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On some oversimplified approaches to inertial confinement fusion

The quest for an unlimited and clean source of energy is a major human endeavor, which cannot be resolved without controlling nuclear reactions. Compared to nuclear fission, which has been successfully explored and exploited for more than 70 years, nuclear fusion has not yet demonstrated its potential. Despite more than 60 years of intense high level international research and multi-billion investments, fusion energy remains evasive; it is still a scientific project, without definite horizon for construction of the first fusion power plant. While the scientific community maintains strong motivation to demonstrate fusion energy production, such a long history of intense research may produce discouragement and foster attempts to propose fast and magic recipes solving all outstanding problems by innovative and original ideas.

Although serendipity and intuition were always great sources of inspiration and scientific progress, they shall not contradict the basic notions of science and not deviate research from the established scientific methodology. Before commenting on the recently proposed "magic" solutions for inertial confinement fusion, it is necessary to recall the basic elements of fusion energy science. In contrast to fission of heavy nuclei by electrically neutral particles, neutrons, fusion reactions involve two positively charged light nuclei. Yet the close contact needed for their fusion is impeded by the strong Coulomb repulsion. For this reason, the probability of fusion in a collision of two nuclei is very small (by roughly two orders of magnitude) compared to elastic scattering. The only known method to overcome Coulomb repulsion, actually by tunneling the potential barrier, is to heat the fuel to high temperatures and maintain it for a sufficiently long time, so that a surplus of energy in fusion reactions can be produced. Schemes based on particle acceleration are not suitable for efficient fusion energy production because the projectiles lose their kinetic energy via Coulomb collisions. That is why thermal equilibrium is necessary. The condition for energy production from fusion reactions is known as the Lawson criterion. For the fusion of hydrogen isotopes, deuterium and tritium, the required temperature is at least 100 million kelvin and the product of pressure to the energy confinement time should be larger than 10 atm·s. These are extremely challenging conditions, which nobody has succeeded in achieving so far; they are even more extreme for other fusion fuels.

Two approaches to fusion energy are being actively pursued. Magnetic confinement fusion aims at a steady process with energy confinement time of a few seconds. Inertial confinement fusion is a pulsed process; the energy gain must be achieved in each pulse and confinement is limited by the time of propagation of a rarefaction wave across the fuel. Moreover, the energy release in each pulse is capped. It cannot be more than a few gigajoules, corresponding to a few hundred kilograms of high explosives. This latter condition limits the fuel mass to a few milligrams and consequently the confinement time is limited to a fraction of nanosecond or even less. For this reason, the Lawson criterion can only be fulfilled through strong compression of the fuel, typically by thousand times in volume.

Two more points need to be recalled about inertial confinement fusion. Firstly, compression and heating of fuel to such extreme conditions requires a lot of energy, typically about 0.3% of the total energy that can be produced from fusion reactions in a given mass of fuel. This is a large number accounting for losses related to incomplete burn, low efficiency of compression and heating processes and a limited efficiency of the driver and conversion of fusion energy in electricity. Therefore, the volumetric heating of the fuel is highly inefficient and fusion target designs are aiming at heating only a small portion of the fuel where the fusion process is ignited locally. This is similar to the spark in the combustion engine. Secondly, in the most studied scheme the target compression and heating are achieved by optical laser radiation, since this is the most powerful energy source currently available. However, the compressed fuel is opaque to the laser light, thus making direct laser heating incompatible with the Lawson criterion. To overcome this problem, fuel compression and heating are achieved by the pressure force produced by ablation of the external part of the target by a temporally shaped laser pulse.

These well-known basic elements form the cornerstone of all target designs in the inertial fusion with different versions including direct and indirect drive, fast and shock ignition and magneto-inertial fusion. All these approaches require a lot of knowledge and perseverance; the progress is slow but steady. Nevertheless, from time to time, "magic" solutions are proposed, attracting public attention and inducing skepticism about the "traditional" conservative science. We recall the story of "cold" fusion that was explored more than 30 years ago, when two scientists, Martin Fleischmann and Stanley Pons [1], announced excitation of deuterium fusion reactions at room temperature by electrolysis of a heavy water. However, it proved impossible to replicate the claimed results, and no explanation was found for cold fusion mechanisms. The proponent of cold fusion did not explain how the Coulomb barrier was suppressed in their device and the scientific interest in this controversial topic vanished. A few years later, in 2006, two Swedish scientists, Shahriar Badiei and Leif Holmlid [2], announced creation of superdense clusters of hydrogen and deuterium by irradiating the surface of palladium samples with a low-intensity laser light. Their results were never explained nor reproduced, but they have been used for speculations about a novel root to the fusion energy [3].

Now we are witnessing promotion by well-known scientists Laszlo Csernai, Daniel Strottman, Norbert Kroó and István Papp [4,5] of a new approach to deuterium-tritium fusion based on laser absorption by nanoparticles, direct laser energy deposition in a volume of weakly compressed fuel and creation of a detonation wave propagating at the speed of light. These claims are, however, at odds with the basic notions of fusion science. Nanoparticles cannot improve laser absorption in plasma at a temperature of 100 million degrees; the fuel is in a plasma state where no chemical structures can survive. Adding heavier elements will just increase radiation losses and cool the fuel down. Even a weakly compressed fully ionized hydrogen plasma has an electron density of about 10^{23} cm^{-3}, which is at least 10 times larger than the critical density for optical lasers. No optical radiation can penetrate into the plasma volume. In a weakly compressed deuterium-tritium plasma, the rate of fusion reactions, which is proportional to the square of the particle density, is very low and no surplus energy can be produced during the inertial confinement time. Consequently, no fusion energy can be deposited in the plasma, no detonation can be produced and no relativistic effects may be expected. All these explanations have been provided in the critical comment by I. Foldes and G. Pokol [6] but, apparently, this did not convince L. Csernai *et al*. [7] and did not stop them from publicizing their "breakthrough" idea in fusion science.

This new fusion scheme will certainly quietly disappear, similarly to all previous "discoveries", but ethical problems remain. When published in high-level peer-reviewed journals, such articles create confusion and false expectations, not only in the scientific community but also in the general public. Any of us has the right to make a mistake and scientific journals are the right place for open public discussions. The peer-review system is a well-accepted and proven mechanism for selection of papers on common grounds of scientific significance and correctness. Publication of erroneous papers, such as the ones mentioned above, shows that peer-review systems and journal editorial boards are not sufficiently watchful and attentive. Open discussion of such cases is the best way to correct the errors and misunderstandings, to

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recall the basic ideas on a clear and comprehensible level, and therefore to strengthen the credibility of the fusion energy program.

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