Prof. Carbajo in his laboratory at UCLA Samuel School of Engineering and Applied Sciences.

Shaping Light, Shaping Science: Prof. Sergio Carbajo's Vision

Prof. Sergio Carbajo hardly ever stops thinking, writing, and experimenting. In addition to his position as an assistant professor at UCLA's Electrical & Computer Engineering (ECE) and Physics & Astronomy Departments, he is a visiting professor at Stanford University's Photon Science Division at SLAC National Accelerator Laboratory. He is also a scholar of gender, race, and queer studies in STEM education, as well as the general impact of new technologies on society, with numerous reviewed publications on these social science subjects.

The main topic of this article is however based on Prof. Carbajo's overarching interest in the shaping of ultrashort pulses of light. He believes that precisely controlled shaping of the phase and amplitude of picosecond and femtosecond pulses can optimize the interaction of light with matter in many different ways - from individual electrons to complex materials. Pulse shape optimization can cover applications as diverse as high-resolution spectroscopy or high-fidelity transfer of quantum states from photons to electrons for quantum computing. Since emerging applications often require novel techniques, Prof. Carbajo enjoys developing both aspects – inventing new methods and using them to advance specific applications. In line with this philosophy, he contributes to the development of LINAC Coherent Light Source (LCLS) and is also one of its users pursuing his independent research.

Here, we will provide two examples of the widely ranging achievement in phase and amplitude transfer demonstrated by Prof. Carbajo's team using Light Conversion's ytterbium amplifiers, harmonic generators, and optical parametric amplifiers. The first use-case involves the accurate phase transfer from one wavelength to another arbitrarily chosen wavelength; the second use-case concerns the shaping of laser pulses to optimize the momentum distribution of the electron bunch emitted by the photocathode. We will also briefly cover the use of lasers to tailor the electron distribution after the first linear acceleration stage.

Transferring phase to different wavelengths via four-wave mixing (FWM)

Any study of matter requires light at wavelengths that precisely address electronic, vibrational, or excitonic energy states. Optical parametric generation (OPG), either via an oscillator (OPO) or amplifier (OPA), is typically used to convert a fixed "pump" laser wavelength into the tunable output of a parametric device. Because of its non-linearity, this process is generally inefficient (10-20%). Many users are therefore interested in optimizing the efficiency of these parametric processes to obtain a sufficient signal or to minimize the power – and cost – of the pump laser. However, other applications require very precise control of the phase of the nonlinearly generated wavelength, which is a non-trivial task.

Prof. Carbajo is studying four-wave mixing (FWM) in gas-filled hollow-core capillaries to circumvent these challenges in the nonlinear spectro-temporal shaping of light[1]. FWM is a nonlinear optical process that combines the frequencies of signal and pump photons to produce idler frequency photons. This technique allows for precise spectral phase transfer from the

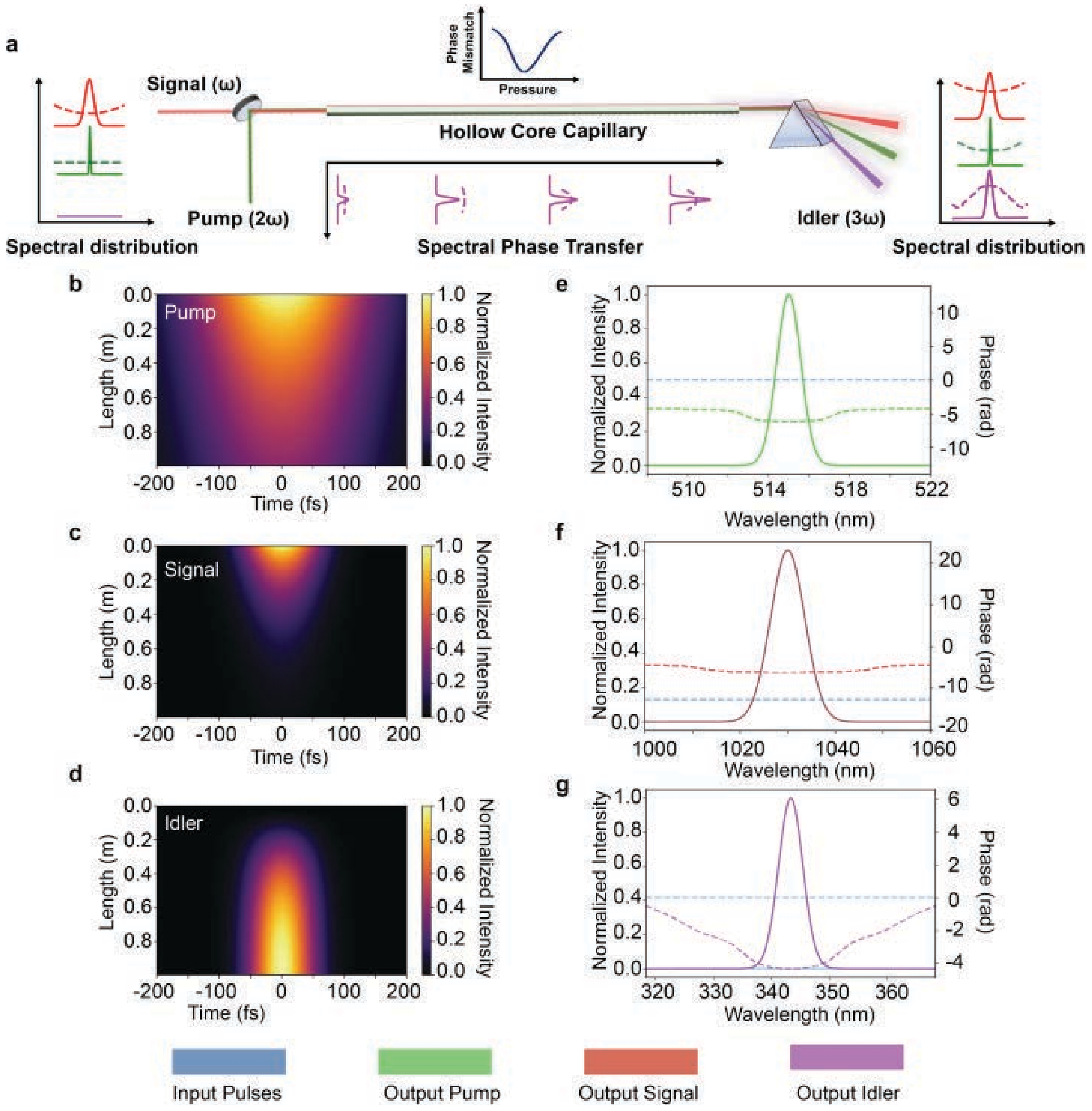

Figure 2. Example of phase transfer via FWM in a gas-filled capillary. Left: Changes in the intensity of the pump, signal, and idler along the propagation path in the capillary. Right: The phase of the signal (515 nm, dashed green line) is transferred to the output phase of the idler at 343 nm.

signal to the idler on ultrashort timescales and at extreme power levels. However, achieving this is complicated by competing linear and nonlinear dynamics, which create significant trade-offs between spectral phase transfer fidelity and conversion efficiency. Carbajo's team investigates the upconversion of femtosecond pulses from the infrared (IR) to the ultraviolet (UV) spectrum, which is traditionally challenging to manipulate (Figure 2). They have examined an intermediate energy regime that optimizes the balance between the fidelity of FWM-mediated phase transfer and nonlinear conversion efficiency. These insights help establish key principles and scaling laws vital for applications such as high-precision imaging, spectroscopy, quantum transduction, and distributed entangled interconnects. They also enable advanced control over ultrafast photonic and electronic wave packets in quantum materials with unprecedented spatial and temporal precision.

Among others, Prof. Carbajo is exploring how laser pulse shaping, both temporal and spectral, can further enhance quantum dot single-photon emitters for photonics quantum computing platforms. Through FWM, it is possible to minimize dephasing and enhance coherent control of quantum dots, which are critical requirements for implementing quantum gates and performing high-fidelity quantum operations, enhancing the performance and utility of quantum dot single-photon sources.

Photocathode and electron bunch optimization at Stanford LCLS-II

As Prof. Carbajo explains, Free Electron Lasers (FELs) are the flagships of ultrafast laser science and technology. An X-ray FEL (Figure 3) is substantially different from any other type of laser because the conventional atomic, molecular, or crystalline gain medium is replaced by free electrons organized in bunches and accelerated by magnets over distances ranging from a few tens to thousands of meters. These energetic electrons are then channeled through an “undulator”, that is, a perioding arrangement of magnets that forces the electrons to move in a sinusoidal path. According to quantum electrodynamics, this sinusoidal path causes the electrons to emit coherent radiation. The emitted wavelength depends on the electron energy, as well as the period and strength of the undulator magnets, ranging from THz to hard X-rays. The energy per pulse and average power of the optical beam depends on many factors, including the number and energy of the electrons, their organization in bunches, and the parameters of the undulators. Some of these elements play a role both in the wavelength and power of the optical beam. What makes FELs unique is the combination of wavelength tunability, short pulse durations (from attoseconds to picoseconds), and energy per pulse, especially at exotic wavelengths like soft and hard X-rays. A large FEL may end up costing a billion euros to build and many millions per year to operate.

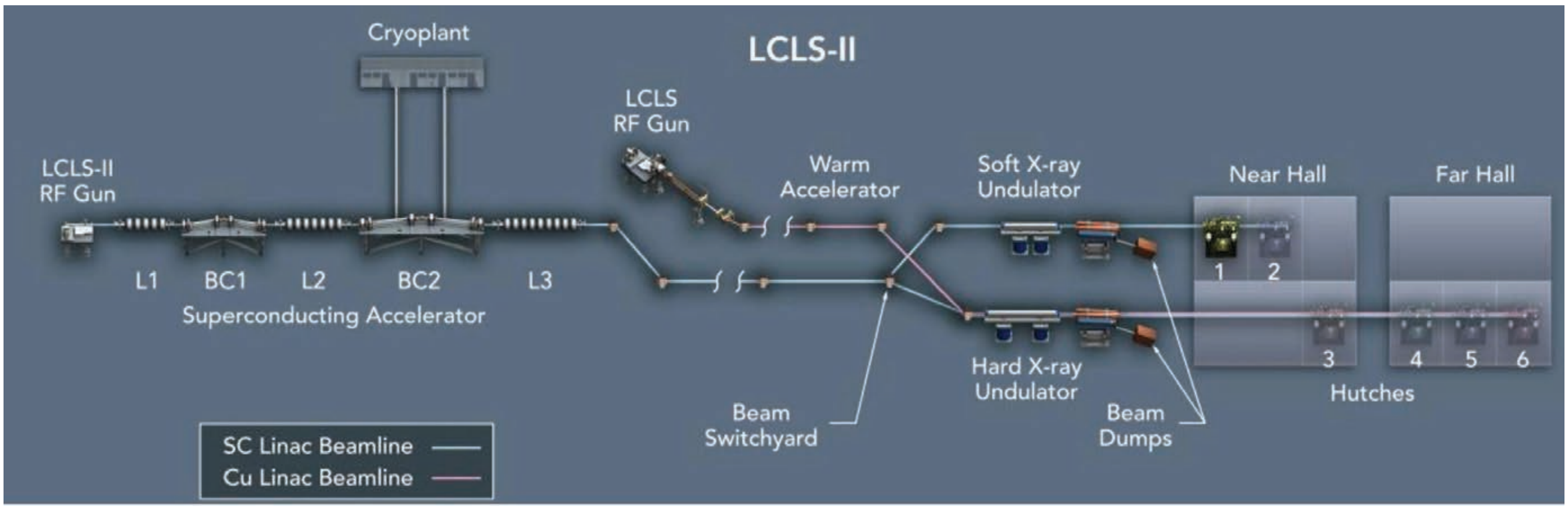

Figure 3. LCLS-II injector, LINAC, and instruments layout. L0B: injector, L1B-L3B: LINAC stages, HTR: laser heater, BC1B, and BC2B: bunch compressors.

For this reason, costly machine times of FELs are allocated in parallel to many groups of visiting scientists based on the merit of the proposed research. The range of FEL applications is huge: chemistry, material sciences, AMO (atomic, molecular, and optical) physics, and biology. A notable example of application is the socalled "diffraction before destruction", where intense hard X-ray femtosecond pulses from the FEL enable to image by diffraction the full structure of a protein or DNA molecule before the sample is completely destroyed by the radiation. LCLS and LCLS-II at Stanford's SLAC National Accelerator Laboratory are two state-of-the-art examples of FELs. LCLS operates at 120 Hz, and its experimental halls use mostly Titanium Sapphire lasers operated at 120 Hz. LCLS-II, however, is intended to progressively scale up operation to 96 kHz, resulting in much faster data acquisition rates[2]. The higher repetition rate requires supporting laser technology based on Ytterbium. In the following, we will refer specifically to LCLS-II.

In addition to the massive financial and engineering effort to build one of these devices and its infrastructure, an X-ray FEL is also a prime example of the complex yet fully deterministic transfer of properties from light to matter and vice versa. A key aspect of this process is the physics and engineering of the photocathode, the element generating the very first electrons of the bunch and largely defining the properties and quality of the FEL pulses. In one of the configurations, Light Conversion's **CARBIDE** femtosecond laser is used to generate IR pulses, which are optimized for subsequent conversion to UV pulses with a temporal shape that optimizes the electron emittance of the photocathode. The electron bunch is then accelerated in a linear accelerator, or LINAC, stage. The accelerated bunch is partly "thermalized" by another femtosecond laser – Light Conversion's 40 W **CARBIDE**. Additional LINAC and compressor stages bring the electron bunch to an energy of 4 GeV when they enter the undulators, where the free electron laser radiation generates broadly adjustable wavelengths. Among its

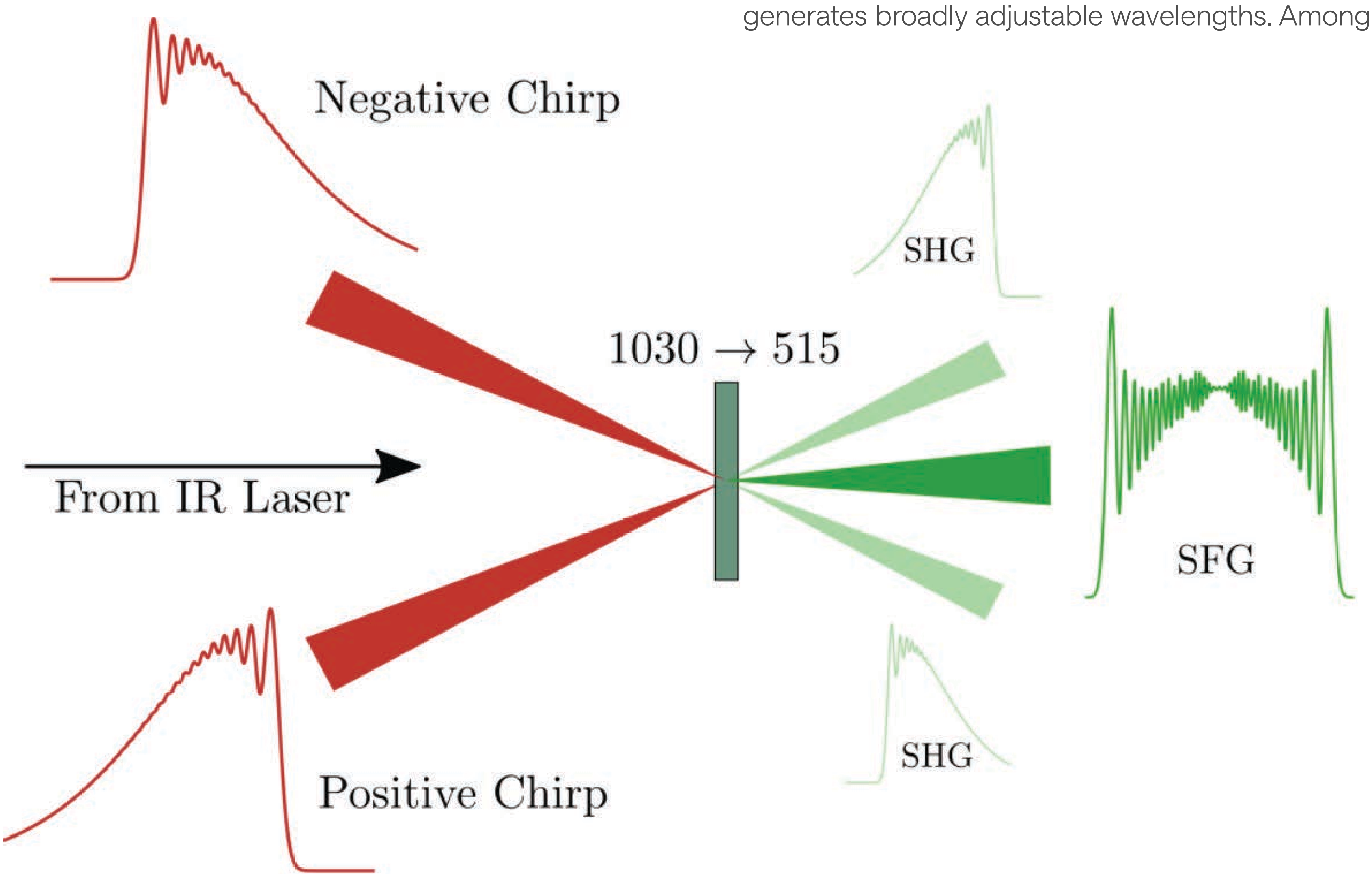

Figure 4. The beam from CARBIDE (red) is split in two, temporally chirped with opposite signs, and then recombined on a non-linear crystal for Sum Frequency Generation at 515 nm (green). A spectral filter is applied to eliminate the rapid modulation detrimental to photocathode emittance (black line). The subsequent second harmonic generation will maintain the temporal properties of the green pulse.

most extraordinary feats, LCLS-II is able to generate attosecond hard X-ray pulses beyond the TW peak power level, something impossible with any other technique. According to Prof. Carbajo, the global transfer function, from the properties of the laser pulses on the photocathode to the X-rays at the FEL output, would require solving hundreds of linear and non-linear differential equations.

Here we illustrate qualitatively how the laser pulses affect the electron bunch from the photocathode to minimize emittance. Emittance is a representation of the position and momentum of each electron with respect to ideal propagation along one of the three axes. The 3D spatial shape of the electron bunch is like a cigar. High emittance values indicate that the bunch will spread more than is desirable, with the cigar shape expanding in either transverse or longitudinal directions. It has been known for some time that a laser pulse with a Gaussian temporal shape does not minimize emittance, unlike a “flat-top” or super-Gaussian temporal profile. Prof. Carbajo and his team first simulated and then demonstrated experimentally pulse shape optimization to reduce photocathode emittance. To get a flat-top (ideally) or super-Gaussian (more realistically) distribution, the 1030 nm, <300 fs pulses from Light Conversion’s **CARBIDE** femtosecond laser are split into two beams, temporally chirped in opposite directions, and recombined in a non-linear crystal to produce ~20 ps pulses at 515 nm (Figure 4), for subsequent conversion to 257 nm via a second harmonic generation. The key element in the optimization process was the identification of the optimum chirp (second and third-order dispersion) and the bandwidth of the spectral filtering[3,4].

A highly complex device like LCLS comes with continuing and multiple opportunities for performance improvements and Prof. Carbajo is now picking up the challenge to further optimize the photocathode emittance using Light Conversion’s **ORPHEUS-ONE-HE** mid-IR collinear OPA. The OPA is used to introduce phonon vibration in the semiconducting sample with the idea that the photoemitted electron will have a higher degree of coherence rather than the more random paths leading to photoemission.

Laser heating

While X-ray pulses are produced from the undulation of the electron beam, the inverse process is also possible, where laser radiation can be coupled into the electron bunch to modify its properties. LCLS uses Light Conversion’s **CARBIDE** femtosecond laser at 1030 nm for this purpose; temporal shaping of the pulses is used to tailor the properties of the electron bunch, for example, to shorten the X-ray pulses to the attosecond regime or to obtain multiple pulses. Broadly, heaters are used to improve the performance of the electron beam by reducing microbunching instabilities[5,6]. These instabilities can degrade the quality of the beam, leading to a less coherent and less stable FEL output. As the electron beam is accelerated, shot noise and various collective effects (such as space

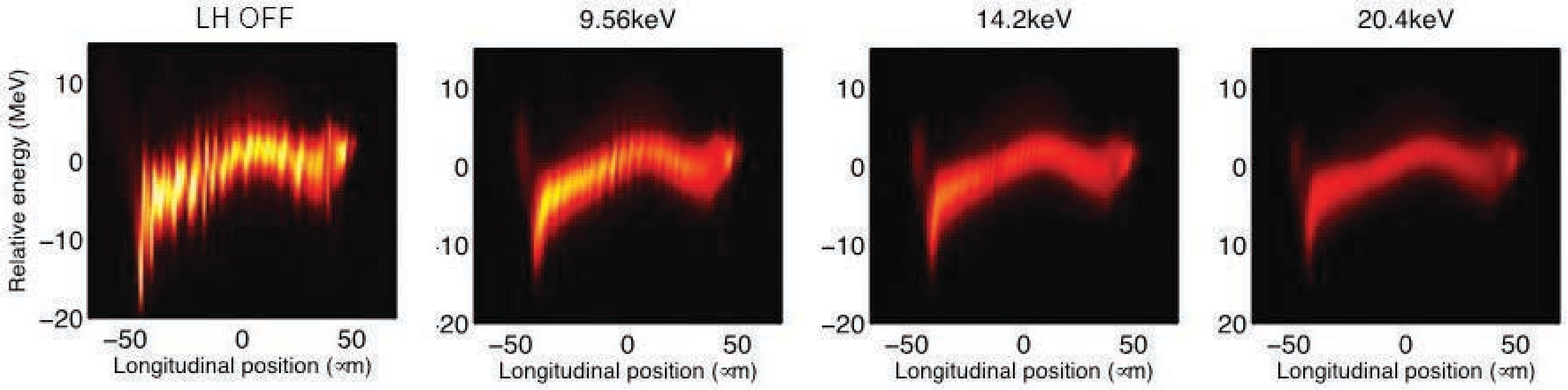

Figure 5. From left to right: effect of microbunching when the laser heater is off (leftmost) to the highest heating (rightmost). As the electrons "heat," their energy spread increases up to approximately 20 keV at the heater (values shown at the top of each image) and the microbunching is mitigated (shown in the images).

charge forces) can cause small density fluctuations or micro bunches along the beam. If not controlled, these instabilities can grow and lead to energy spread and emittance growth, deteriorating the FEL performance. When "heating" is implemented in a controlled way, it spreads out the energy distribution of the micro-bunches, thereby suppressing the growth of micro-bunching instabilities or allowing only specific macro-bunches to emit coherent radiation via the FEL process. One example is shown in Figure 5.

Conclusion

We described several applications of phase and amplitude shaping of laser pulses, some of which are fundamental for the optimization of large-scale projects like LCLS-II at Stanford as well as quantum light-matter interactions in solid-state physics, such as quantum dots, spearheaded at UCLA. According to Prof. Carbajo, the time is right to take advantage of machine learning techniques in conjunction with feedback loops that measure the relevant output performance. Such loops could then be used for dynamic optimization of the output properties or to re-optimize the system for a different set of desired output parameters since light shaping can be carried out with programmable and smart devices.

Beam time in facilities like FELs is highly sought after and competitive. For these reasons, the system must operate 24/7, apart from scheduled maintenance. Since a laser with a size and volume many orders of magnitude smaller than the FEL is essential for its daily operation, reliability, repeatability, and rapid support are of paramount importance. Quantum photonic platforms, on the other hand, while compact, are very complex to optimize due to critical gaps in theoretical frameworks and many-body interactions. This level of intricacy can also greatly benefit from AI-driven optimization routines. According to Prof. Carbajo, Light Conversion’s **CARBIDE** platform satisfies in full these demanding requirements.

References

1. H. Zhang et al., Optimizing Spectral Phase Transfer in Four-Wave Mixing with Gas-Filled Capillaries: A Trade-Off Study, arXiv:2404.16993 (2024).

2. M. Dunne, LCLS Strategic Plan 2023-2028 (2022).

3. R. Lemons et al., Temporal Shaping of Narrow-Band Picosecond Pulses Via Noncolinear Sum-Frequency Mixing of Dispersion-Controlled Pulses, Phys. Rev. Accel. Beams. 25, 013401 (2022).

4. N. Neveu et al., Nonlinearly Shaped Pulses in Photoinjectors and Free-Electron Lasers, arXiv:2306.16590 (2023).

5. D. Cesar, Electron Beam Shaping Via Laser Heater Temporal Shaping, Phys. Rev. Accel. Beams. 24, 110703 (2021).

6. S. Li et al., “Beam à la Carte”: Laser Heater Shaping for Attosecond Pulses in a Multiplexed X-Ray Free-Electron Laser, arXiv:2404.02299 (2024).