TIMES

FUSION ENERGY

What a shrimp can teach us about nuclear fusion

Studying the pistol shrimp's use of shockwaves to kill its prey helped inspire a new approach to fusion energy

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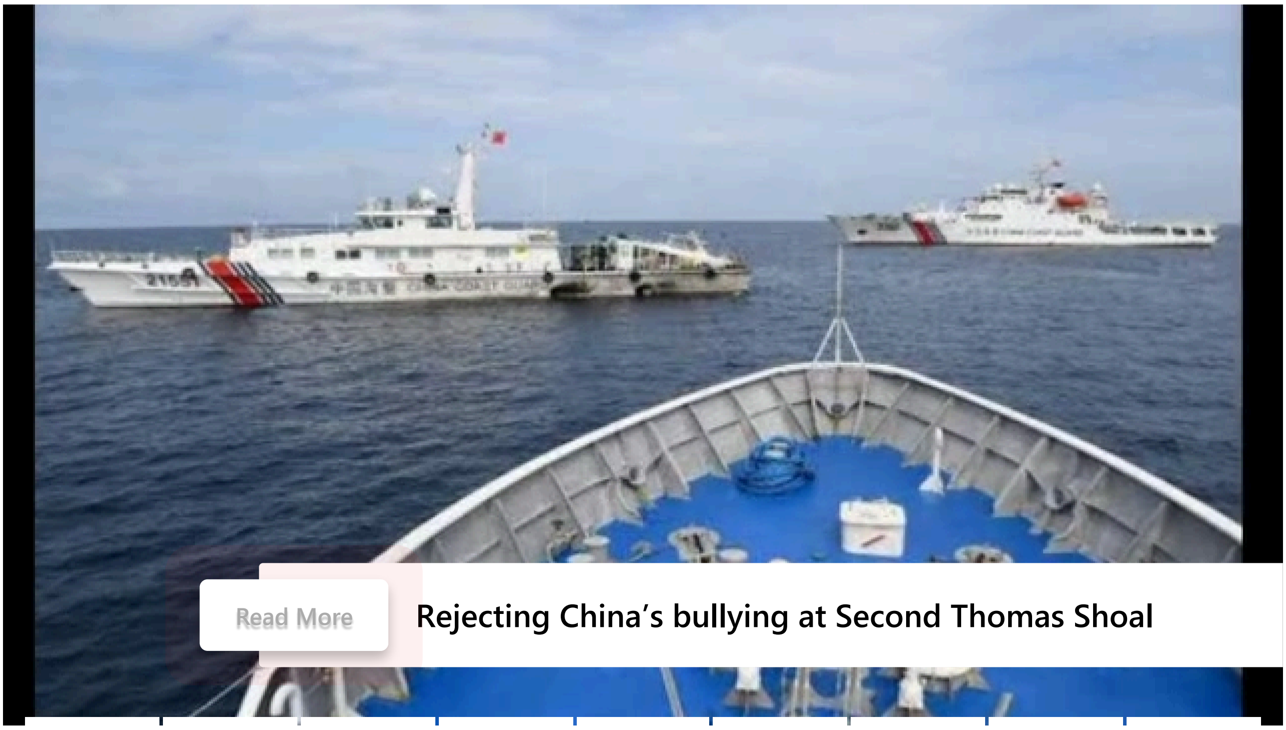
In **my last article**, I described a potentially revolutionary approach to generating fusion energy, by impacting super-high-velocity projectiles onto specially designed targets.

First Light Fusion, the company pursuing this "projectile fusion" method, has a pulsed power device called "Machine 3" capable of accelerating projectiles up to velocities of 20 kilometers per second, or 75,000 kilometers per hour.



"Machine 4", which will be able to reach three times higher velocities, is in the works. First Light Fusion hopes Machine 4 will achieve a fusion gain of 100, i.e. 100 times more energy released from fusion reactions than was put into the fusion fuel.

To reach such results, however, much more is required than just high velocities. Given the extreme pressures and temperatures needed for fusion, even the impact of Machine 4's super-high-velocity projectile on a fuel capsule would hardly produce any fusion reactions.

The key to success lies in what First Light Fusion calls the "amplifier." Struck by a fast-moving projectile, this cube-shaped object multiplies the intensity of the resulting shockwave many times over and focuses it onto a pellet of fusion fuel. This changes the whole game.

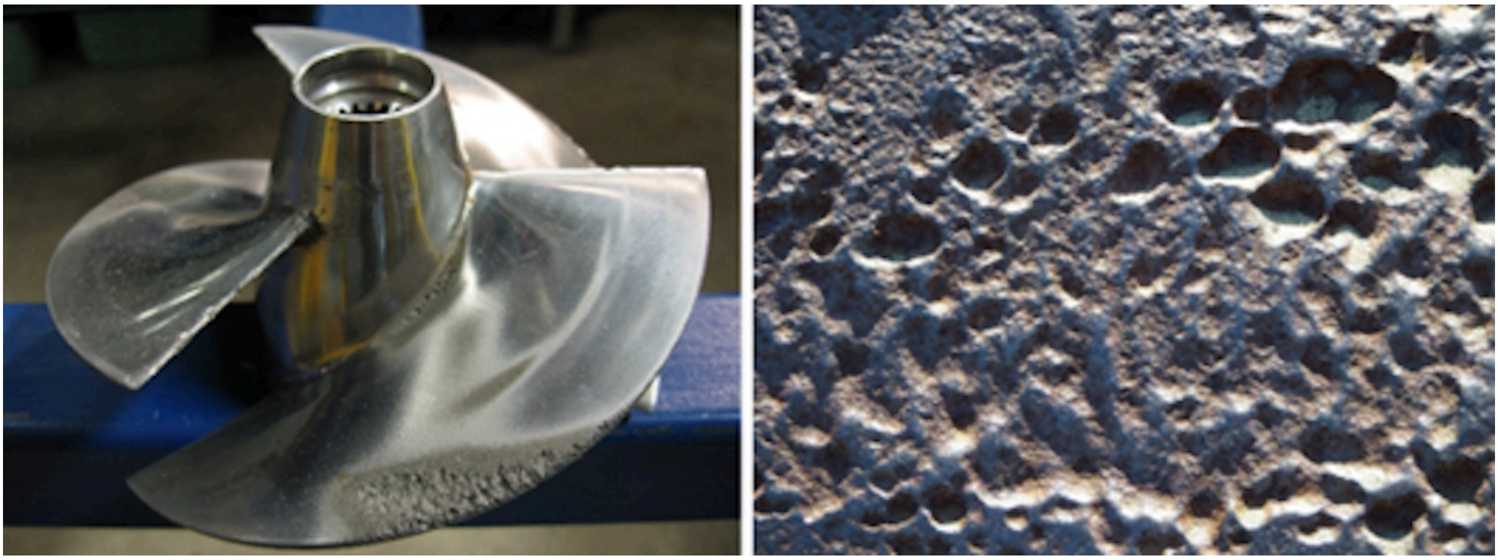
Thanks to the “amplifier,” even the much lower velocities achieved by First Light Fusion’s first projectile accelerator, the “Big Friendly Gun,” are sufficient to trigger measurable amounts of fusion reactions, as was demonstrated in November 2021.

Cavitation and sonoluminescence

So how does the amplifier work?

As metal propellers began to be used on a large scale for the propulsion of ships, they were found to suffer from a peculiar sort of damage where areas on the blades were progressively being “eaten away,” eventually requiring their replacement.

Similar problems affected valves, pumps and other structures in contact with rapidly flowing liquids. Examination revealed a peculiar sort of damage, quite different from corrosion. What was the cause?



Left: Cavitation damage on the edge of a ship propeller; right: closeup view. Photos: Creative Commons

By the 1890s it had become evident that the damage was somehow connected with a phenomenon called cavitation: small bubbles – cavities – in a liquid that form when the pressure momentarily falls below a certain level (the vapor pressure), and that subsequently collapse.

As it turns out, the collapse of a cavitation bubble is a much more violent event than one might suspect at first glance. With a suitable setup, one can easily observe the streams of cavitation bubbles generated in water by a spinning propeller.


Rotating propeller generating a train of cavitation bubbles in water. Photo: Creative Commons

It is easy to imagine how this could occur. A rapidly spinning propeller generates turbulence and large pressure differences in the water as it passes by, giving rise momentarily to regions of much lower pressure and regions of much higher pressure.

Cavitation bubbles form in regions of low pressure, specifically where the local pressure falls below the so-called vapor pressure, inducing liquid water to evaporate. The process whereby the vapor-filled bubbles form is rather complicated but the details are not relevant here.

When the bubbles pass into regions of higher pressure or are struck by a propagating pressure front, the vapor filling the bubble re-condenses back into water, leaving a void and causing the pressure inside to drop below that of the water outside. The pressure difference pushes the walls of the bubble inward, the bubble collapses to a fraction of the original size and usually disappears altogether.

What does this have to do with eating away the surface of a solid metal propeller?

In 1917, the British physicist Lord Rayleigh carried out a theoretical mathematical analysis of a collapsing spherical bubble in a liquid. His equations showed that the walls of the bubble move in at a rapidly accelerating rate as the bubble contracts, finally reaching infinity when the radius reaches zero. At the same time, the pressure and thereby also the temperature and energy density become theoretically infinite.

Of course, this was only a mathematical model. The appearance of such infinities implies that at some point along the line, before the radius becomes zero, physical reality will diverge from the model and something new will happen. Nevertheless, Rayleigh’s analysis provided a first plausible indication for how collapsing water bubbles could generate high enough concentrations of energy to damage the propellers of a ship.

In the meantime, we know that the temperatures at the middle of a collapsing cavitation bubble in water can reach 5,000°C or even much more. The gas inside the bubble has momentarily turned into a plasma, emitting a short flash of light.

It turns out that the cavitation-collapse cycle can be maintained on a continuous basis by subjecting a liquid to underwater sound waves of sufficient intensity. In a typical experiment, an ultrasonic transducer generates a so-called standing wave in a tank of water: with each cycle of the sound wave, bubbles appear and collapse again, producing short flashes of light in synch with the signal.

Such sound-induced light emission is known as **sonoluminescence**, which can now be studied **in single bubbles pulsating in an acoustic field**. So could there be some way to intensify the phenomenon of sonoluminescence up to a point where fusion reactions would be triggered inside the collapsing bubbles?

Researchers have pursued this idea and in 2002 the physicist Rusi P Taleyarkhan at Oak Ridge National Laboratory actually claimed to have detected fusion reactions. His results have not been validated, however, and even became the subject of **an academic scandal**.

It is hard to judge the ultimate feasibility of some sort of "bubble fusion," but in the history of fusion, nothing has turned out to be as simple as it first appeared.

Getting back to our ship propeller, an important question remains unanswered: How does the intense energy concentration arising inside the collapsing bubble get communicated to the surface of the propeller?

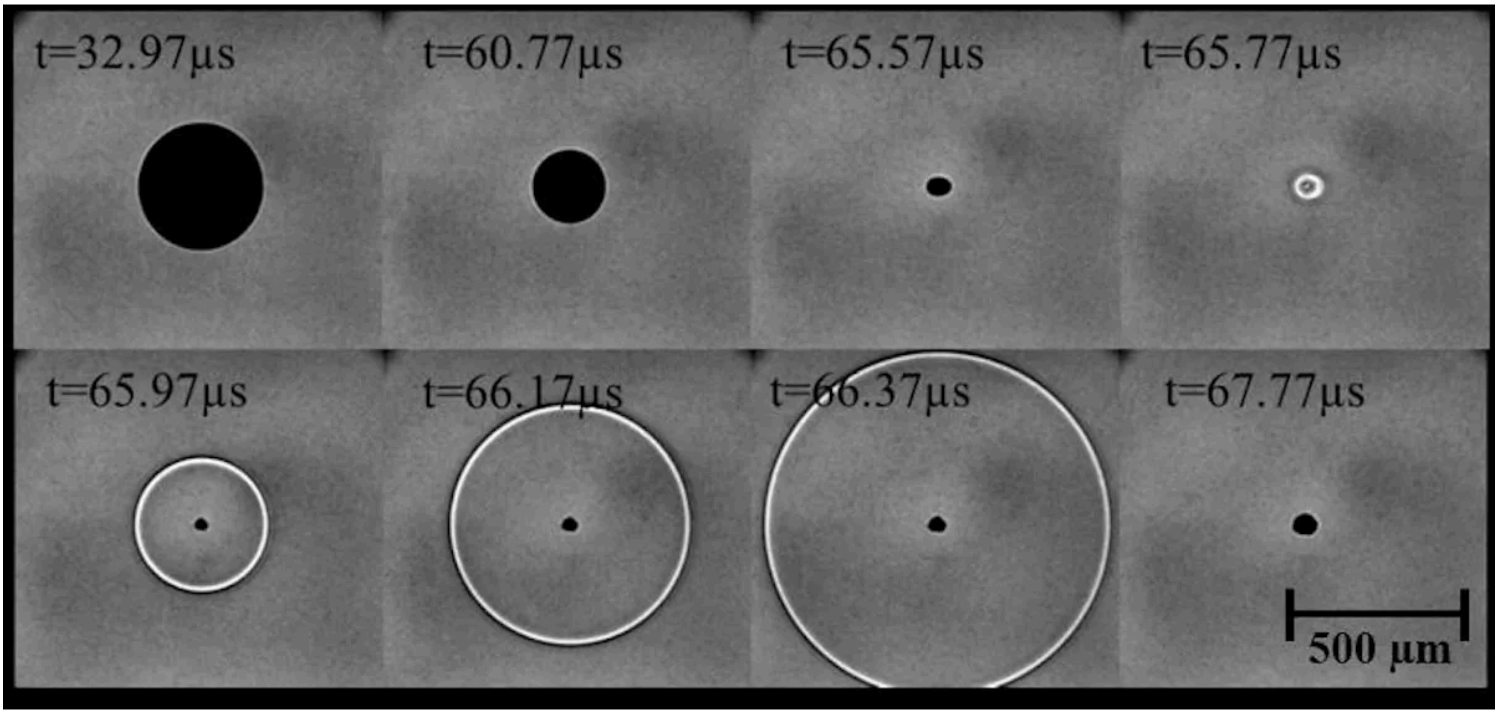
Simulations and direct observation by super-fast cameras (a million or more frames per second) reveal that the collapse occurs very differently when a cavitation bubble is close to a surface: As the bubble collapses, it loses its spherical shape and shoots out **an intense, high-velocity je**t of material toward the surface. This jet has such a high power density that its impact can damage metals.

The production of microjets caused by collapsing bubbles has been the leading explanation for how cavitation damage occurs. But evidently there is an additional mechanism: Collapsing bubbles emit shock waves.

To remind the reader: shock waves are characterized by a sudden, practically discontinuous increase in pressure as a wave passes by. By their very nature, shock waves deliver energy in a concentrated form. Anyone who has ever experienced an explosion from a distance understands the effect.

The August 4, 2020, **Beirut harbor explosion** provides a particularly dramatic example: the shock wave generated by the explosion **damaged buildings** as far away as 10 kilometers. Observers are often taken by surprise because the shock wave takes time to reach them. They see the far-away explosion and think that is all – until the shock wave hits them.

Although it occurs as an implosion rather than an explosion, the collapse of a cavitation bubble also **generates shock waves** – extremely powerful ones, on a microscopic scale. This should not be surprising taking into account the intense concentration of energy in space and time which takes place in the collapse.



High-speed images of a collapsing laser-induced bubble with the emission of a shock wave and a spherical rebound. Imaging is undertaken at 5 million frames-per-second with synchronous 10 ns laser pulses. Photo sequence: Kristoffer Johansen et al., deconvolution of acoustically detected bubble-collapse shock waves, Ultrasonics Volume 73, January 2017, Creative Commons

More than one mechanism can be involved. On the one hand, the inward-rushing walls of the bubble, which can reach supersonic speeds, produce shockwaves inside the bubble.

These are partly reflected back and forth from the walls and partly propagate to the outside. In addition, the high temperatures and pressures inside can cause an explosion-like "rebound" of the bubble: After reaching a minimum radius, the bubble expands again, with the outward-moving walls generating shock waves in the surrounding medium.

So far I have only mentioned the case where the collapse of a cavitation bubble is triggered by a more or less gradual increase in the pressure of the surrounding medium. But bubble collapse can also be triggered by an external shock wave hitting the bubble.

The phenomenon suggests an exciting possibility: Given that the collapse process concentrates energy, the shock waves it generates might possibly be more intense – exerting more pressure in a shorter time – than the original one. That way, the bubble would act as a shock wave amplifier.

Enter the pistol shrimp

In fact, Nature has long since learned how to do these things.

There is a strange underwater creature called **the pistol (or snapping) shrimp**, which uses shock waves to **kill enemies or prey at a distance** with no need for direct contact.

This species of shrimp is equipped with a specially designed claw, which it uses as a kind of gun. The animal first cocks the claw in an open position. At the moment of attack, the claw snaps shut with extreme rapidity and force.

High-speed cameras reveal that a large, irregular cavitation bubble is formed and quickly collapses, generating the "killer" shockwave that knocks out the target animal.

This process is accompanied by a short flash of light, which was dubbed "**shrimpoluminescence**" by its discoverers, Dieter Lohse, Barbara Schmitz and Michel Versluis. It also generates a popping sound, which is among the loudest produced by any underwater animal.

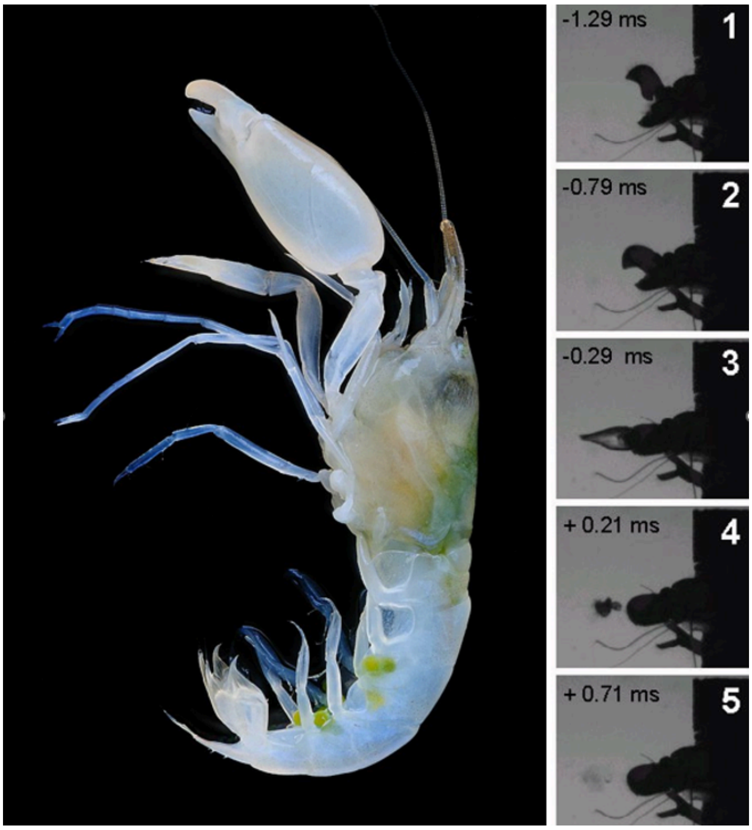
Shrimpoluminescence is emitted by a short-lived plasma with a temperature of 5,000 degrees C or more. Together with Anna von der Heydt, the discoverers also established that **cavitation bubble collapse is the source of the popping sound**, not the shrimp's claw as earlier thought.

Not surprisingly, in this case the collapse process differs greatly from that of a simple spherical bubble, which would hardly be able to produce a shock wave of the observed magnitude.

There is no doubt that the tremendous concentration of energy, embodied in the shrimp's "killer shock," comes about through a highly complex nonlinear process involving a multitude of intermediate shock waves – generated at various stages of the collapse – interacting with each other and with the rapidly changing configuration of surfaces inside the bubble.

The whole process occurs in less than a millisecond. Simulations provide practically the only available means for investigating in detail what might be happening.

In 2011, Nick Hawker, now the founder and CEO of First Light Fusion, was working on his PhD thesis at Oxford University's Department of Engineering Science under Professor Yiannos Ventikos. Hawker was challenged by the phenomenon of the pistol shrimp, which seemed to suggest a new road toward realizing nuclear fusion.



Left, pistol shrimp (Alpheidae); right, sequence of a pistol shrimp 'sho,' 1: Open claw. 2: Closing claw. 3: Stream jet. 4: Bubble. 5: Implosion. Photos: Creative Commons

Hawker often likens what the pistol shrimp does to inertial confinement fusion. The shrimp's shock-collapsed bubble does not reach anything near fusion conditions, but the burst of light testifies to an enormous concentration of energy. In an informative **podcast interview** on the program "Jazz Shapers," broadcast in April 2023, Hawker explains:

"First Light [Fusion] came out from my PhD research where I was simulating a new process for fusion, something which hadn't been explored for inertial [confinement] fusion before, inspired by the pistol shrimp. I was doing simulations, so I was trying to take this natural phenomenon and turn it into something which we could study on a computer and kind of get our head 'round and understand."

Evidently Hawker was not out to discover some novel physical explanation for the "killer" shockwave; instead, he endeavored to model the underlying processes with the help of well-established physics combined with sophisticated numerical methods.

As it turns out, the problems involved have many common features with those of simulating shockwave-induced implosion in inertial confinement fusion.

Developing reliable computer simulations for these sorts of processes – simulations that give accurate predictions without requiring enormous amounts of computer time – poses formidable challenges.

Hawker evidently accomplished major breakthroughs in this field. His PhD thesis was the starting point for a long journey of invention focused on solving the problems of inertial confinement fusion.

Developing simulation methods combining high predictive accuracy with short computation time gave Hawker and Ventikos the capability to develop new ideas and try them out in a way that would have been unthinkable in past times. At the same time, one could develop a "feeling" for how the relevant processes behave.

In the interview, Hawker remarked:

"The brilliant thing about simulation, if you're an inventive kind of person, which my supervisor and I both are, is you can tweak it so easily. You can get an answer back so easily. You say, well, what if I just changed the shape of this: It was like this shape instead of that shape? Or I just put this bit here, what would happen?"

He added:

> There's always trial and error. And there's always ideas which you think are great, but then you test them, and they just don't work as you expect at all. And equally sort of the other way around, ideas that you're really not sure about, but if you put the right physics in the model, you can have the opportunity to surprise yourself by finding something which you weren't expecting, if that makes sense.
>
> So I suppose I think of science in kind of three areas. There's the experimental side, there's the theoretical side, but really important for First Light is the numerical side, the simulations. These aren't just little bits of maths, these are simulations which show emergent behavior.… These are huge engines of discovery.

Hawker's characterization of numerical simulations as "huge engines of discovery" is an eye-opener.

Sophisticated computer simulations are commonplace in nearly every domain of science and engineering today. That applies not least of all to plasma physics and fusion research. But it is far less common to use simulations in the same way as Hawker and his collaborators do to test out new ideas and hypotheses concerning highly complex physical systems.

"Tweaking" a simulation by changing various parameters, can be far simpler, less costly and less time-consuming than carrying out real-life experiments. The precondition, of course, is that the simulations give correct results.

Hawker and his colleagues are constantly testing and validating their numerical methods, comparing simulations with actual experiments using the Big Friendly Gun, Machine 3 and other experimental platforms.

First Light Fusion's 'Big Friendly Gun' was used in the first demonstration of fusion reactions by projectile fusion in November 2021. Photo: First Light Fusion

Over time, First Light Fusion has developed ever more formidable simulation capabilities, employing machine learning and other advanced techniques. The company has its own high-performance computing facilities with over 10,000 processing units (cores). Its software encompasses some 400,000 lines of computer code.

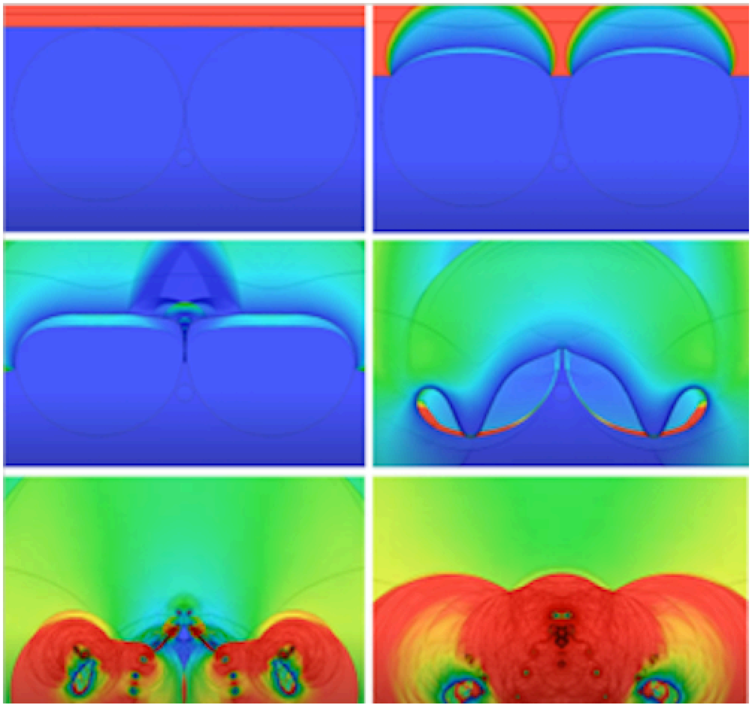
Here is an example of a simulation involving one of First Light Fusion's earlier target designs. The target consists of a toroidal cavity with a small spherical cavity containing the fuel tucked away on the underside.

The video shows a cut-away view of the process. The horizontal line above represents the planar shockwave created by the projectile impact. This shockwave strikes the toroidal cavity first, triggering its collapse and in the process producing stronger shockwaves that converge down on the small fuel cavity and create conditions for fusion to occur.

As the video shows, the process is extremely complicated, with turbulent hydrodynamic flows and a multitude of secondary shockwaves reflected in various directions.

In the meantime, First Light Fusion has moved away from the use of cavities to other means of shock wave amplification and focusing. The designs are constantly evolving.

Hawker has also introduced a sharp distinction between the "amplifier" and what he now refers to as the "target," the latter constituted by the fusion fuel with its immediate "packaging." This makes it easier to make use of the enormous experience gained with different sorts of targets in laser fusion.


Simulation of an advanced target struck by a planar shock wave (coming from above) Graphic: First Light Fusion

First Light Fusion has put forward a preliminary fusion **reactor design based on their projectile fusion scheme**. Unsurprisingly, it is far simpler than corresponding designs for laser fusion. The principal simplification derives from the ability to generate fusion by hitting a target from a single side, rather than needing to bombard it from all sides simultaneously.

The big question is whether First Light Fusion will succeed in actually demonstrating fusion ignition and breakeven with the method of projectile fusion. If that happens, it will be a great day for fusion.

Jonathan Tennenbaum is Science Editor at Asia Times