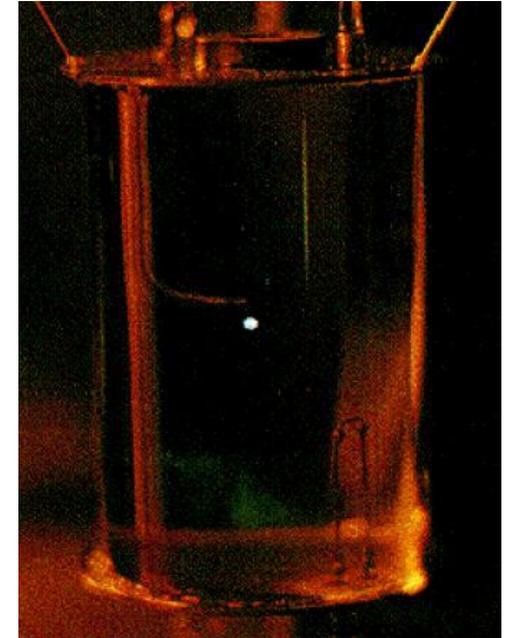
- [sonoluminescence](#)
- [piezoelectricity](#)
- [cavitation](#)
- [plasma](#)

→ What is sonoluminescence?

How can light-emitting plasma be created when a liquid is submitted to strong sound waves? The answer is that if the sound field provides states of strong enough tension in the liquid it may allow the creation of cavitation bubbles. Those cavitation bubbles first grow, but then undergo a quick implosion process as soon as the sound pressure returns to the positive range, and sometimes this implosion process can be heavy enough so that the tiny quantity of vapor and gas inside the bubble gets compressed and heated to form a plasma flashing up and emitting light.

The phenomenon of sonoluminescence has been known for almost 80 years now. Initially it was not clear whether the light emission really stemmed from the implosion process. Many researchers couldn't imagine that the heat gets diffused slow enough and thought that the light would be more probably created when the liquid gets ruptured during bubble nucleation. (**Experiment:** open all future candy, cookie and granola bar wrappings by carefully pulling apart the glued layers of plastic sheets in absolute darkness with well adapted eyes; you will find that some manufacturers use glue which gives off blueish light when the molecule bonds are ruptured.) But exact timing of the light flashes proved them to be created at the end of the implosion phase.

But still: how can such heat concentration occur when the bubble has its tiniest diameter? Why does the heat not get carried away faster? Well, maybe the more correct question would be: of what exact nature and how quick (in comparison to heat radiation and diffusion) is the heating process? There is one ingredient missing so far: a supersonic shock



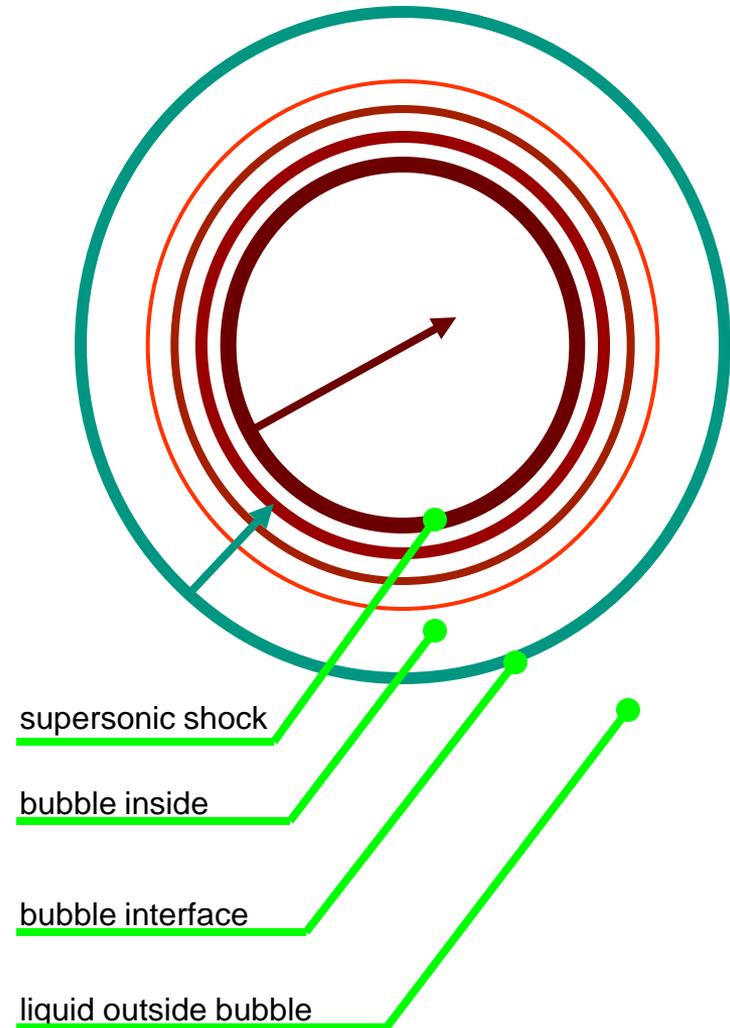
The picture shows the sum of multiple plasma flashes created by a bubble hovering and oscillating in the center of a sound pressure antinode. The repetitive implosion process is fast enough as to create concentric supersonic shock waves inside the gas atmosphere of the bubble.

picture source: Seth Putterman: Sound into Light; in: Scientific American, Feb. 1995, p. 33

→ the physics of sonoluminescence?

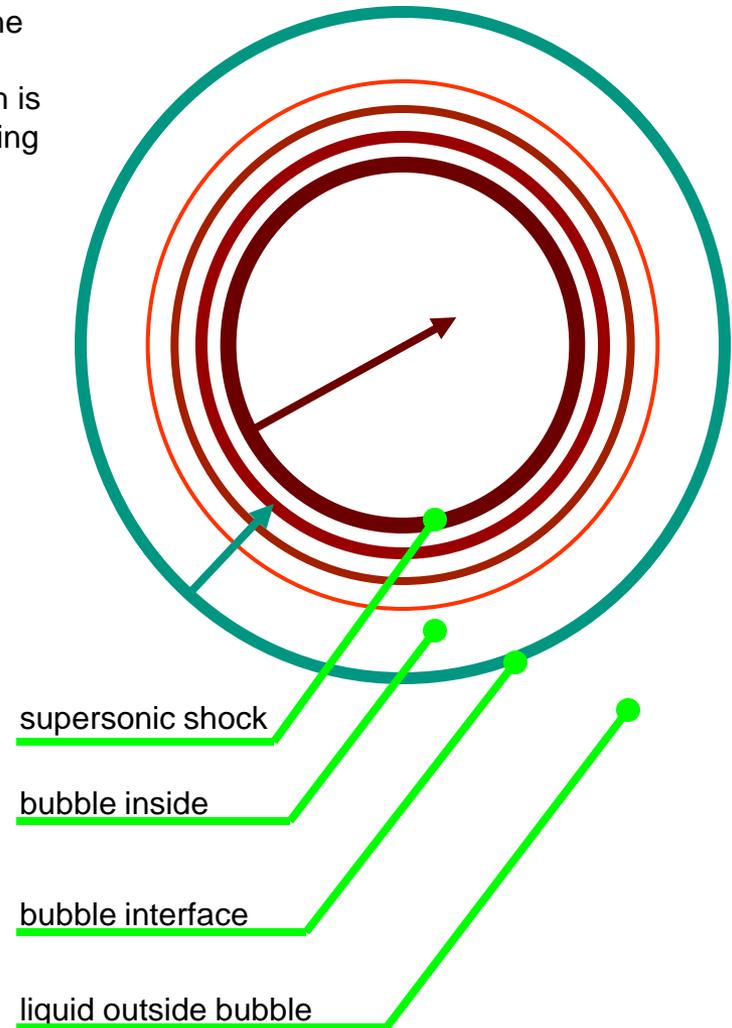
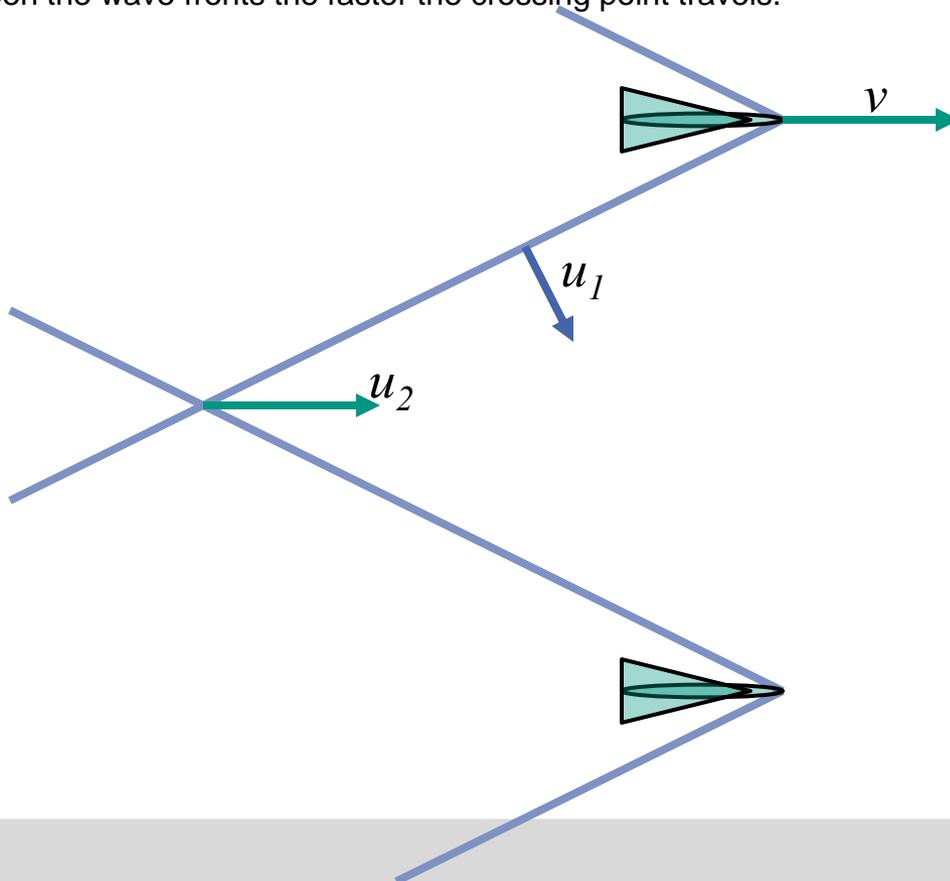
How does the implosion process look like in detail?

The cavitation bubble was once nucleated as extremely tiny bubble and then multiplied its radius many times during growth. So it should be basically empty, which it mostly is, but not completely. Some amount of vapor and gas (the latter only in case we are dealing with a not well degassed liquid) has entered during growth. During implosion most of the vapor can just condense again at the bubble interface. At some point begins a compression of the remaining vapor-gas mixture, but temperature and pressure may at first still be uniformly distributed over all the bubble volume. But at a point later on during implosion things may leave thermodynamic equilibrium. For the most part of the process there is very low pressure inside the bubble, so the bubble interface can continuously accelerate on its way to the center as nothing much slows it down. When the bubble is still big, both, interface speed and interface curvature increase moderately over time. But if you consider the very latest part of the implosion, you will find a time-span during which the interface speed just went up the last percentile, but the curvature multiplied many times, and this can have a decisive consequence: it may create a supersonic shock wave. A first sign of the pressure distribution inside the bubble leaving the thermodynamic equilibrium is a pressure mound building-up in front of the advancing interface as soon as the interface speed reaches the sound speed inside the bubble, the speed with which pressure changes are communicated over the bubble volume. And then, the curvature comes into play ...



→ the physics of sonoluminescence?

Imagine two jet planes flying next to each other at supersonic speed v , so that they create shock waves leaving their trajectory at an angle. Of course, the shock wave itself proceeds with the speed of sound c . The velocity vector of the wave front is labeled here as $u_1=c$. Now look at the point where the two shock waves from the two jet planes meet. This point travels with the speed u_2 , which is clearly identical with the speed of the planes. Now, for two shock waves traveling at sonic speed and meeting at an angle we can formulate the rule that the crossing point travels at a speed faster than sound, and the sharper the angle between the wave fronts the faster the crossing point travels.



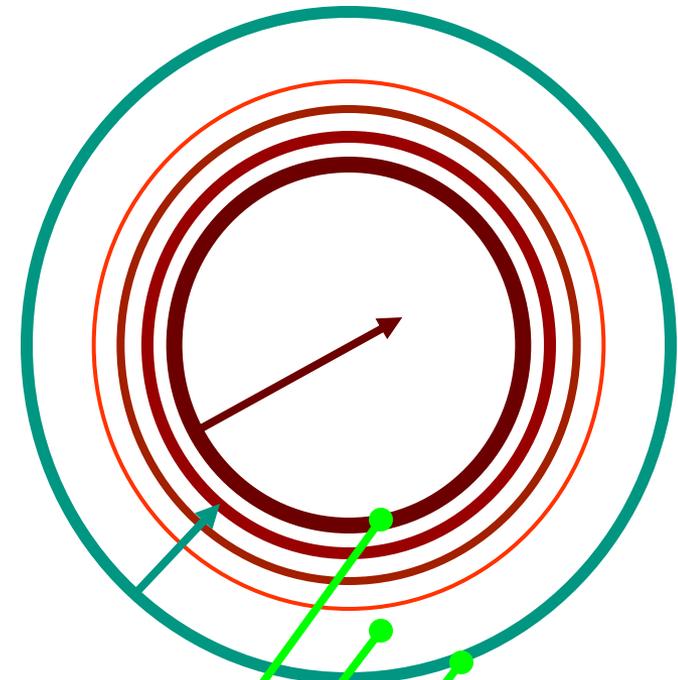
→ the physics of sonoluminescence?

Returning to the bubble implosion scenario depicted on the right, let us now imagine that the spherical shock wave traveling towards the bubble center can be decomposed into many many plane waves at small angles. In this thought experiment sharper angles correspond to increased curvature. This picture should make it plausible, that during the final moments of the implosion phase (when the speed of the bubble interface does not increase very much any more) the speed with which a supersonic shock wave can travel ever increases with curvature and surmounts the interface speed at a certain moment. Then the shock wave will detach from the interface and start to run ahead towards the center.

Finally, when the shock runs over the center of the bubble, this creates a moment when many particles with extremely high speed and momentum share a concentric movement which can create an inertially confined plasma – but of course this plasma core stretches only over a tiny area of space, spans less than a nanosecond in time, and involves only a handful of atoms. The light emitted by this plasma core and stemming from the liquid domain hosting a strong sound field and a bubble imploding in that field, is called **sonoluminescence**.

Does sonoluminescence have a colour? Yes, the repetitive light flashes emitted by a single bubble hovering in sulfuric acid containing some dissolved argon show a black body radiation spectrum of blueish color, which means that this plasma must be hotter than the surface of the sun (6000 K). The article by Suslick and Flannigan cited below suggests up to 15.000 K at the surface of sonoluminescence plasma cores.

Let us summarise that the main accomplishment of the spherical supersonic shock wave is to concentrate a small amount of energy quickly enough onto a tiny amount of matter so it can temporarily outweigh the phenomena carrying heat away from the point of concentration: diffusion, radiation, and heat conduction.



supersonic shock

bubble inside

bubble interface

liquid outside bubble

Wikipedia links:

- [plasma](#)
- [black body radiation](#)

Kenneth S. Suslick, David J. Flannigan: Inside a Collapsing Bubble: Sonoluminescence and the Conditions During Cavitation, Annu. Rev. Phys. Chem. **59**, 659–83 (2008)



Could there be sonofusion?

or

How hot can sonoluminescence plasma get?

Metals cannot transmit electromagnetic radiation, they reflect light and other electromagnetic waves, even if it is just a thin layer of metal as gold leaf or on metallised plastic film (e.g. candy wrapper). The reason is that in a metal the electrons can move freely and thus equilibrate/annihilate any electrical field, and hence there can be no light traveling through metal, because next to being a swarm of photons, light is also a moving wave of electromagnetic field. Because in a plasma both sorts of charge carriers, electrons and positive ions are moving around freely and independently, the same holds for plasma, which makes it opaque. Therefore, the light spectrum emitted from the outer region or surface of a dense plasma cloud does not allow one to infer the temperature in the center of the plasma. Therefore, researchers have tried to start out from experimental evidence like sound pressure amplitudes, bubble maximal and minimal radii, sound signals, plasma spectra, etc. and to infer by calculation the rest of the way towards estimates for the values of maximal plasma temperature $T_{max,plasma}$, pressure $p_{max,plasma}$, particle densities, enclosure times, peak particle species collision rates and so on. If deuterium or tritium were present in the plasma, these computations would yield the likeliness or rate of fusion reactions as a function of experimental conditions. **Can such calculations give a definite answer about whether sonofusion can be achieved with contemporary sonoluminescence setups? No**, as will become clearer below. But let us consider more closely some of the elements that can be part of such an estimation for two purposes: to point out where most of the error bars for $T_{max,plasma}$ and $p_{max,plasma}$ come from and to make plausible why it can still make sense to try to pose the sonofusion question to mother nature experimentally.

one example of an extensive theoretical investigation estimating whether fusion conditions can in general be reached by sonoluminescence plasmas: Nigmatulin, R.I., Akhatov, I.Sh., Topolnikov, A.S., Bolotnova, R. Kh., Vakhitova, N.K., Lahey, R.T., Jr., Taleyarkhan, R.P. " Theory of Supercompression of Vapor Bubbles and nanoscale Thermonuclear Fusion" *Physics of Fluids* **17**, 107106 (2005)



Could there be sonofusion?

or

How hot can sonoluminescence plasma get?

more thought elements:

- Empty bubbles are better than bubbles with a lot of vapour or gas inside, because compression of the bubble content once condensation cannot keep up any more cushions the implosion. If the bubble is emptier, the interface collapse speed can get faster, and the available energy has to be distributed among less particles, less energy gets lost in dissociation of chemical bonds.
 - A spherical cloud of many bubbles is better than a single bubble, because the transition of the sound pressure cycle from tension to positive pressure reaches the bubbles at the center of the cloud later, but with much steeper rise, and, most importantly with multiplied amplitude. As the pressure rises outside the bubble cloud, row after row of bubbles collapse from the outside inwards, for one part this delays the start of positive pressure rise in the bubble cloud center, and for the other part it creates another spherical pressure wave front growing in amplitude on its way to the center and setting the stage for the strongest bubble implosions in the middle of the bubble cloud. Imagine that single bubble sonoluminescence plasma reaches at least 15,000 K in a sound field with an amplitude of around 1.5 bar, but according to the calculations of Nigmatulin et al. a bubble cloud can amplify the outside pressure field by almost a factor of 100.
 - Low sound speed inside the bubble is better than a fast one, because the supersonic shock wave will be stronger.
 - Whether one allows the electron and ion systems to have two independent temperatures or not in the calculations has great consequences on the rate of heat transported away by electromagnetic radiation and greatly influences estimates of maximal temperature and pressure. (See Nigmatulin et al.)
 - The molecular dynamics (MD) simulations of Bass et al. show that it makes a huge difference whether all the particles forming the content of the bubble have the same mass or are of different species. In the latter case there is a segregation mechanism: the heavier particles form the shock wave, expell the lighter ones, and those start to „surf“ on the front of the shock wave. When the cloud of lighter particles finally gets smashed by the collapsing spherical shock front of the heavier ones, this yields maximal plasma temperatures several orders of magnitude higher than if there were just the light particles alone.
- Nigmatulin, R.I., Akhatov, I.Sh., Topolnikov, A.S., Bolotnova, R. Kh., Vakhitova, N.K., Lahey, R.T., Jr., Taleyarkhan, R.P. " Theory of Supercompression of Vapor Bubbles and nanoscale Thermonuclear Fusion" *Physics of Fluids* **17**, 107106 (2005)
- Bass, A., Ruuth, S.J., Camara, C., Merriman, B., Putterman, S. „Molecular Dynamics of Extreme Mass Segregation in a Rapidly Collapsing Bubble“ *PRL* **101**, 234301 (2008)

Wikipedia links:

- [molecular dynamics](#)



Could there be sonofusion?

or

How hot can sonoluminescence plasma get?

Those many intricacies should make it clear why it is not surprising that different research groups starting with different theoretical analysis approaches come to different results when asked whether sonofusion in principle can happen. When describing the detailed physics of sonoluminescence you find that the phenomenon's nature is extremely multi-scale in time and space. To describe the imploding bubble's inside, one seems to peruse one set of equations of state after the other going through the temperature scale, and besides ... don't assume you are ever close to equilibrium. At this point the sonofusion question looks like this:

- Experimentally you cannot access the plasma core because it is opaque.
- Theoretically there are too many intricacies where we cannot expect quick answers.

So, **how about the direct experimental detection of fusion neutrons** flying out of a sonoluminescence setup when you run it with some deuterium and which stop flying out if you take away the deuterium? Couldn't that be a much easier way of addressing the question? Why not just take one of those glass chambers, glue a piezo ring on it, fill it with different deuterated liquids, hook up your living-room amp, feed it some sine waves, hook up some hosing and a pump to degass the liquid, watch or listen to the sonoluminescence going on and put a neutron detector next to it?

→ The controversy about sonofusion sparked in 2002

So why not just introduce some deuterium into the sonoluminescence setup and **directly try to detect 2.45 MeV D-D fusion neutrons?**

Exactly this has been undertaken by R. Taleyarkhan et al. in 2002 and they reported positive findings in several published articles.

The problem is:

- **No independent group could successfully reproduce the experiment.**

(On top of that, Taleyarkhan's research conduct has been put into question by a Purdue University investigation; see the below link to several articles published in the New York Times.)

At this point in the discussion our group wants to address the purely scientific/technical part of the controversy. Independent from any occurred conduct of research and publication by the Taleyarkhan group, could there be technical facts preventing successful independent reproduction of the experiment?

- **Could there be a logic technical explanation of why the sonofusion experiment might have worked out one time but why the original setup is difficult to reproduce?**

- R. P. Taleyarkhan, C. D. West, J. S. Cho, R. T. Lahey Jr., R. I. Nigmatulin, R. C. Block "Evidence for Nuclear Emissions During Acoustic Cavitation", *Science* **295**, 1868 (2002)
- R. P. Taleyarkhan, J. S. Cho, C. D. West, R. T. Lahey Jr., R. I. Nigmatulin, R. C. Block "Additional evidence of nuclear emissions during acoustic cavitation", *PRE* **69**, 036109 (2004)

Wikipedia links:
• [bubble fusion](#)

New York Times link:
• [Timeline of Purdue University's investigation](#)

Science link:
• [Science 295 1868](#)



NUCLEAR FUSION

'Bubble Fusion' Paper Generates A Tempest in a Beaker

The heat from the controversy alone is nearly enough to trigger a nuclear reaction. This week in *Science* (p. 1868), scientists led by nuclear engineer Rusi Taleyarkhan of Oak Ridge National Laboratory in Tennessee claim to have seen evidence for nuclear fusion in a beaker of organic solvent. That stunning claim, if true, could eventually have important consequences for nuclear proliferation and energy production. But other scientists, citing another Oak Ridge experiment that seems to belie the claim, are likening the paper to cold fusion. Adding to the brouhaha are a series of exchanges in which the magazine's editors say outsiders tried to revise, delay, or

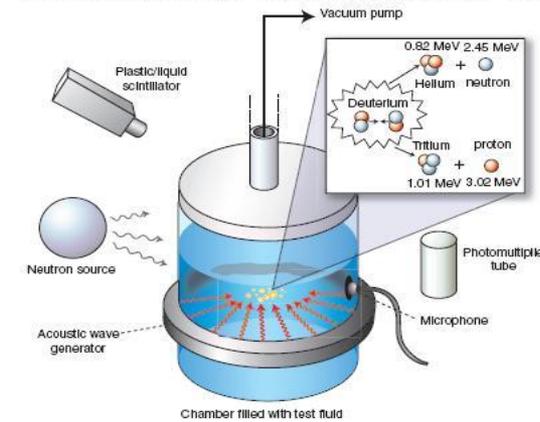
kill publication of the paper. Unlike nuclear fission, fusion is very difficult to initiate. Only at extremely high pressures and temperatures can atomic nuclei slam together hard enough to merge, or fuse, releasing energy in the process. A hydrogen bomb achieves those pressures by first setting off a small fission bomb to get the process going. A handful of labs are gearing up to do the same with enormous lasers or powerful magnetic fields (*Science*, 18 August 2000, p. 1126; 25 January 2002, p. 602). Small-scale "tabletop" fusion reactions, meanwhile, have remained far out of reach. And the scientific community is still wiping egg off its face from the 1989 debacle involving so-called

cold fusion, in which some researchers erroneously claimed to have seen fusion catalyzed by a lump of palladium metal.

It is against this backdrop that Taleyarkhan, Richard Lahey, a nuclear engineer at Rensselaer Polytechnic Institute in Troy, New York, and colleagues make their case for tabletop fusion. The work relies on a phenomenon known as acoustic cavitation, in which sound waves rattling through a fluid create tiny bubbles and then cause them to expand and compress. Under certain conditions, those bubbles give off tiny flashes of light as they collapse, a phenomenon known as sonoluminescence. Many scientists believe that the bubbles, compressed by the acoustic waves, reach great temperatures and pressures. Some speculate that under the right conditions, those bubbles might—just might—provide conditions extreme enough to trigger fusion.

Taleyarkhan and colleagues set out to test that idea. Starting with a small cylinder of acetone in which all the hydrogen atoms had been replaced with deuterium (a heavy breed of hydrogen that has an extra neutron), the team subjected the cylinder to acoustic waves. At the same time, they zapped the deuterated acetone with high-speed neutrons. The neutrons, which each carried about 14 million electron volts (MeV) of energy, struck the molecules of acetone and gave them a punch of energy. "You get vaporization on a small scale," says Taleyarkhan. The pockets of vapor nucleate bubbles and cause them to grow to about 1 millimeter across—much bigger than they would normally get in an acoustic field. "They grow to be mammoths," he says. "You can actually see the bubbles."

The catastrophic collapse of a millimeter-sized bubble to a few nanometers across heats the deuterated acetone to the point at which deuterium atoms collide and fuse, the authors argue. "I thought, doggone! I'm depressed I hadn't done that experiment," says Lawrence Crum, a sonoluminescence expert at the University of Washington, Seattle, who acknowl-



Pop! Embattled paper suggests deuterium nuclei undergo fusion inside sonoluminescent bubbles.

1808

8 MARCH 2002 VOL 295 SCIENCE www.sciencemag.org

→ What we identify as the main and yet unapproached problem

Could there be a logic technical explanation of why the sonofusion experiment might have worked out one time but why the original setup is difficult to reproduce?

We think the difficulty to reproduce resonator chambers with similar vibration characteristics could be one possible explanation for the lack of successful independent repetitions of the sonofusion experiment.

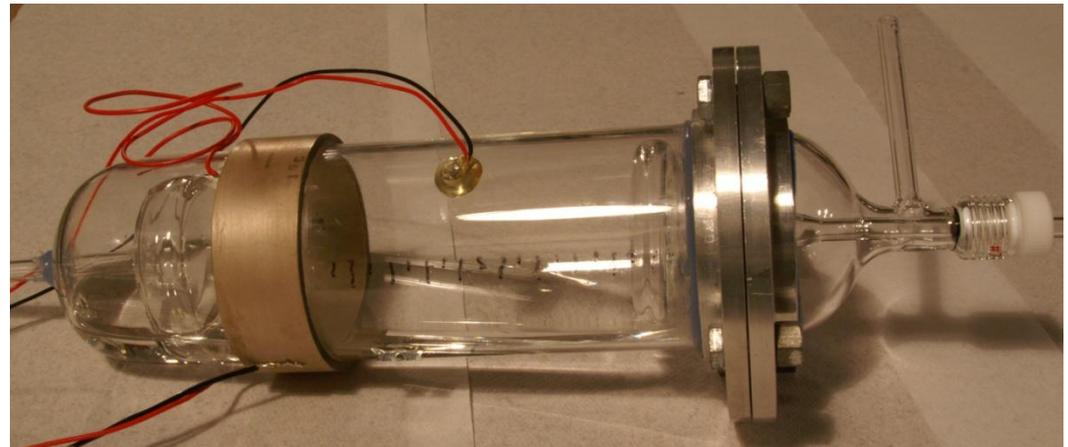
We have set up a 2D axisymmetric FE-simulation in the commercial FEM software Ansys to simulate the forced harmonic vibration (in response to a sinusoidal voltage across the piezoelectric transducer) of the style of acoustic resonator test sections used by the group of Taleyarkhan. In a sensitivity study it was examined how the maximal sound pressure amplitude along the central axis of the test section in the interesting range of frequencies varies under variation of many design features like glass part thicknesses, curvature radii, diverse keypoint distances, etc. The model turned out to be sensitive to variations of the majority of examined parameters. The resulting variation of the maximal sound pressure amplitude covered one order of magnitude.

on the right: resonator of the current design

This design has been invented by Colin West et al. in the 1960s [1]. Such resonators have been in use for the claimed successful sonofusion experiments of Taleyarkhan et al. at ORNL, and for the sonofusion repetition trials [2] of our collaborating group at the Rensselaer Polytechnic University (RPI), Troy, NY.

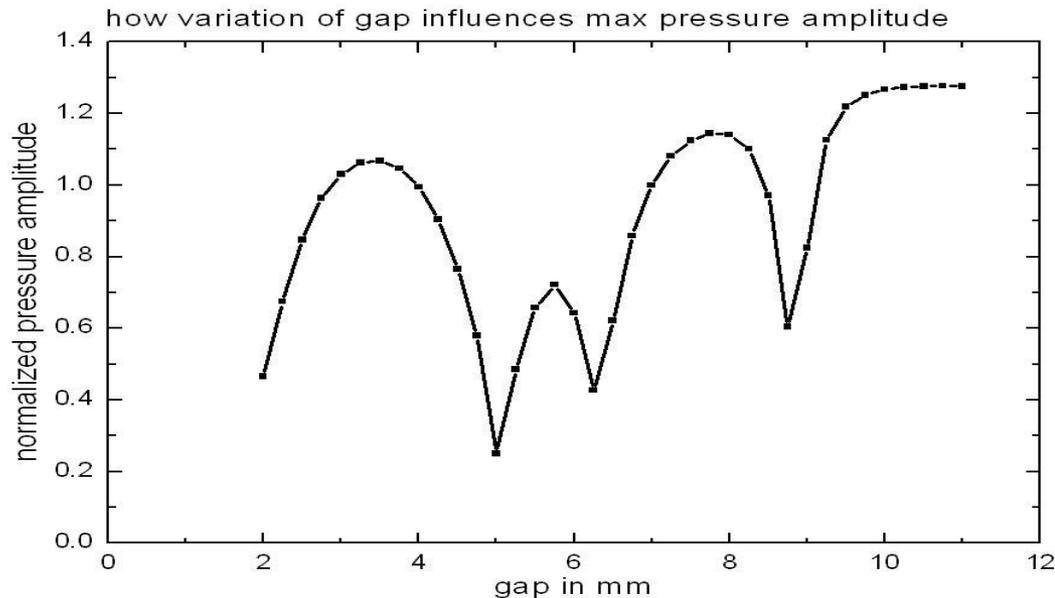
literature:

- [1] C. West and R. Howlett, *Some experiments on ultrasonic avitation using a pulsed neutron source*, Journal of Physics D: Applied Physics **1** (1968): 247-254.
- [2] Saglime, F. J. III. *Experimental results for the RPI bubble fusion project*. Troy, NY: MS thesis, Rensselaer Polytechnic Institute, 2004.

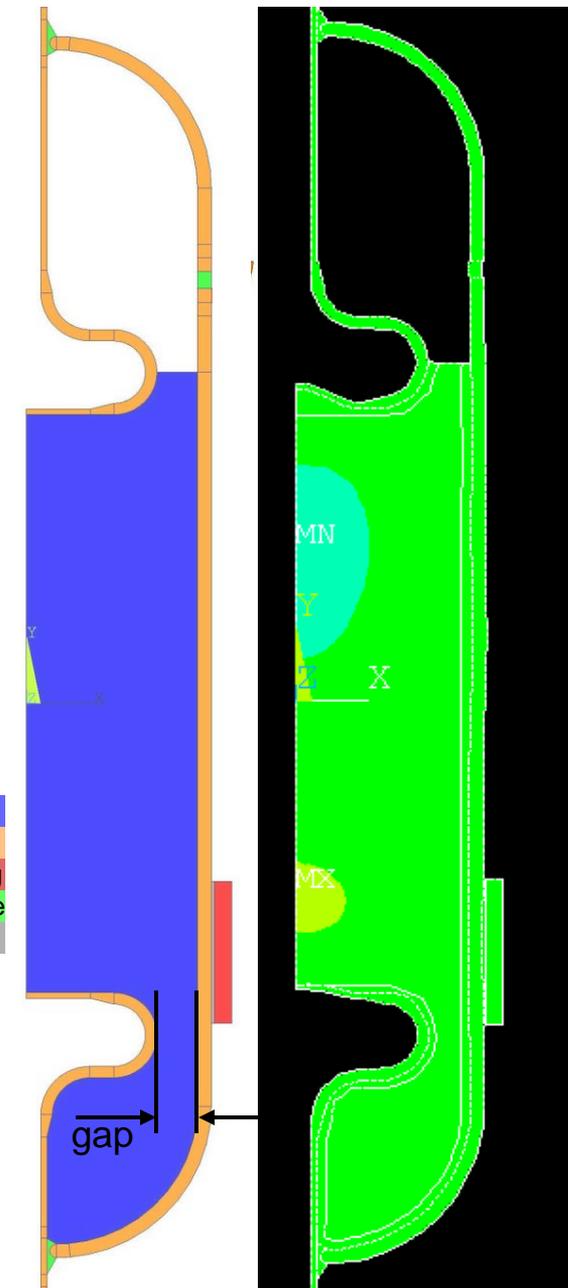


→ What we identify as the main and yet unapproached problem

The cuts on the right show a schematic of the type of acoustic resonator used by the group of Taleyarkhan and the motion shape of that one resonance which yields best cavitation results in the real lab setup. It is important to note that all glass parts (orange) of this design have to be manufactured manually through glassblowing. Furthermore, all the parts have to be assembled manually. Our FEM simulations (using [Ansys Classic](#)) show that the max sound pressure (p_{max}) performance of the chamber is sensitive to a majority of the examined parameters. One of the most influential parameters turned out to be the horizontal gap between the two pistons' rims and the inside of the main glass cylinder. The plot below shows that when this **gap** changes just a bit **from 4 to 5 mm** it can **decrease p_{max} by a factor of five**. This lets us believe that if you just try out 2 or 3 test sections it is a pure **game of luck** whether you have a well-performing one among them. (The influence of slight asymmetries like tilted pistons, where a 3D model is required, has not been examined yet.)



blue: liquid
orange: glass
red: piezo ring
green: silicone
grey: epoxy



→ sonofusion chamber optimisation

Sorry folks, that was a lot of explanation, but now finally, we have all the context to describe our ongoing work.

We would like to suggest an **improved test section design** for sonofusion experiments:

- **all parts must be precisely machinable**
- **with the same piezo ring and the same applied voltage the new chamber should produce the same or higher sound pressure amplitude as the old design in the best case**
- **the resonance peaks should not become much wider as this would hint to too much damping**
- **there must be at least two points with low displacement, one at the top, one at the bottom, where nozzels and tubing can be attached, and where connections to plastic hoses do not damp the vibration motion too much; so the chamber can be emptied and refilled completely without disassembling it**

For any new more or less complicated design idea there are 5 to 20 design parameters, which have to be tuned to a good combination in order to find the global optimum of highest sound pressure p_{max} . Because of the many resonances in the interesting frequency band between 15 and 23 kHz, the search space for the best parameter combination is high-dimensional and has many local optima. Therefore, we decided to use evolutionary algorithms for that search.

To sum it all up:

We want to contribute a little step of progress to the bubble fusion controversy by

- **pointing out** (see our ICSV17 conferece paper) **the great performance sensitivity of the resonator chamber style used by Taleyarkhan et al., and by**
- **suggesting new design ideas, which can be machined and assembled reproducibly under high precision, and which have been optimised by the use of evolutionary algorithms.**

M. J. Stokmaier, A. G. Class, T. Schulenberg, B. A. Malouin, R. T. Lahey
„Acoustic Chambers for Sonofusion Experiments: FE-Analysis Highlighting
Performance Limiting Factors“, *Proceedings of the 17th Intl. Congress on
Sound and Vibration (ICSV17)*, Cairo, Egypt, 2010

Wikipedia links:

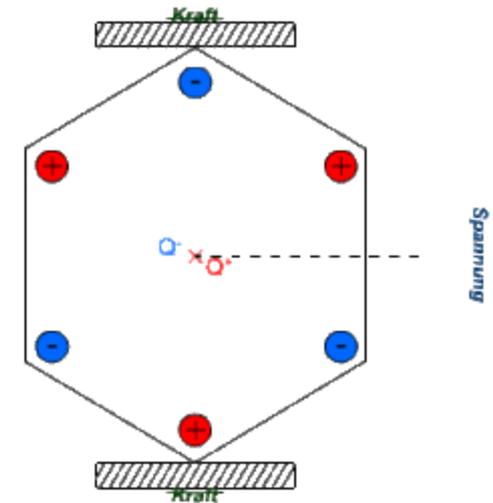
- [metaheuristic](#)
- [evolutionary algorithm](#)

A piezoelectrical material changes its polarisation after mechanical distortion leading to large voltage differences across opposing sample surfaces; inversely, a piezo cristal slightly changes shape when applying an electrical field across its volume.

Experiment:

Just disassemble the ignition part of a lighter (the clicking sort, not one with a metal wheel and a flint, because the clicking ones work with a piezo), take that top part with the click-mechanism between your fingers, squeeze it, compressing the spring inside ... at some point it clicks, i.e. some hammer is accelerated by the loosened spring and thrown against the piezo cristal, hits it, and you can feel a little electric shock going through your fingers – that's what I call hands-on physics!

(Don't play with bigger pieces of piezo ceramic, though. They might already produce really scary shocks just after unintentionally warming the sample in your hands!)



from: <http://de.wikipedia.org/wiki/Piezoelektrizit%C3%A4t>

Wikipedia links:

- [piezoelectricity](#)

→ back ←

Cavitation

see: <http://en.wikipedia.org/wiki/Cavitation>

Take a solid like rubber: you can put it under compression, like the shoe sole under your feet, or you can put it under tension when you pull a rubber band, or at least it's easy to put the rubber band under tension in one direction. How can you put a piece of rubber into an isotropic state of tension, i.e. equal tension in all three space directions? Well, you could take a rubber cube, glue a square steel plate on each of its six faces, attach hooks at the plates's centers and pull at each of the six hooks with equal force away from the cube. That would create an isotropic state of tension in the rubber material.

Can you create tension forces in an ideal gas? No. The ideal gas is an ensemble of independent particles of equal mass with a distribution of speed/momentum, and each particle can transmit momentum upon collision with another particle or something else, but there are no attractive forces being able „to pull“ any single particle. When you pump up your bicycle tyre where compressing the air feels like compressing something soft like rubber, the force you feel is just the many molecules of O_2 and N_2 bombarding your pump's piston, being reflected, and transmitting momentum. Their constant stream of momentum is the repulsive force you feel. And when you push the piston inward, the particles reflected by the piston have more kinetic energy than before their collision with it; this is what heats the air up when you compress it. The other consequence is the reduction of the volume inside the pump which leads to the same amount of air molecules covering less space. When they have cooled down again to ambient temperature, the particle ensemble's Boltzmann distribution of kinetic energies looks the same again as before the compression, but the density is still higher. Let's say the volume was cut in half and the density doubled. This means that after reaching thermal equilibrium with the outside, your pump's piston's front surface is bombarded exactly twice as often per unit of time with the same distribution of momenta – so the pressure simply doubled. This is the ideal gas law. You would then need to hold up against the doubled force, at least if your pump was really tight.

Now, when you go on a space travel and leave the earth's atmosphere, you can measure the air pressure outside decrease as you mount through the atmosphere and finally go to zero when you reach the open space – the bombardment of air molecules ends. It is clear that the hull of your space ship in open space can feel no tension forces from the outside unless some band of alien kids start plastering it with bubble gums and tugging it from everywhere.

But now comes the big question: can there be less than zero pressure, i.e. can there be tension in a liquid? A first intuitive answer might be: „No, of course not. Imagine I took my lego-man friend in his little lego-submarine in a bowl of water with me on my space travel and chugged the whole aquarium out my window into open space. Then, because of the lowered pressure the blob of water would boil immediately and evaporate quickly, it would all turn into gas and flee into the space and maybe only a few ice crystals would remain on the submarine's hull. So as any liquid turns to gas at finite pressure, its vapor pressure (at finite temperature above the melting temperature) we can never reach zero pressure inside the liquid and hence never cross that threshold into the realm of negative pressure.“ Well spoken, I'd say, but wrong. A liquid is not just a dense gas. Take a liquid's surface tension as the most visible property hinting towards the strong attractive forces between its molecules, capturing neighbouring particles with low enough kinetic energy in each other's attractive potential. If there are attractive forces between the liquid's constituents, there must also be states of isotropic tension when each particle is just „pulling at its neighbour“. And it is true that through sound fields of strong amplitude or via turbulence of high enough vorticity tension states in liquids can be easily created experimentally as long as you ensure that the liquid is pure, with no dissolved gasses, and that there are no nucleation sites like impurities or residual bubbles of noncondensable gas. It is just difficult to measure exactly how far you can go until the liquid ruptures (i.e. measure cavitation strength), because the surface of any pressure measuring device (like a hydrophone) will serve as a nucleation site itself. A liquid under tension can be seen as in an extremely superheated, metastable state, and it would begin to bubble/boil/rupture immediately if you introduced nucleation sites.

Experiment: take a plastic syringe, hold it under water, empty it of all air bubbles, fill it half with water, close the tip with your finger, and pull strong enough. You will immediately create a cavitation bubble, which will disappear again as soon as you let go of the piston. If a tiny little bubble remains, it stems from air, which had formerly been dissolved in the water and has diffused into the cavitation bubble, and which now forms a bubble of noncondensable gas. If you repeat it in your bath tub in soapy water, the cavitation bubbles will form as white fog or foam and the water will clear again upon return to ambient pressure.



A ship's propeller moving fast, leading to low local pressures and creating cavitation in water. Where does the low pressure come from? Responsible are the centrifugal forces induced by a vortex.

source:
<http://en.wikipedia.org/wiki/File:Cavitating-prop.jpg>



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standing sound waves

Another everyday-life-instance of an oscillating pressure field is an organ pipe. Here too, (just as in a flute, sax, or trumpet,) we have a well-determined volume of fluid (air) set to vibrate due to some excitation force and the elasticity of the fluid.

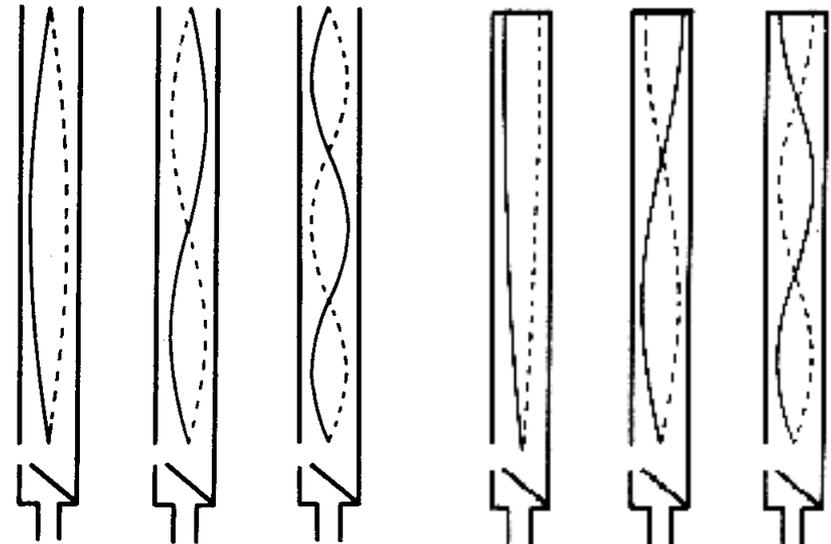
In a saxophone the excitation comes from a beating wooden reed, in a trumpet from your beating lips, and in a flute from a flip-flopping von Karman vortex street. In an organ pipe wooden or metal reeds are used as well as flute-like mouth pieces. And the elasticity of air? You can feel it when compressing a bicycle pump while keeping the nozzle shut tight with your thumb.

The constant of elasticity, the Young's modulus, of most liquids is much higher, that means liquids are stiffer or harder to compress than gases. This means that the resonance frequency of a volume filled with water will be much higher as the resonance frequency of the same volume filled with air.

left: open organ pipes;
for both ends of the pipe the pressure boundary condition is constant atmosphere pressure; for the displacement we have a forced sinusoidal displacement created by the turbulence at the mouth or reed, and a free displacement boundary condition at the top end

right: closed (stopped) organ pipes;
the boundary condition at the top end changes to:
zero displacement, but any pressure you like

Do the wave envelopes on the right look familiar? In fact they look like vibrating rubber bands or guitar strings, which are other examples of standing waves in everyday life.



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