Thermonuclear fusion: a view from Russia

Dr. Valentin Belakogne, a specialist in shock waves and explosive processes in gases and plasmas, discusses the history, and future, of fusion "microexplosions," with Dr. Jonathan Tennenbaum.

The Russian-Ukrainian physicist Valentin Belakogne is one of the leading proponents of the technology of fusion "microexplosions" in the former Soviet Union. This approach to fusion energy, sometimes referred to as "inertial confinement fusion," centers on the ignition of fusion reactions in pellets containing hydrogen (and, possibly, helium) isotopes, compressed and heated to the order of 100 million degrees by the action of powerful lasers, particle beams or other so-called "driver" systems. Extensive investigations in this direction were made in the United States and the Soviet Union beginning in the 1970s, and, since then, notably also in Japan and several other countries. At present, plans are being made in the United States for the construction of the largest-yet laser-fusion experimental facility, the National Ignition Facility. The NIF is projected to achieve fusion ignition by means of laser pulses of up to 1.8 megajoules and 500 terawatts, delivered in 192 beams to a tiny pellet in the center of a specially constructed explosion chamber. The maximum projected fusion energy release will be about 50 megajoules "per shot."

Valentin Belakogne is a long-time specialist in the relevant field of shock waves and the dynamics of explosive processes in gases and plasma, as well as in a number of other areas in applied physics, including the development of novel types of flying vehicles. He pioneered an original scheme for fusion by means of "supercompression" by implosion of numerous layers. He is presently director of the Interdisciplinary Laboratory for Long-Term Prognoses of Energy Technology and other future technology, at the Moscow State University and the Academy of Cosmonautics.

The following interview is taken from discussions between Dr. Belakogne and Dr. Jonathan Tennenbaum, chairman of the Fusion Energy Forum in Germany, last year in Moscow.

Tennenbaum: You are known to be a fanatical proponent of thermonuclear fusion microexplosions as the decisive large-scale source of energy for the 21st century, and as the most promising power source for the propulsion of ships, ekranoplanes [special, low-flying aircraft utilizing the "ground-effect"—ed.], large aircraft, and space transport systems, as well as for bases on the Moon. Similar views can also be heard among scientists at the Lawrence Livermore National Laboratory in the United States. But very often, such views are dismissed as utopian, and skeptics never tire of saying that the optimistic projections made in the past turned out to be wrong.

Belakogne: You are not entirely right. Of course, the previous forecasts of such classic experts on thermonuclear microexplosions as John Nuckolls undoubtedly exerted a very strong psychological effect on me. That they didn't come to pass was due not simply to fundamental mistakes by Nuckolls and his colleagues. Fifty percent, so to speak, of the disappointment concerning hopes to achieve this kind of thermonuclear fusion, was caused by a lack of understanding of the thermonuclear problem by the major part of the U.S. leadership and among the financial magnates. Now, in the U.S., there is a brake on these developments, despite generous financing having started. This is because other people are running the show at Livermore, instead of Nuckolls, and they are not his equal.

Tennenbaum: Let me play the role of "the devil's advocate." Why are you so absolutely convinced about the feasibility of inertial fusion (or fusion microexplosions)? At first glance, results obtained in the period 1975-95 do not inspire great confidence. But even if deuterium-tritium (D-T) fusion were realized in some form, there would still remain the problem of radioactivity produced by the neutrons, which are a byproduct of the deuterium-tritium reaction. On the other hand, the more interesting, "clean" form of thermonuclear power, based on a fuel consisting of deuterium and helium-3 (D-^3He), is evidently much more difficult to achieve.

Belakogne: You are absolutely justified in feeling doubts about the near-term *commercial* utilization of microexplosion fusion. What is more, from the standpoint of so-called common sense, you can also express justified doubts about the feasibility in the immediate 10-15 years ahead of even a demonstration engineering experiment, in which the energy released by the microexplosion, matches the energy received by the "driver" of the thermonuclear pellet.

However, the skeptical point of view was significantly undermined by the results of the American experiment series "Halite-Centurion" around 1986, which modelled (simulated) the effect of future driver systems (whose development still presents difficulties) on the aforementioned pellet, by using specially filtered radiation produced by the underground explosion of a nuclear warhead-type device. . . .

Tennenbaum: Very little has been written about the Halite-Centurion program, at least in the open literature. From your standpoint, what were the most important features of those experiments? And what do they signify for the future?

Belakogne: The veil of secrecy over the American investigations was partly lifted on March 21, 1988, when the scientific correspondent of the newspaper *New York Times,* William Broad, published an article on the success of the super-secret program Halite-Centurion, conducted at the Nevada nuclear test site by the two most authoritative national laboratories of the United States, the Lawrence Livermore and Los Alamos laboratories.

The still sparse information permits us, with a sufficient amount of confidence, to speak about a new direction *in the use of nuclear tests,* successfully utilized by the Americans to *make the breakthrough into the energy technology of the 21st century.* The Americans succeeded in creating a miniature hydrogen bomb explosion, whose energy was somewhere between 1,000 and 10,000 megajoules—a million times less than the energy of a real thermonuclear warhead. It is possible to completely contain such an explosion inside a reaction chamber, whose (minimal) size is comparable to a steam locomotive boiler. Detonating up to 100 such "microbombs" per second in a reaction chamber would provide an economical source of electrical and thermal energy. It would be possible to place such a reactor on a ship, a space vehicle, or even an airplane (a big one, however, whose mass would certainly be not less than 2,000 tons).

The American specialists succeeded in directing part of the radiation from a nuclear warhead detonation into a specially designed container, in the middle of which was suspended a sophisticated target-pellet containing several tens of micrograms of thermonuclear fuel (a mixture of heavy isotopes of hydrogen—deuterium and tritium). The energy content of this fuel exceeds that of oil by several million times.

The burst of radiation, emitted by the explosion of the nuclear device, heated the walls of the special container, irradiating the surface of the thermonuclear pellet during a very short interval of time, but with such an enormous intensity, that the surface of the pellet was evaporated in an explosive manner, and the pellet itself was "imploded" due to the reactive pressure of the evaporated layer—a pressure reaching 100 million atmospheres. In other words, incredible reactive forces are generated.

(To be more precise, I should add, that the action of this reactive, compressing force must be "shaped" in such a way as to ensure that the beginning shock is not too sharp. Programming the compression in this way ensures a "low-entropy" regime for reaching supercompression of the thermonuclear fuel, which, in practical terms, means economizing the work of compression, and thereby ensuring a higher net efficiency for the energy-producing process as a whole.)

Some crucial aspects of the construction of the target-pellet are top-secret. But it is necessary to compress the thermonuclear fuel, by the implosion of the pellet, to a density of not less than 50-100 grams per cubic centimeter. Like at the center of the Sun! But compared with the Sun, the temperature required for ignition of the thermonuclear fuel is higher—tens of millions of degrees. In fact, the fuel is heated to a peak temperature of hundreds of millions of degrees Kelvin.

Creating the microexplosion of their tritium-deuterium pellet, the Americans provided the experimental demonstration in 1986, that useful thermonuclear power can be generated from this supercompressed fuel.

I have almost no doubts, that the Americans did not stop with this success in utilizing the fuel (which, due to the presence of tritium, is radioactive), but that they are also trying—or have already succeeded—to achieve compression and heating of the more interesting fuel, consisting of deuterium and helium-3. (As fantastic as it might sound, the Americans are seriously planning to import helium-3 from the Moon as a commercial venture. This would be possible, using our colossal Energia space rocket, the best in the world.)

The Halite-Centurion test in Nevada was an historic opportunity for the Americans. . . . Having obtained macroexplosions by means of nuclear detonations, they are preparing to replace the latter by compact laser or other power sources. This new energy technology will be used on the Earth, in plants producing energy and energy-intensive materials; in the air and at sea, to power various transport systems; and in space, in propulsion systems for interplanetary missions. It is also not to be excluded as a power source for "Star Wars.". . .

So, while not denying the existence of ignoramuses and cheaters, I insist on the practicability in principle of inertial confinement fusion in the next 10-15 years. As for its industrial usefulness (replacing coal and oil energy generation, let's say), that depends too much on the political and economic decisions of governments. . . .

Tennenbaum: Of which governments?

Belakogne: The governments of really or potentially powerful states. By the year 2010 these will be (listed by the degree of their potential and importance for the given problem): the U.S.A., Japan, the Federal Republic of Germany (or the European Union as a whole), France, Russia, England, Sweden, Ukraine, India, Australia, China, Israel, Italy. The authorities' decision will depend, of course, on their competence in energy politics and their ability to risk investing resources on the scale of $10-30 billion over 15-20 years. But there was a comparable risk in aviation also, and, even more so, in space programs, and it turned out to more than justify itself in the 20th century. I would stress here, that in taking on the risk, competent fanatics played a historic role. . .

By the way, in popularized economic discussions about fusion, there is a good deal of talk about its fuel being virtually free—that refers to deuterium, of which "there are inexhaustible supplies in the oceans." Indeed, the price of deuterium in 1983 was 20¢ per gram, which is approximately equivalent to an energy value of 1¢ for 10,000 megajoules of "raw" thermonuclear energy—on the condition that pure deuterium can be used by itself alone to "feed" thermonuclear reactors (about which there remain well-founded doubts). First-generation reactors need tritium in order to "burn" deuterium—which also means producing neutron radiation—or otherwise the non-radioactive light isotope of helium can be used, helium-3. But, both these components of thermonuclear fuel have a manufacturing cost (U.S.A., 1983) of around $10,000 per gram. That would bring the "raw" costs of energy to nearly 1¢ for 100,000 joules which coincides with, in an amusing enough manner, the cost of "raw" energy of modern petroleum. But a much higher cost is forecast for the extraction of thermonuclear energy, than of petroleum energy.

We can expect a drastic reduction of the cost of the raw material of thermonuclear energy of the future—helium-3—on the basis of importing this isotope from the Moon. This has been shown by recent calculations made by American specialists (Kulchinsky and Schmidt). For this purpose, there is probably nothing more suitable than the space transport system designed under the leadership of V.P. Gloushko on the basis of the Energia rocket—assuming economical methods of reconstruction of this system.

Tennenbaum: But besides inertial fusion there exist other approaches, such as: magnetic fusion, combinations of magnetic and inertial fusion, hypervelocity impact fusion (as a separate form of inertial fusion), cold fusion, etc. Some of these might give better results than inertial confinement fusion by lasers, or by particle beams.

Belakogne: I don't see the fundamental difference between "inertial" and "impact" fusion; both produce microexplosions and both are based on the key idea of superdense compression of fuel immediately prior to the microexplosion. The attainment of superhigh density is precisely the key idea leading to the realization of both macro- and micro-thermonuclear explosions. This is the invention of Ulam, which was attributed evidently and not-so-evidently to Teller, although Ulam, having proposed this idea in deepest secrecy in 1950, probably knew about the experiments of German scientists, who began similar work not later than 1942. . . . By the way, the origins of analogous experiments in the U.S.S.R. is a big puzzle. A. Sakharov never declared his explicit authorship of this idea. . . . There are also references in the newer historical literature, which point to the conclusion, that the key idea was transmitted from the U.S.A. to the U.S.S.R., probably by no one other than George Gamow . . . , but this subject is for another discussion. In any case, for microexplosions as well as macroexplosions, superdense compression is the key idea, which up to 1971 was worked on secretly at Livermore and at Los Alamos. Then, at the 1972 Montreal Conference, it was made public by Edward Teller. This was a revelation for our thermonuclear scientists—beginning with Basov's group. . . . The point is, that the typical energy of a fusion microexplosion is given by

$$y_{joules} \cong 10^{13}/\rho^2_{DT} \cong 10^{15}/\rho^2_{D^3He}$$

for which it is necessary to achieve the compression up to the density:

$$\rho \approx 100\text{-}1000 g/cm^3$$

Otherwise we obtain not a micro-, but a macroexplosion, considering the dividing-line between them to be 1,000 megajoules.

Incidentally, microexplosions solve not only the energy problem, but also the problem of *power,* insofar as a fusion microexplosion produces a pulse of the order of:

$$\dot{y}_{watt} \approx 10^{19}\rho M$$

where M is the mass of the burned fuel in grams.

If the military are interested in this power for the pumping of super-lasers for the SDI, I personally am interested to design a generator of gravitational waves, even as far as creating a *gravisor*—the gravitational analog of a laser, but with rays of gravitons rather than photons, although the ray can also be a mixture. . . .

Tennenbaum: I am aware of these things, although it is useful for our readers to recall them here. But you avoided my main question: Why do you consider fusion microexplosions to be not only feasible in *principle,* as an energy source, but actually as a *near-term perspective?* Furthermore, what have you done yourself, as a physicist and engineer, to bring on the

While not denying the existence of ignoramuses and cheaters, I insist on the practicability in principle of inertial confinement fusion in the next 10-15 years. As for its industrial usefulness, that depends too much on the political and economic decisions of governments.

era of fusion microexplosions? What are your qualifications to make judgments concerning these matters?

Belakogne: My own efforts had some results. At the time when superdense compression was a tightly kept secret, I independently came to the idea in 1962, working in the area of gas dynamics of flight and of detonations. In 1968 I succeeded to defend a dissertation thesis at the Keldish Applied Mathematics Institute. In the presence of Ya. B. Zel'dovich, who had participated in the realization of supercompression for the Soviet hydrogen bomb (as a colleague of Sakharov), I spoke openly about superdense compression of a thermonuclear plasma (on a rather abstract level, not a concrete scheme), thinking that I had made a completely original discovery. . . . But when Teller declassified the work at Livermore, I tried to elaborate my own compression method, which differs greatly from the Livermore scheme. I do not use a compact ready-made target-capsule, but rather a system of initially separated elements, whose simultaneous collision produces "softened" supercompression in a special kind of shock-driven thermonuclear microexplosion, which might be achieved using multi-round super-velocity rail guns or similar apparatus.

In other words, I have not simply read, listened, and accepted. I actively worked in this direction, therefore I have the basis for independent judgments. . . .

Tennenbaum: Now I would like to hear your judgment concerning the history of the various prognoses of the realization of inertial confinement fusion.

Belakogne: My personal interest, generally speaking, has been in the "scenario" type of forecasting, whose logic is of the form: "if . . . then." For example, concerning laser fusion: "If the laser impulse has such-and-such energy/power, and the form of the impulse is such-and-such, then the amount of compression will be *X* and the energy of the microexplosion will be *Y*." In 1972 several groups proclaimed the near-term realization of inertial confinement fusion, or more precisely, of the proof of its "physical" achievement, already by 1974-76. This forecast turned out to be a complete fiasco. . . . I think, that these 1972 forecasts were mainly made in order to assure a large funding for inertial confinement fusion. The authors of such forecasts were leading physicists: Nuckolls, Brueckner, Basov. . . . But in fact a more precise, secret forecast (scenario!) had been produced *10 years earlier,* by one of the few pioneers of thermonuclear fusion, Ray Kidder of Livermore.

Tennenbaum: What is the nature of the various prognoses? And what is your own forecast for the realization and application of inertial fusion?

Belakogne: The history of the forecasts spans more than 20 years. Kidder's forecast was—at the time he made it—not very optimistic. His estimate was: To reach the critical regime of "breakeven," one would need 100 kilojoules at a laser wavelength of 0.69 micrometers with a radiation intensity on the target of $5 \times 10^{14}/cm^2$. I think that time will confirm the truth of his estimate by no later than the year 2005. Or even three to four years earlier, I hope. Kidder's forecast was in 1962. And in 1973 Lowell Wood told me a lot of John Nuckolls's ideas of laser fusion. Up to the time Nuckolls was later working on weapons, not on the peaceful use of the atom.

It is not superfluous to note, that laser fusion was related to classified work, and for that reason, in the U.S.A., they kept it a secret for 10 years. The hope was to make, on the basis of laser fusion, a "clean" hydrogen bomb (without uranium or plutonium), and also to use the neutron burst from a laser fusion pellet for breeding plutonium—as atomic ignition material—under conditions, which practically do not permit international control. . .

In any case, Wood managed (around 1968-69) to convince Nuckolls, that one could ignite a "bare" fuel pellet (without a liner) with a laser pulse of maximum 10 kilojoules, compressing the fuel up to a density of $1 kg/cm^3$. And they began to "push Kidder aside.". . .

Meanwhile KMS, up to that time the only *private* firm in the world involved in fusion, announced to its stockholders that already by Dec. 31, 1973, a pellet would be ignited by no more than 1 kilojoule. . . . Beginning in 1976, Livermore came to the old forecast of Kidder: *not less than 100 kilojoules.* . . . And Lowell Wood came to insist on a date of around 1980—*under the condition,* that the fusion scientists would be given as much money, as they could spend. Wood promised the creation, by 1990-91, of an electric power station based on fusion microexplosions with a net power output of 300 megawatts. They didn't give him the billions which he demanded, and now he has the right to blame the powers that be. It is not to be excluded, that he is right, although the task probably would be accomplished not by Wood, but by Kidder.

. . . If I were given three times less money, then by my method (compression of the "slamming the book shut" type), this more economical form of fusion could be achieved in 10 years for a cost of $2 billion. . . .

Tennenbaum: Leaving your claims aside, what projections would you make on the most likely course of events for the realization of fusion microexplosions as a source of energy?
Belakogne: My projection at present is the following:

In 2003-06, the final decision will be made on the type of driver for an inertial-confinement fusion demonstration plant and propulsion. Assuming a $10-12 billion crash program, the required driver would be finished by 2010-12. A surface facility to demonstrate inertial confinement fusion for *space* propulsion would be finished by 2012-15. The first flight of a fusion-powered aeroplane and/or spacecraft would come in 2015-20, by D-^{3}He.

In terms of the most likely system to drive inertial confinement fusion for propulsion, I would assign the probabilities as follows: non-solid-state laser 75%; light ion beam 15%, railgun accelerators of macroparticles 5%; solid-state lasers 2.5%; other systems 2.5%.

Tennenbaum: How do you see the long-term implications of fusion microexplosions, as the basis of a far-reaching technological revolution?

Belakogne: Superdense compression, now being developed for D-T fusion, in the future will have many other applications, which cannot be predicted now, because it means a new degree of freedom in technology. Furthermore, it makes it possible *in principle* to increase the efficiency of energy systems to practically 100%, and at the same time to reduce the inevitable thermal loss to the environment. Also, inertial confinement fusion provides incomparably greater power, in pulsed form, than any other energy system—up to $10^{18\text{-}20}$W × 10^{-10}s. And the technology and industry of the future will need power density as much, or more, than energy itself.

The first generation of commercial power plants of the inertial fusion type will also make it possible to render harmless the dangerous radioactive isotopes produced by breeder reactors and atomic power stations: The neutrons from the microexplosions would be used to transform unwanted, dangerous isotopes into less dangerous ones, and even into isotopes which are useful and not in sufficient supply. The "transmutation" of dangerous isotopes by this method was proposed by Livermore scientists by 1978.

The technology of thermonuclear microexplosions will provide another great benefit. The present-day concept, of using conventional, chemically fueled rocket systems to send cosmonauts to Mars by a journey which would take many months—an idea which borders on sadism—will become an anachronism. Rocket propulsion systems, based on microexplosions of superdense plasma, make it possible to reach Mars in a couple of weeks, or a couple of months at the most.

This most promising application of fusion microexplosions was underlined by Andrei Dmitrievich Sakharov at our meeting on March 16, 1988. He promised me, a few months before his somewhat mysterious death, to give a more detailed interview for publication on this problem; but her saintly reverence Yelena Bonner screamed at me, and then at him, and her aggressive opposition destroyed the possibility of learning about the detailed views of this unique physicist, concerning the best energy of the future.

Tennenbaum: Finally, what about matter-antimatter reactions as a long-term possibility for space propulsion?
Belakogne: Power generation by annihilation remains a subject of speculation, both trivial or non-trivial, depending on the scientific level of the authors of the speculation.

But let's look at the cost of antimatter, and give some general indications on the possibilities of its utilization for power generation.

According to a 1988 estimate (a conference in Utah), the production of anti-hydrogen (with an anti-proton for a nucleus), by currently feasible procedures, costs $100 billion per gram, i.e., the "raw" energy for annihilation is 1¢ for 10 joules—a "mere" 10,000 times more expensive than the current cost level for "raw" thermonuclear energy from helium-

3. This estimate assumes that complete annihilation is achieved, a result which, however, is technically nearly impossible because of the Alfvén effect, which impedes the complete mutual annihilation of matter and antimatter. The exception would be for the case—extremely difficult to achieve—of superdense compression of the antimatter in special target-pellets, analogous to the ones used in inertial confinement fusion.

The accumulation of antimatter in magnetic vacuum traps with preliminary supercooling (in order to remove heat disturbances due to excessive fluctuations of the velocity of the anti-particles) is possible in principle and has been calculated in some detail. In 1963, I suggested a laser-like method for utilization of antimatter as the coherent power source for prospective photon rockets, which are unlikely to be created before the period 2050-70. (This method was proposed for consideration to A.M. Lyulk, general designer of aviation turbine engines, in December 1963. Later I recalled this proposal in an article in 1970 and in various conference presentations, such as Kaluga 84 and 86.)

On the backdrop of this information about antimatter, it was a big surprise to see the report in the magazine *Aviation Week and Space Technology* from March 21, 1988, on the U.S. Air Force forecast that antimatter could be utilized for some rocket propulsion in space, practically at the *beginning* of the 21st century.

My position on this is somewhat unusual:

I think the Americans undertook a conscious act of disinformation, exploiting the readers' trust in this usually very well-informed, prestigious magazine, whose reports are reprinted by the *New York Times* and other very widely read press outlets. They needed such disinformation to produce "white noise," to keep people from paying proper attention to the incomparably more realistic announcement in the *New York Times*—which was corroborated by authoritative specialists much later—about the successful Halite-Centurion program at the strongest U.S. research centers, the Livermore and Los Alamos labs. In 1986 they had already succeeded in obtaining compressions up to 100 g/cm^3 of D-T pellets, which are analogous to those that will be used with laser or ion beams in the future.

It is logical to expect that they would be working on compression not only of D-T capsules, but also the more promising D-^{3}He capsules, to densities on the order of 1,000 g/cm^3. The above-mentioned disinformation achieved its goal in some sense: In our scientific and popular science press, and even more so in the political press, this report about the *real* most important success of the Americans did not get the coverage it deserved, and consequently was not discussed as it should have been.

Meanwhile, the United States goes on to the global monopoly in the future thermonuclear energetics. . . .