Shining a Light on

Laser Plasma Accelerators:

Compact, Efficient Accelerators of the Future

INTERVIEW WITH Dr. Lieselotte Obst-Huebl

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Lieselotte Obst-Huebl, PhD, *is a research scientist at the Berkeley Lab Laser Accelerator (BELLA) Center. Dr. Obst-Huebl received her PhD in Physics at Technische Universität Dresden and was awarded the Outstanding Doctoral Thesis Award by the American Physical Society (APS) for her research at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in laser-plasma acceleration of ions with PW-class lasers. Her current research focuses on high energy density science and laser-ion accelerators. In this interview, we discuss the principles and mechanics behind laser plasma accelerators (LPAs) for both electron- and ion-acceleration. We cover the challenges in using LPAs to create compact accelerators as well as the various applications of LPAs in fields ranging from radiobiology to astrophysics.*

BSJ: How would you describe your role at the BELLA Center?

LOH: I am a research scientist, which means that I have many primary responsibilities that are mostly related to high energy density science (HEDS). Indeed, the experiments we do at BELLA iP2 (interaction point 2) with very high intensity laser-plasma interactions fall within the field of HEDS. The investigation of ion acceleration and the usage of these ions for applications, such as in radiobiology, are my area of expertise. Although my primary focus is on HEDS, I also contribute to and support other experimental areas such as electron acceleration and laser science.

BSJ: In 2021, you were awarded the Outstanding Doctoral Thesis Award by the American Physical Society (APS) for your work in laser-plasma acceleration of ions with PW-class lasers. How has your doctoral research carried over to your current work at BELLA, and how has your research focus changed over time?

LOH: The main focus of my doctoral research was to develop proton- and ion-beam sources that were more efficient, both in terms of energy[1] and particle number, in comparison to conventional accelerators. The increased efficiency would theoretically open up this technology to a number of potential applications, as conventional accelerators require bigger machines and are, therefore, more costly. Now, however, my scope has broadened. I get to work more on lasers and application experiments (for example, in radiobiology). I also support user experiments; people can apply through LaserNetUS for beam-time at our experimental facility, and their proposals involve all kinds of different interesting research, such as the development of very thin films made of liquid crystals that are used as optics in plasma experiments.

BSJ: How do you define a laser plasma accelerator (LPA)? Can you walk us through the physics occuring inside an LPA, starting from the initial firing of the laser to the acceleration of particles?

LOH: The laser plasma accelerator, in its simplest form, generates beams of charged particles as a result of a

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[1] ***Specifically, proton and ion beams with several 10 MeV of energy***

very high-intensity laser interaction with a plasma. The laser pulse ionizes the material, meaning it strips the electrons off of the atoms, and creates a so-called plasma in the target. Following that, the interaction of the laser with this plasma, mainly with plasma electrons, results in charge-separation between the electron cloud and the mostly fixed ions. Because of the charge separation, you get very strong electric fields—all of this happens at an incredibly small scale. The laser focus and its resulting field structure could be anywhere between a few to 100 micrometers in diameter. This allows us to create extremely strong accelerating fields on a very small footprint, contributing to compactifying accelerators.[2]

BSJ: Can you briefly explain the wakefield acceleration technique and describe how the laser and plasma interact to accelerate subatomic particles?

LOH: When the laser pulse is sent into a gas target, the charge separation between the electrons and the ions, which I described before, happens in the form of a wave. The laser pulse pushes plasma electrons away, and after the laser pulse has passed, the electrons are re-attracted by the ions, resulting in an evolving wave structure. Then, if you inject electrons at the right phase of this wave, they can surf down the electromagnetic potential. A useful analogy is that of the surfer and a water wave. First, the movement of a boat through the water drives a wake[3] following the boat; then, if a surfer catches that wake at the right time, the surfer would descend on the gravitational potential down that wave [Fig 1]. This analogy can help one visualize the equivalent surfing effect for electrons; though, of course, the potential in both cases is different. In the plasma, it is an electromagnetic potential, whereas with the water wave, it is gravitational potential. Additionally, the scales are very different. The water wave would be meters in diameter; in the plasma, the wave is on a 1- to 100-micrometer scale.

BSJ: You mentioned that electrons must be injected at the right phase of this wave to be accelerated; how is that done? Do you shoot a separate electron beam through the existing plasma wave?

LOH: There are different ways of injecting electrons into the plasma for electron acceleration. Some research groups do exactly that: they inject a separate "trailing" or "witness bunch" at the right time. However, there are other ways of creating electrons in the wake. For example, another precise electron beam injection method is to use a separate laser that ionizes previously unionized atoms in the plasma to create an electron beam. In addition, one could also inject electrons using a density ramp, created by modifying the density profile of the gas jet. At the edge of the density ramp, electrons are "thrown into" the wake from the surrounding plasma. Notably, the different methods of injection critically influence how the beam will look in the end, so there is an entire area of research concerned with optimizing injection methods.

BSJ: Can you break down how BELLA's multistage LPA design works and how it was devised?

LOH: In laser-driven wakefield acceleration of electron beams, the laser pulse does work to create the wake in the plasma, so the laser pulse loses energy as it passes through the plasma. Eventually, the laser is depleted of all of its energy, which sets a fundamental limit on the achievable particle beam energy. Ideally, if the laser pulse did not lose any energy, we could simply elongate a single-stage accelerator to allow the laser pulse to create a larger wake and allow the electrons to surf a longer wave. However, since the laser pulse eventually loses all its energy, we can instead try to operate this wakefield in several stages. In the first stage, the electron beam is created via laser wakefield acceleration; upon exiting this stage, it enters the second stage. At the second stage—having the same gas-column set-up, just with another laser beam—the second laser pulse drives another wakefield to further accelerate ("post-accelerate") the electron bunch, after which the electron bunch moves onto the next stage, and the cycle continues. To achieve collider-relevant energies needed for particle physics research, we need a multistage LPA with 100 or so stages, each

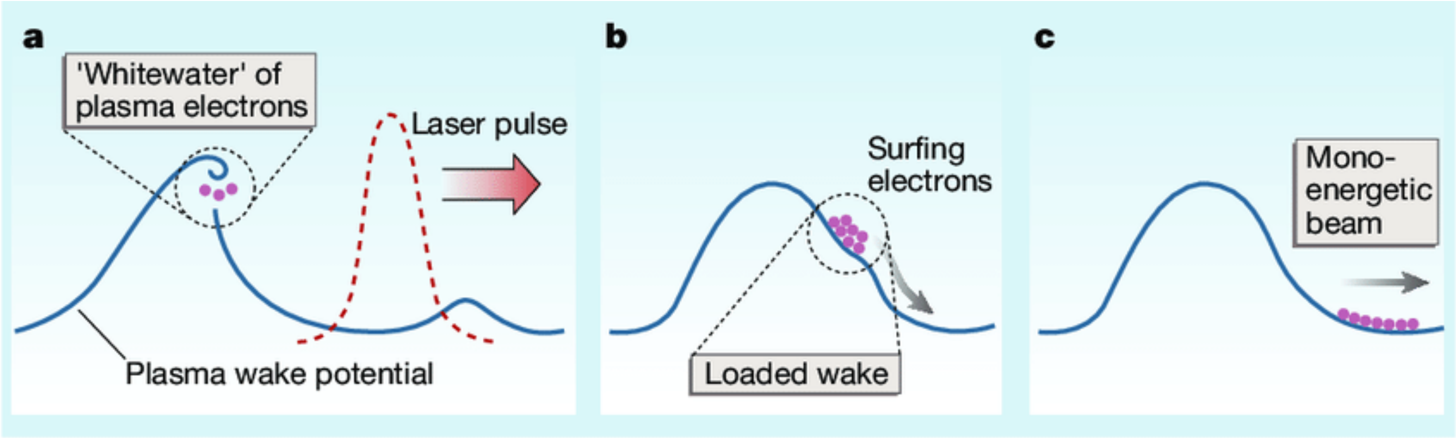

Figure 1: Surfer and Wake Analogy for Wakefield Acceleration of Electrons. The laser pulse creates a wake (the blue peak), which accelerates the plasma electrons that "surf down," turning electromagnetic potential into kinetic energy.

[2] ***While the acceleration length of conventional accelerators is on the scale of meters to kilometers, that of LPA is only micrometers to tens of centimeters.***
[3] ***A wake, in fluid dynamics, is the wave pattern on the water surface produced by a moving object.***

with a fresh laser pulse. These energies cannot be achieved in one stage since a single stage would be very inefficient and require energy on the order of 10 kJ per laser pulse, which is incredibly difficult to achieve with today's laser systems. Instead, having a multistage design of 100 stages, each with 10 J-laser pulses, is a more feasible long-term solution.

BSJ: What are the benefits of a multistage LPA design compared to previous LPA designs?

LOH: Several studies have investigated whether it is better to use a single-stage design or a couple stages. To achieve a TeV[4] electron beam, you need to operate at very low plasma density, which is a result of how the LPA works. However, using these low plasma densities results in a very low accelerating gradient, too. With such a low gradient, a kilometer-long wakefield stage would be necessary to achieve 1 TeV energies, which is contradictory to the goal of using lasers to create compact accelerators. Thus, single-stage LPA designs are unattractive due to the combination of a kilometer-long accelerating distance and high-kilojoule laser pulses. Instead, staging the acceleration is critical to achieve these TeV energies.

BSJ: Magnetic vortex acceleration (MVA), generated by the interaction of special thin, foam-like targets with the laser pulse, can produce energetic proton and ion beams. Can you break down the process of generating MVA and how it relates to the function of the LPA? Why do foam-like targets, specifically, create MVA?

LOH: Importantly, magnetic vortex acceleration (MVA) is mostly used for laser ion acceleration, not electron acceleration. For electron acceleration, we use gas targets to allow the laser pulse to propagate through the entire length of the target and drive the plasma wake. This is where our previous analogy, with a boat creating a water wave in front of the surfer, comes into play.

However, for ion acceleration, we usually use thin foil targets that have a relatively high density—basically, solid-state density. In solid-state density targets, the largest portion of the laser energy is reflected off the target like a mirror rather than absorbed into the plasma. A thin layer of plasma is created at the front surface, allowing a bit of the laser pulse to get absorbed into those electrons, but most of the laser pulse is reflected away.

An important aspect of using MVA is to absorb much more laser energy into the plasma. To achieve that, we need to lower the core density of the target; this allows the laser pulse to propagate much further into the target and interact with more electrons, which subsequently can absorb more of the laser energy. Simultaneously, the laser pulse drills into the target a very thin channel, in the center of which a portion of the electrons create a strong current. This current induces a strong toroidal magnetic field surrounding the electron current. As the laser pulse breaks through the target rear, the magnetic field suddenly expands into the vacuum. This magnetic field acts like a propeller, pushing forward ions that are in its vicinity [Fig 2]. In summary, by combining charge separation, very efficient electron heating in the target by the laser pulse, and the propulsion from the magnetic field vortex, MVA can improve ion acceleration.

Our research group has conducted a number of simulations that show that lower-density foam targets yield not only higher proton-energies, but also a lower divergence angle. Ideally, we want to minimize the divergence angle so that protons come out of the target in a parallel, small, collimated beam since such proton beams are better for applications of interest. For example, beams with a low divergence would make it easier to irradiate a sample compared to a beam of protons diverging at large angles, which would require additional capturing and focusing. Thus, reducing the divergence angle is another area of study that we have conducted simulations on; we have also started some experiments delivering 10 MeV protons to a radiobiological sample site. We are planning to extend our capabilities to deliver 30 MeV protons to a sample soon.

BSJ: In addition to the flagship BELLA PW Laser, the BELLA Center also includes a collection of laser-driven accelerators, such as the BELLA HTT, BELLA HTU, BELLA kHz-TW, and the BELLA High-Energy Fiber Acceleration System. Can you briefly describe how these lasers differ in design and function in comparison to the PW laser?

LOH: The biggest difference between these laser systems is the laser pulse power and repetition rate that they generate; these, in turn, affect the scientific goals that each pursues. The BELLA petawatt (PW) provides petawatt (10^{15} W) laser pulses, which create the highest accelerated particle-energies at the BELLA center, enabling us to accelerate electron beams up to 8 GeV. The BELLA PW laser is the workhorse laser that we mostly use for our accelerator research and high energy physics, but also for fusion energy science research. We use the BELLA PW to build potential future accelerators, investigate their applications, and pursue laser-solid interaction studies relevant for high energy density science and proton acceleration.

The BELLA HTT (Hundred Terawatt Thomson) and HTU (Hundred Terawatt Undulator) are 100 TW-class systems dedicated to generating photon beams, such as x-rays and mono-energetic gamma ray beams of 1^{-10} or 20 MeV energies. In the HTT lab, a mono-energetic gamma ray beam results from colliding the LPA beam with another laser pulse. This collision results in electrons oscillating in the electromagnetic field of the second pulse, causing those electrons to emit radiation. The mono-energetic beams from the HTT lab can increase precision and reduce the radiation dose when applied to specific applications, such as medical imaging with x-rays. Additional applications of the HTT lab include nuclear non-proliferation and electron-energy beam diagnostics.

The HTU lab is designed to investigate LPA-free electron lasers: by sending the LPA beam into an undulator, the goal is to generate coherent x-ray radiation like that created in a free electron laser. The applications include, for example, investigating ultrafast biological processes, such as protein folding and unfolding, using very high precision measurements with resolutions on the nanometer scale.

In the BELLA kHz-TW lab, we work on super-compact electron sources on the MeV energy level—significantly lower energies

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[4] ***TeV: Tera electron Volt, 10^{12} electron Volts. An electron Volt (eV) is a unit of energy equal to the work done on an electron to accelerate it through a potential difference of one volt. One TeV would be able to accelerate an electron through a potential difference of 10^{12} V.***

compared to electrons generated at the BELLA PW and HTT/HTU—but with a very high repetition rate of 1 kHz. BELLA's other experiments operate at 1 Hz or, at most, 5 Hz. Thus, the kHz-TW can achieve higher signals and accumulated current. It is specifically used for medical and ultrafast electron diffraction research.

Now, all the previously mentioned lasers are not very energy efficient in the way that wall plug power is converted to laser pulse power. To scale up these lasers to fire pulses at repetition rates in the kHz range required for certain applications is not very feasible with our current technology. Thus, we also develop new laser technology through the BELLA High Energy Fiber Lab; this project promises to further increase our laser pulse energy at a more manageable wall-plug power to achieve kHz repetition rates.

BSJ: What are the primary challenges in the current progress of BELLA's research in the development of compact lasers/LPA? How is the lab working to overcome these challenges?

LOH: There are many small challenges, but the three biggest include (1) generating high beam quality in the LPA and maintaining high beam quality throughout the beam transport and, in the case of electron LPAs, potential staging modules, (2) delivering these high beam qualities in a stable manner from shot to shot, and (3) improving the wall-plug efficiency of LPAs. High beam quality and beam stability are required for many applications, such as injecting beams into subsequent stages in multistage LPAs; wall-plug efficiency is essential for LPAs to become a cost-effective technology for future installations and applications.

The first two challenges, achieving and maintaining high beam quality, crucially depend on the quality and stability of the laser pulse. A substantial portion of our work focuses on improving our laser systems—for example, through active feedback stabilization methods. These methods allow us to track the quality of the laser pulse and, subsequently, adjust and stabilize the pulse on every shot. In fact, kHz lasers are essential for enabling active stabilization methods. With a kHz laser, creating 1000 pulses per second, it would be easier to accelerate very high-quality electron bunches at 1 Hz since there would be 999 diagnostic pulses in between each pulse used to drive the accelerator. These additional diagnostic pulses can be used to set up an active feedback loop to track and adjust the laser's performance before the next shot is launched; this tracking and adjusting can help us generate stable, high-quality electron bunches. This is in addition to the other important application of kHz lasers mentioned above, which is generating LPA beams at high repetition rates, such as 500 Hz; in that case, we could use every other pulse for active stabilization.

However, these kHz laser systems require a very high wall plug power, so we are building more efficient laser technologies, such as fiber lasers. Additionally, at the BELLA Center we have started to look into energy recovery methods to reduce the overall power consumption of LPAs.

Essentially, these three challenges are all aimed at the overarching goal to build compact and cost-effective particle colliders up to 10^{-15} TeV, based on multistage LPAs, while retaining the support of the broader public for these kinds of investments.

BSJ: The BELLA center has proposed the kBELLA initiative to build a "high intensity short pulse laser at high repetition rates" with a goal of increasing average beam power by nearly 100-fold. Can you tell us more about the current status and the near-future outlook of the kBELLA initiative? How does the lab plan to achieve these impressive beam power enhancements?

LOH: To use the LPAs for particle colliders would require the laser to fire more than 1000 times faster than it can now (i.e. > kHz compared to Hz level), as mentioned before. kBELLA is an initiative to meet this need for a higher power precision laser-plasma accelerator. It would leverage next-generation laser technology to advance plasma accelerators in this direction. One candidate for creating kHz lasers is fiber laser technology since fiber lasers are the most efficient high-power and high-repetition rate laser technology demonstrated so far. Although the laser pulse energy that can be generated from a single fiber might be limited, by combining large numbers of laser pulses in space, time, and color, we can theoretically create high-energy pulses at the kHz rate. The high-energy and high rate pulse can enable the powerful active feedback methods, as mentioned above, to stabilize the accelerator performance. kBELLA is currently in the proposal stage, so once funding is approved, we are ready to start construction.

BSJ: The paper you co-authored that was published in January of 2022, titled, "A new platform for ultra-high dose rate radiobiological research using the BELLA PW laser proton beamline," describes the FLASH effect, a type of radiotherapy that delivers ultra-high rate doses of radiation. This has been shown to more effectively target tumorous cells compared to conventional methods while limiting damage to nearby cells. Can you describe your work with laser applications in radiobiology?

LOH: At the BELLA PW we explore biological effects that take place in this ultra-high dose rate regime, specifically with protons. The proton radiation is delivered in a very short and very intense (meaning very high number of particles) burst, and we assume that the bunch length, at the moment it is created, is around a few 100 femtoseconds[5] long. Then, due to the relatively broad energy spectrum in the bunch, the particles in the bunch slightly dephase over time, yielding on the order of 1^{-10} nanosecond bunch lengths at the sample. One of the biological effects that we look at in this ultra-high dose rate regime is the so-called "FLASH effect," which has created quite a bit of excitement in the community over the past 10 years or so. Studies have shown that, when irradiating at these high dose rates, healthy tissue is spared compared to tumor tissue. Differential sparing of this degree is not observed when radiation is applied at a lower dose rate, with the same total dose applied over a longer time. In radiation therapy of tumors, usually some radiation is unavoidably applied to healthy tissue. Indeed, even though we can quite precisely target the tumor with proton radiation, there is always an entrance dose and distal-edge dose applied to the healthy tissue. This irradiation of healthy tissue can result in toxicity and inflammation, can affect the tumor treatment protocol, and can even lead to cancer in the long term. Thus, there is significant interest in reducing the radiation damage to healthy tissue.

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[5] ***Femtosecond: 10^{-15} second, equivalent to 0.3 light micrometers ("How short is a femtosecond?")***

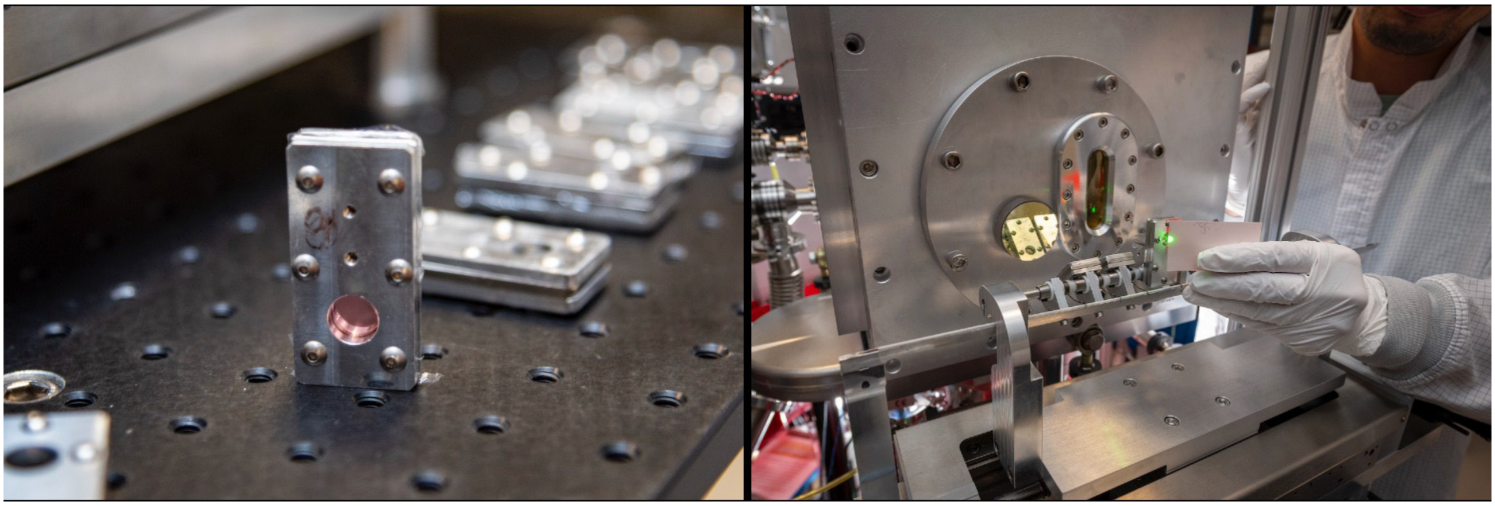

Figure 2: In vitro Experiments of FLASH Effect. A cartridge containing human cells cultured on ultra-thin mylar sheets (left) is placed on the cartridge inserter (right) prior to proton irradiation for in vitro experiments of the FLASH effect.

So far, our preliminary in vitro cell studies have shown that laser-accelerated proton irradiation can induce the differential normal tissue sparing effect in cell samples. This is the result of an experiment we conducted at the BELLA PW; we irradiated cell samples with laser accelerated protons, and we observed that the healthy cells were spared compared to the tumor cells. This effect was not observed to this degree when compared to x-ray radiation at the same dose but with a longer irradiation duration (i.e., a lower dose rate). Additionally, the tumor cells were still effectively killed in this study. This means that when using ultra-high dose rates, you would get the same degree of tumor killing while reducing the damage to healthy tissue. In fact, this January, we conducted our first in vivo experiment with live animals to investigate this effect in a living organism, and we have another experiment planned for later this year. We had never conducted live-animal experiments at BELLA before, so this was quite a change to our normal operation, and we learned a lot.

BSJ: In the aforementioned paper, it was also noted that "the main limitations for the use of ion therapy severely hinder world-wide patient access." Limitations include "size and cost of building and maintaining the required accelerator facilities and treatment planning, which is more technically demanding for ion therapy compared to conventional photon-based therapy" (Bin et al., 2022). How do you think laser-driven radiotherapy will change the broader field of radiotherapy?

LOH: This technology is still in its infancy, and we are still doing basic research to study and develop these sources. There are many open questions and challenges—many of which I mentioned previously—that still need to be solved before we can consider applying laser ion sources for radiotherapy. Proton treatment facilities are very expensive, so there are not many around the world, limiting patient access to proton radiation therapy. However, protons have huge advantages compared to x-rays, with the benefit of a very localized deposition of radiation in the tumor volume, which is especially important for deep-seated tumors. If we want to continue to use protons and ions for therapy, laser ions could eventually provide a more compact and cost-effective alternative to conventional radiofrequency-driven accelerators.

As I mentioned before, the laser ion sources can access these ultra-high dose rate regimes, reaching dose rates on the order of 10^7 to 10^9 grays[6] per second within the proton pulse, which is on the order of 1000 to 10,000 times more than can typically be achieved by conventional proton accelerators. Even the conventional proton accelerators that are now being modified to access the FLASH regime fall short of what can be achieved with one laser-driven proton pulse by orders of magnitude. So, using laser ion sources for this type of research in the ultra-high dose rate regime is where we can contribute to and fill a gap in the research of the FLASH effect.

One big challenge to achieve therapy-relevant proton beams is the current maximum proton energies that we can reach. Now, the community has demonstrated experiments where around 100 MeV could be achieved. However, one would need at least double that energy to penetrate into the human body far enough to be able to treat these deep-seated tumors. We are quite a ways off in that regard, but our work on improving the ion acceleration performance—for example, via MVA—aims to increase the maximum proton energy to beyond the 100 MeV level. The studies we have conducted at BELLA, however, show that we can already contribute to radiobiology studies aimed at radiotherapy by investigating this basic research area in the ultra-high dose rate regime.

BSJ: BELLA's high intensity lasers are purported to enable further research in materials science with precision doping,

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[6] ***The gray (symbol: Gy) is the unit of ionizing radiation dose in the International System of Units (SI), defined as the absorption of one joule of radiation energy per kilogram of matter.***

[7] ***Inertial confinement fusion (ICF) is a fusion energy process initiated by heating and compressing a small target with thermonuclear fuel (usually deuterium and tritium). ICF is one of two major branches of fusion energy research, the other being magnetic confinement fusion (MCF).***

in cancer treatment using the FLASH effect, and in high-density science and high-energy particle physics. You have personally conducted research in a plethora of fields, including in Matrix-Assisted Laser Deposition/Ionization Mass Spectrometer (MALDI-MS) detection of the COVID-19 spike protein and FLASH cancer treatment. Would you like to highlight any other particular laser applications that you think are most promising or exciting?

LOH: The recent experiments at the Livermore Lab's National Ignition Facility (NIF), whose results came out in December 2022, have demonstrated inertial confinement fusion. I think it is quite exciting that the first demonstration of inertial fusion ignition was achieved with lasers. This gives us hope that fusion could become a powerful and comparatively clean source for energy in the future, although it needs substantial further development.

One of the important questions in that area is, again, the question of laser efficiency, which is being explored, for example, with fiber lasers. Additionally, some physics processes involved in inertial confinement fusion[7] require further study. I think it would be really cool to contribute to this kind of research at the BELLA Center in the future. The NIF laser is a huge machine that generates incredible energies, but it is so energy-consuming that the NIF can only produce a few laser shots per day, at most. In contrast, at BELLA, we can do hundreds to thousands because we have repetition rates of up to 1-5 Hz. Even with the much lower energy laser pulses that we generate, we believe that we can explore some processes involved in fusion in smaller-scale experiments here. In addition, since we are part of the LaserNetUS network, we get user groups who come to the lab to do different kinds of experiments—some of which, to my excitement, are directed at these fusion processes.

Other than that, we work closely with scientists from the lab's accelerator modeling program, who use exascale plasma modeling codes. They operate huge computer simulations to model plasma processes, including those that are involved in fusion. They can model the microphysics important to, for example, fusion efficiency, which are not easily accessible with diagnostics in experiments.

Another pretty cool application that has started to grow in a collaboration within the Accelerator Technology and Applied Physics division (ATAP) division at Berkeley Lab has been to use laser ion sources to create and test new materials. Using our laser ion source, we can accelerate a certain ion and implant it into a material like a silicon wafer or synthetic diamond, which could become useful in making qubits, the building blocks of quantum computers. Or, alternatively, another area to explore is implantation of ions into materials such as boron or gold to build high-temperature superconductors, which can carry electricity efficiently without needing to be operated in extreme cold. This also ties into generating more energy-efficient accelerator facilities because accelerators need magnets to guide and focus the beam. Mitigating the need to cool those magnets down so much will make the process more energy efficient, enabling us to reach higher magnetic fields at more manageable operating costs.

Furthermore, to aid in astrophysics research, we can replicate the plasma environment in which stars are born in the lab. Ultimately, there are a plethora of other interesting phenomena that can be studied with high power lasers.

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