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HIGH POWER LASER SCIENCE AND ENGINEERING

INTERVIEW: 10TH ANNIVERSARY OF HPLSE

An interview with Vladimir Tikhonchuk

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He obtained Ph.D. and doctor of Science degrees from the P. N. Lebedev Physics Institute, Russian Academy of Sciences in Moscow. He is a senior member of the Institut Universitaire de France, Edward Teller Awardee from the American Nuclear Society, Divisional Associate Editor for *Physical Review Letters*, advisory board member of the journal *Matter and Radiation at Extremes* (MRE) and board member of the Division of Plasma Physics of the European Physical Society. He has supervised more than 30 graduate students and postdoctoral fellows and co-authored more than 500 peer-reviewed papers.

Note**:** *In the following content, 'Tikhonchuk' stands for Prof. Vladimir Tikhonchuk, and 'Zhu' stands for Dr. Ping Zhu.*

Zhu: Could you comment on the NIF's recent breakthrough in laser fusion ignition?

Tikhonchuk: This is a real breakthrough event for me and the community as well. My career started exactly at the same time when the first articles on ICF were published. One article was published by people from my home institute in Moscow. Another one in the United States, by a group from Lawrence Livermore National Laboratory (LLNL). We waited for 50 years to come to this milestone of ignition. But it is only a milestone, not a solution to the problem. The last 10 years were difficult for the ICF community, and we lost many young scientists because some people made over-promising statements about how quickly the ignition will be obtained. Unfortunately, they did not deliver the results in time. With fusion, it has happened like that already many

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times; it is not the first time and probably not the last time that the promise does not become reality. The problem is very complicated and challenging. But I appreciate very much the courage and the persuasive activity of our colleagues in LLNL, who made a big step forward during these 10 years of hard work and complicated life. In fact, they achieved this promise of ignition, although with a delay of 10 years. It was certainly very difficult to live these years, but this breakthrough immediately opened the door for much broader development.

There is a lot of skepticism around that achievement. Some people are saying: 'Well, they produced 1 MJ or 3 MJ of fusion energy, but compare how much energy is invested in the laser? 300 MJ! So, it's peanuts,' 'How often do they produce this energy?' So, there are many challenges that we will discuss later. But this is a major milestone; it demonstrates that, indeed, with a laser, you can achieve ignition. I am pretty sure that the next breakthrough will come from NIF in less than one year: they will achieve a higher energy release; there is no doubt about that. Certainly, the approach they use may not be optimal, but it is the most reliable today. I really appreciate this breakthrough very much and expect that this event will produce a lot of activities in the U.S., Europe and all over the world. I hope it will stay in the news for a certain amount of time.

Zhu: What are the major challenges in laser fusion research, and what scientific and technical issues are urgent to tackle currently?

Tikhonchuk: This question I can speak the whole hour and even more! There are so many challenges that you cannot numerate them today. The first challenge for ICF is the energy source to demonstrate ignition with repeatability and robustness. That means you need not to wait one year between one successful shot and another. You should be able to do it for at least a few times a day or an hour, and this is what we call robustness. This needs to be done with different approaches, which will open the ways for producing energy. Today, what we are compensating is just the energy of the laser, but what we really need is to compensate for energy from the wall plug, so we need to multiply the gain at least by a factor of a hundred. The target design should be much simpler because if you would like to produce energy, you need to shoot at least one time per second, maybe more, maybe less, depending on the applications. I cannot predict what it will be, but certainly, when you produce these targets in such quantities, they should be sufficiently simple, cheap and reliable. This is one of the challenges from the point of view of the physics of laser fusion. This is the physics with which we will be working in the next 5 or 10 years.

In addition, there are also technical level challenges; first of all, lasers. The laser is a unique driver because one can concentrate the photons in such a small volume that it produces all these marvelous things, such as implosions, heating and so on. But the high-power lasers, which we are using for publishing articles in your journal, are not reliable. They are shooting rarely: NIF produces 500 useful shots per year. In France, LMJ produces 40 useful shots per year. We are far away from one shot per second, which we are looking for. We need to go from one successful shot per year to lasers that can shoot 24 hours per day, 7 days a week. It is impossible to change the optics each day or each hour. So, fighting optical damage may not be such a scientific challenge because we know how to do that, but it is a very significant technical challenge.

Related to this one is also the choice of wavelength. It is an open question in terms of energy production; there are different possibilities. The most reliable are the solid-state lasers based on glasses. The third harmonic of Nd laser 3ω (351 nm) is the option that was chosen because we cannot use the 4ω (263 nm), which would quickly destroy your optics, or 2ω (527 nm), which would produce some undesirable processes such as parametric instabilities. 3ω gives you an acceptable balance between these two extremes, but 3ω driver will not be operational one shot per second, the optics will not withstand it. In turn, if you stay with a glass laser, it will probably be 2ω. This is what we consider in Europe. It is a challenge even to operate these 2ω lasers and a challenge for scientists to make use of these 2ω photons. Then there are excimer lasers, which are good candidates and could be quite efficient. However, excimer lasers have a very complicated structure and face the problem of the extraction of so much energy from gas media, which has a very low density.

There are challenges for lasers, and then there are technical challenges for the reactor. We do not have a solution today for the material for the first wall of the reactor, which is common for magnetic confinement fusion. For me personally, the materials for optics and reactors are the biggest challenges. Honestly, I do not know how to solve these problems. In fission nuclear reactors, people know how to deal with material aging. The neutrons have much lower energy, and the containers containing the fissile materials that are damaged by the neutrons can be replaced quite often, say, once a month. In fusion, the neutrons are more energetic and damaging; in all the solutions we have today, the first wall materials withstand less than one month of operation. But there is no such option as a once-a-month replacement of the reactor chamber. It is impossible, so we need to find other solutions here. This is a very attractive domain of research.

Zhu: What do you think the future laser fusion driver will be like, and what will its key features be?

Tikhonchuk: As I already gave you a hint in my previous response, honestly, I do not know. Probably, the first version of the laser fusion driver will be a solid-state laser if everything goes as we are expecting now. Solid-state laser with a 2ω green light is the most technically developed option. It is sufficient for building the elementary module. It will probably deliver 200 joules or 1–2 kilojoules, somewhere in this range. It will be possible to produce such a module in the next couple of years, and I am pretty sure that it will be done in a very short time scale. We will produce a module that will be operational, not with a Hz repetition rate, but in a minute time scale with a flash-lamp pumping because diode pumping is too expensive now. But these will be units that we can build as many as we need. For me, the nearest future with a laser driver is a solid-state laser with 2ω.

The lasers operating at a repetition rate of a few minutes are key features for making the next step towards fusion energy; I see it in three steps. First, it operates on the minute repetition rate with a conventional but intelligent flash-lamp pumping. This is the first step. The next step will be diode pumping with a repetition rate of the order of one shot per second or more. This is not only my personal vision. It is the vision that we are sharing with our colleagues. But our project today is not going to the commercial level. It goes to the level of the demonstration of the demo reactor, where the major features are demonstrated and major components are developed and tested. This will open the next step for technological improvements and commercialization. Our responsibility as scientists and engineers is to develop this scientific and technical background from where commercial energy can be developed. And then maybe other lasers will come, maybe excimer or fiber lasers will finally make it work better. Fiber lasers, which are operational now, are quite reliable, but they are of low power. We are talking about lasers delivering a large amount of energy and very much about power and efficiency.

Zhu: What is your opinion on inertial fusion energy?

Tikhonchuk: You know that I'm personally optimistic, and I think this is an interesting and needed option. We may compare the two solutions, either magnetic confinement or inertial confinement. Magnetic confinement is limited by the intensity of the magnetic field that one can produce. Moreover, the magnetic field is created with gigantic superconducting coils. In magnetic confinement fusion, you need to combine very cold coils, creating the magnetic field with superconducting wires and a very strong energy flux coming from a very hot plasma. If you have a chance to see how the magnetic fusion device is constructed, you will appreciate the complexity of this intrinsic combination of hot and cold; it creates strong mechanical and thermal constraints. In the ICF, we are lucky because we can separate the laser and the reactor chamber. There is a connection between these two, but separate, modular structures give much more space for engineering.

Another important issue for magnetic confinement fusion is that it is limited in terms of the minimum energy that each unit can produce. We are talking about GW power station; the bigger is the better for magnetic fusion. For inertial fusion, it may be quite the opposite; we may eventually arrive at a unit of 100 MW or so, which could be much more compact, cheaper and capable of producing the energy where it is needed. The major limit is the size of the chamber, which is limited by the energy flux on the wall. We are talking about the gigawatt level. If the chamber is small, the energy flux will be very big. This is the problem of material, which I was talking about; this is the big challenge. If we were capable of designing materials resisting high fluxes, we would be able to make a smaller chamber, and the reactor would be much cheaper.

So, I do see the potential inertial fusion for energy production, but it is complicated and very challenging. You know, the combustion engine was invented more than a hundred years ago, and during this time, it made remarkable progress. Only now it is partially replaced by an electrical engine. So, the inertial fusion engine will evolve with time.

Zhu: Could you comment on the ultra-intense laser development and application? And what possible contributions could be made to the laser fusion research?

Tikhonchuk: It's a little bit more complicated for me because, as you know, Europe is pioneering in ultrashort-pulse lasers, but we need to advance nanosecond lasers, too. Professor Gérard Mourou, who invented these ultra-short-pulse lasers, has made a lot of efforts to promote them worldwide. I know him quite well, and his vision is to get the highest power possible. We are now talking about petawatts (PW): 10 PW lasers are coming into the physics research, and the next step, 100 PW laser system, is under construction here in China. But we are achieving this extremely high power because of a short pulse duration; the energy is limited in all these machines. When you are reducing the pulse duration below one picosecond, the laser interacts with light particles: electrons, positrons and photons, maybe mesons. The physics related directly to ultrashort pulse lasers is called quantum electrodynamics. It is an interesting physics, and there are many challenging questions around it. But when we are talking about inertial fusion, we need to move heavy particles, the ions. Because only the fusion of heavy particles, isotopes of hydrogen, produces energy, in that sense, the short-pulse lasers are not very useful for inertial fusion. Though they cannot be used for producing energy, the scheme of fast ignition, which originated 25 years ago, proposes to use energetic electrons or protons produced with ultrashort lasers. There are several groups that are working on the problems related to fast ignition, and they need ultrashort and high-power lasers.

In my vision, short-pulse lasers are more useful for the creation of secondary sources of energetic particles. In the context of inertial fusion, we need to develop high-performing diagnostics for which ultrashort lasers are indispensable. Without diagnostics, we are completely blind: we do not know where we are going and what we are doing. This was the problem of NIF 10 years ago when the facility was not sufficiently equipped with appropriate diagnostics. During these 10 years, the NIF scientists and engineers developed many high-performance diagnostics, and these allowed them to tune the laser fusion process. So, it is completely indispensable to have short-pulse lasers in our toolbox. They will not, from my point of view, provide the first demonstration of ignition because fast ignition is technically much more challenging and complicated compared to central spot ignition. For me, the short-pulse, high-power laser development is complementary to high-energy lasers, and they will be indispensable for diagnostic purposes.

Zhu: Would you share your vision regarding the future of high-power laser and physics development? And what practical applications will be spun off or even realized?

Tikhonchuk: The technical progress is so fast that it is difficult to predict what will happen 100 years from now. But just looking back, you can see that the 20th century was a century of electronics, even the second half of the century, because electronics appeared at the end of the [19]40s and achieved maturity in 30 or 40 years. In my view, the 21st century is a century of optics and optics-based technology. All kinds of optical instruments and processes are constantly being created everywhere, and this new technology may replace many things. So, I think laser is the word which probably most well defines the century. What concerns the extremely high-power lasers is more difficult to say. The companies producing lasers are more interested in increasing the repetition rate than the power since there is a constantly growing market for laser processing technologies. High-power and high-energy lasers will lead to changes in many fields, including laser processing. Initial fusion certainly is one of the domains that creates the demand for their development. If we succeed in launching a program for initial fusion energy, it will promote high-power and high-energy lasers.

Another promising domain of high-power laser applications is the creation of secondary sources of high-energy particles. It will make a lot of good changes. There are many promising applications, such as the radiography of opaque objects, laser-driven sources for medical diagnostics and treatment and the development of high-power neutron sources, which some private companies bet on. The high-power lasers would produce neutrons or high-energy photons using a compact particle accelerator. Physicists need high-power lasers, too. So, one cannot stop the development of technology. Still, the question is how to equilibrate the best applications going to the society directly through private companies and university groups, and larger scale projects like fusion energy, which need a coordinated development of science and technology on a large scale, national or international.

Zhu: Why did you choose academic work as your career path? What inspired you to engage in high energy density physics research?

Tikhonchuk: An academic career comes with a natural curiosity. I would recommend all the younger generation: if you are curious, try to develop your curiosity, and an academic career will give you such a possibility. If you are more interested in applications, go to engineering, it is also a very interesting domain where you can demonstrate yourself and promote yourself very well. But for myself, I am just curious, and I have had this curiosity throughout my life. This may distract me when I am doing several things in parallel. I like to do things on a small scale, nonlinear optics, and we are doing quite interesting things here. But I also like high energy density physics with the mission of energy production. Both of them are interesting, and I share my time between several projects in parallel. I was not specially designing myself for that. I finished my university 52 years ago, and at that time, lasers were created, and people were trying to do with lasers whatever they could. It was a great idea to combine laser with nuclear reactions, which came from academician Basov, the director of the institute where I started my academic career. He and his colleagues developed this idea and presented it in 1971 at a conference in the United States. In 1972, John Nuckolls, with his colleagues, published the proposal of ICF, and the article of Basov was published in the proceedings of this conference at the same time. At the same time, France also applied for patents on laser fusion energy production. Concerning myself, I completed my master's thesis exactly in 1971. With the director of my thesis, Professor Silin, we were working on parametric stabilities driven by electromagnetic waves. It was quite natural that Basov appealed to Silin when he read in the paper that parametric instabilities could create issues for ICF. So, laser people came to us and asked, would we be interested in working on not the microwaves but the lasers? This is how it came, and my Ph.D. thesis was related to the processes of nonlinear laser interaction with plasma. High energy density physics appeared much later; at that time, we called it just laser–plasma interaction. But step by step, we are going in the direction of laser fusion. Just two years after these two seminal publications, we already had eight beam lasers in our institute, and we started to see what kind of instabilities it would produce. This is how inertial fusion and high energy density physics come into my life.

Zhu: As you also mentioned about curiosity, from your personal experience, how do you maintain academic passion and creativity?

Tikhonchuk: It is an interesting point; if you work on the same project for a long period of time, sooner or later, it will get annoying. Because you already know what you are doing, you are repeating the small steps. This will not help to develop your curiosity. What I am doing in my life, and it happened many times (maybe three or four times at least), is changing the subject of research. Do not jump into the complete unknown because then you will need to start from zero, which is not very efficient, but go with your knowledge and your background to something new. For me, it was just a play between different applications of the laser. We started, as I said, with studies of parametric instabilities in laser–plasma interaction. Then, with my neighbor colleagues working on nonlinear optics, we started the development of optics of photorefractive crystals. It is a different physics, but the approach is similar because it is still nonlinear optics. Then I returned back and came to France to start to work on inertial fusion in a broader sense, not only on laser–plasma interaction. This was, again, a new turn in my career. Then, once, I read a PRL article that was wrong, and I wrote a comment. I struggled for almost one year to publish it because the authors did not like it. Finally, it was published, but two years later, one of my colleagues called me and said, 'You published that this is impossible, and we are seeing it.' Together, we found the answer. It was quite interesting. Since that time, I have collaborated quite efficiently with that group on nonlinear optics, which has nothing to do with high energy density physics but has other interesting applications.

So, my advice on how to maintain passion and creativity is to change your research subject from time to time. Each time you are going to a new domain or new area, you need to work hard to achieve some recognition from your colleagues. But do not abandon what you were doing before, which is still useful. By moving between different domains, your creativity will increase because of the cross-fertilization of your knowledge from one domain to another. It is an important part of the research. You need to find some new turns, some novelty in the domain, each time you publish an article. Certainly, in each paper, you need to describe what things have already been done and how you approach it. But if there is no originality, there is no article. We need, first of all, to have this creativity, and this creativity maintains our career.

Zhu: What is your perspective on the education and workforce situation in our community?

Tikhonchuk: As a professor, this is my major domain. I was teaching in France at Bordeaux University for 20 years. It was not myself who started this education in high energy density physics in France. It was another colleague, Jean Jacquinot, who came to me and told me that he is mandated by the French Atomic Energy Commission to create a specific education in nuclear fusion in France. I was quite skeptical. Universities have their own interests, and creating something in common between several universities is a very difficult task. But Jean is a very motivated person. The motivation was that there were two big projects in fusion at that time in France. The ITER project in magnetic fusion was started exactly at the same time as the LMJ project in inertial fusion. People in the Atomic Energy Commission understood that the workforce is the key. These are two long projects that need continuous training, transfer of knowledge and a motivated workforce. We were fortunate in France to have these two branches of fusion coming together. We worked together for a couple of years to create this national program for education in fusion. It was started in 2006 with six or seven universities and high schools in France. We created a common program and started moving the students and the professors around. We had a joint committee that more or less coordinated this activity. All that worked quite well, and during the first 10 years of this program, we produced more than 300 master students, and probably 80% of them work in the scientific domain. I meet our students everywhere.

So, I think that education and training are really very important questions. If you would like to promote inertial fusion energy, you need to create an international basis for education on the master's level or maybe on the Ph.D. level. Master level maybe is more important, because we will need not only researchers but also many engineers. If we succeed in creating such a program on an international level, it will be a common basis for the applications in materials, lasers, plasmas, applied mathematics and problems of safety and security. There are many issues that are interrelated, and people who are coming in need to know the elements of everything; this is the only way to coordinate such a large multi-disciplinary project. For this reason, we are now trying to create a common educational program in inertial fusion in Europe. I suggest that in China, you also need to somehow coordinate the research activities in universities and institutes. It is not easy. In France, the Atomic Energy Commission facilitated this work and invested in it. When you ask universities, they are very reluctant because they have different specialties and very diversified interests. You need another research body, such as the Chinese Academy of Sciences, that may take this initiative and promote education in fusion. If you produce more students than you need, it is not bad, and they will find out that a good education guarantees employment in any case.

Zhu: Would you give some advice for the students and postdocs pursuing academic careers in our community?

Tikhonchuk: This is what I said: just be curious and ask questions; do not ask your professors what to do. When you go to a lecture, do not try to copy what the professor tells you; just think critically, ask yourself what is happening, and do you agree with the lecturer. Do not hesitate to ask questions! In my experience when I was a student, I met one really famous professor who was teaching us quantum mechanics. One day, when he was teaching the second or third lecture, he stopped and said, ‘Why don’t you ask me questions?’ Listening to silence, he threw the chalk and went away. Next time, he sent his students to teach us the rest of the course. So, this is what you need to do all the time: ask questions. When sitting at the conference, do not hesitate to ask stupid questions. Because if you are worried this question is stupid, it is not as stupid as you think. Normally, all lecturers and professors are happy to have questions. It is annoying when you are speaking to people who are looking outside or sleeping there, showing no interest in the subject. At conferences, only very few people are asking questions. I often ask questions that are not easy to respond to. But it is not because I have something against the speaker; I think it is interesting to ask questions. It is important for both you and the speaker. At least, you start understanding what this person is talking about, and this person also starts thinking about his work from a different point of view.

So, this is probably the advice. If you are interested in making an academic career, you need to be curious, and you need to ask questions. Ask questions to your colleagues, your professors and everywhere. When you ask questions, this is an activity in your brain and gives you something to respond to as well. All academic research is based on independent thinking and personal intellectual independence.

Wishes to HPLSE

Zhu: What contribution, in your opinion, [is] made [by] the journal *High Power Laser Science and Engineering* to our community?

Tikhonchuk: Our high-power laser science and engineering community started 25 years ago when the United States of America made the decision (and France followed it) to build the really big lasers, megajoule lasers. But we did not know how to build this kind of laser at that time. It was a big problem with optics damage to construct it, so we needed to build a community and knowledge. For that, you need to have some special tools – journals, which are helpful to promote knowledge in the community and increase its size because the community starts from a relatively small number of people. To attract more people to build a shared vision, you need journals like *High Power Laser Science and Engineering*. It is one of the journals which put an objective to build this community. This is its originality. If you look at the other general audience journals, which we know very well, such as *Nature*, *Nature Physics* and *Physical Review Letters*, these journals have a long history of publishing interesting papers, disseminating knowledge and making connections, but they are not dedicated to the development of specific branches. I think *High Power Laser Science and Engineering* does an excellent job of promoting science for a narrower community, with more focus on laser fusion and laser technology. That is what we need.

Overall, the idea of *High Power Laser Science and Engineering* is to build the community around the high-power lasers. Nowadays, high-power lasers are very important for inertial fusion and high energy density physics. For this, I think the journal is unique in that it focuses exactly on this domain, which has a bright future. I do believe in that. This journal brings people from different countries and motivates them to focus on this highly important subject. So, I think this is an excellent time to celebrate the 10th anniversary of this journal and its milestone for the next step of development. I wish the journal to increase in the next 10 years even more.