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TOWARDS SHORT-PULSE GENERATION AT FLASH VIA LASER-ASSISTED ELECTRON BUNCH MANIPULATION*

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Abstract

The FLARE project aims to investigate special operation modes of the laser heater at the free-electron laser FLASH in Hamburg that enable the generation of few- or possibly sub-femtosecond soft X-ray pulses. To this end, laser pulses of the laser heater are split and then recombined after one pulse has been delayed. By controlling the interference of both pulses via their temporal overlap, a longitudinally non-uniform heating of the electron bunches can be achieved. Utilizing this, two short-pulse generation schemes are to be implemented as part of the FLARE project. In the first scheme, the energy spread of the bunch is increased to a degree that inhibits lasing, leaving only a small unheated region which emits a short FEL pulse. The second scheme works by imprinting an energy modulation with a linearly increasing amplitude onto the longitudinal phase-space distribution of the bunch. In subsequent magnetic chicanes, this phase-space structure results in a localized compression of the bunch, creating an extremely short current spike, which might be used to produce an X-ray pulse on the same time scale. The FLARE setup as well as first experimental results are presented.

BUNCH SHAPING BY LASER HEATER

With a laser heater, the uncorrelated energy spread of an electron bunch is increased [1–6]; the bunch is "heated". An early and controlled increase of the energy spread can be beneficial for the performance of a free-electron laser (FEL) as the microbunching instability (MBI) is suppressed [7]. If not suppressed, the MBI can drive a gradual uncontrolled energy-spread blow-up [8]. *Adding* an adequate amount of energy spread early in the beamline results in a net *reduction* of the final energy spread: an unsuppressed MBI causes more additional energy spread than needed to suppress the MBI. However, if the laser heater-induced energy spread surpasses the unsuppressed MBI-caused energy-spread, a net increase of the final energy spread results; we call this effect "overheating".

Within a bunch, the FEL process is not equally efficient everywhere but depends critically on the local charge density and energy spread. In a laser heater, the temporal structure of the added energy spread is inherited from the field profile of a laser pulse that drives the process. In longitudinally dispersive parts of the machine, non-uniformities in the energy-spread profile of a bunch can result in a local variations of the charge density. The laser-heater pulse profile therefore influences both critical properties – local charge density and local energy spread. Consequently, the time structure of the resulting FEL pulse can be manipulated by tailoring the laser-heater pulse profile [9–11]. To achieve specific phase-space structures at the undulators, the complex longitudinal dynamics that results from bunch compression and collective effects between the laser heater and the undulator section has to be taken into account [11].

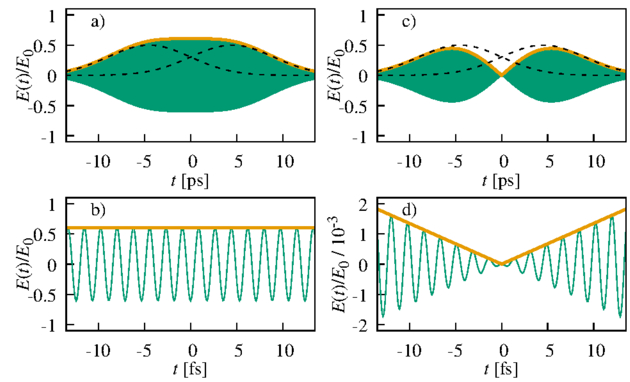

Figure 1: Relative electric field strength (green) and envelope (orange) of two Gaussian laser pulses (dashed) with $\lambda = 532$ nm and rms pulse duration $\sigma_L = 4.5$ ps, separated by $2\sigma_L$ that interfere constructively (a,b) and destructively (c,d) within the overlap region.

If the bandwidth of the laser-heater pulse is sufficiently large, spectral pulse-shaping techniques can be applied [9]. A more limited pulse shaping approach that is applicable to narrow-bandwidth pulses is sketched in Fig. 1. Depicted is the normalized electric field of two overlapping laser pulses with a Gaussian field envelope separated by $\delta \approx 2\sigma_L$, where σ_L is the rms pulse duration of a single pulse. By controlling the delay δ, the pulse envelope can be manipulated: If $c\delta/\lambda \in \mathbb{Z}$, the pulses interfere constructively; the resulting pulse is longer, with a flat envelope at its center, see Figs. 1a and 1b. If $c\delta/\lambda + \frac{1}{2} \in \mathbb{Z}$ (Fig. 1c and Fig. 1d), destructive interference results in a bimodal field envelope, which vanishes in the pulse center. Around the center, the envelope rises linearly in both directions with negligible quadratic contributions. Other values of δ result in intermediate field profiles with a non-zero central minimum.

FLARE SETUP AT FLASH

Recently, a laser heater [5, 6] was installed at FLASH [12, 13]. Figure 2 shows its basic layout: an undulator in which an energy modulation is imprinted on the bunch via resonant

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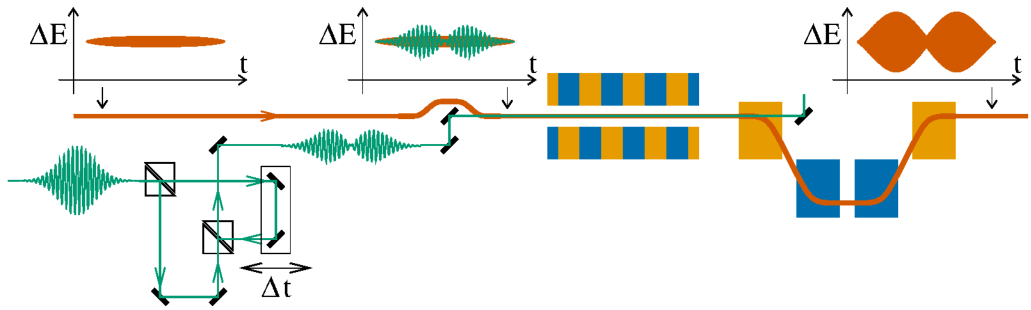

Figure 2: Sketch of the layout of the FLASH laser heater together with the FLARE interferometer setup.

interaction with a laser pulse, followed by a magnetic chicane where the modulation is converted into energy spread as it is "washed out" by the longitudinal dispersion. As part of the FLARE (FLASH Laser-Assisted Reshaping of Electron bunches) project, the above-mentioned laser pulse shaping technique was implemented by means of an interferometer-type setup as depicted in the left-hand side of Fig. 2. A laser pulse is split into two pulses which are then delayed relative to each other via a motorized delay stage in one of the interferometer arms. After recombining the pulses, field configurations as discussed above are achieved.

At FLASH, the effect of such a shaped laser-heater pulse on the longitudinal phase-space density (PSD) of an electron bunch can be directly measured at two locations via transverse deflecting structure (TDS) setups, one of which is located downstream of the FLASH2 undulators [14]. In a TDS, a strong correlation between longitudinal position and transverse velocity is imprinted on the six-dimensional PSD of a bunch. Observing the bunch on a screen in a transverse-dispersive section downstream of the TDS then allows a measurement of its longitudinal PSD. With the help of such TDS measurements, the viability of the "flat pulse" operation mode of the FLARE setup was verified: Figure 3 shows the relative change of the beam size along the energy-axis of a central longitudinal slice of the bunch as a function of the timing shift between the bunch and the laser-heater pulse. As described earlier, in this regime despite an initial increase of the energy spread, the resulting suppression of the MBI causes a reduction of the beam size (and its fluctuation) when the laser-heater pulse overlaps with the measured bunch slice. For the flat-pulse setting, the FLARE delay stage was set to $\delta \approx 12\,\mathrm{ps}$, which is compatible with the measured broadening of the overlap region compared to a single Gaussian pulse.

TOWARDS SHORT PULSES

Due to the resulting non-uniform field profile, operating the interferometer in the destructive mode allows to increase the energy spread only in certain longitudinal regions of the bunch while leaving others nearly unheated. This effect can be directly utilized to shorten the duration of an FEL pulse generated by a bunch: By choosing a sufficiently high laser pulse energy, the bunch is overheated around the location of

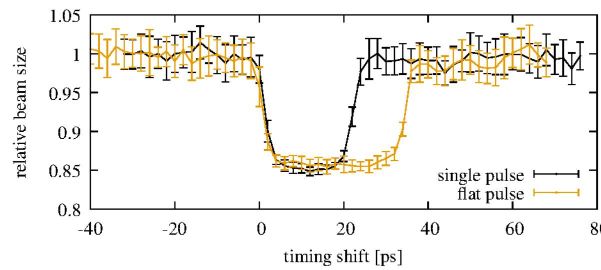

Figure 3: Relative broadening of a bunch slice on a TDS screen versus timing shift between bunch and laser pulse for a single Gaussian pulse (black) and two constructively interfering pulses (orange). Curves are aligned at their falling edge to facilitate comparison.

the two maxima of the field envelope, so that the FEL process is suppressed in these regions. If the interferometer is set close to the destructive setting, the minimum of the envelope at the center of the pulse is small enough to not overheat the beam. As the field envelope decreases monotonically from each of the maxima towards the center, there exists a region between the maxima in which the envelope drops below the overheating regime. Within this "gap", the FEL process is not suppressed but rather enhanced due to the MBI suppression. Consequently, the duration of the resulting FEL pulse is determined by the width of the gap. To a degree, this gap width can be controlled via the slope of the envelope around the center by adjusting the total laser heater pulse energy; the minimal separation between the maxima is however limited to $2\sigma_L$. In order to transport the energy spread profile imprinted at the laser heater largely unperturbed to the undulator section, the bunch must not be compressed too strongly.

Figure 4 shows TDS measurements of the longitudinal phase-space distribution of a 300 pC bunch downstream of the FLASH2 undulator section at a beam energy of 860 MeV and a FEL wavelength of 25 nm. In Fig. 4a, laser pulses are blocked, so that the bunch is not heated at all: in the region $t < 0$ the bunch shows the characteristic jagged structures that the longitudinal PSD acquires during the FEL process. When the laser heater is active with the FLARE interferometer in destructive mode, the FEL process is limited to a

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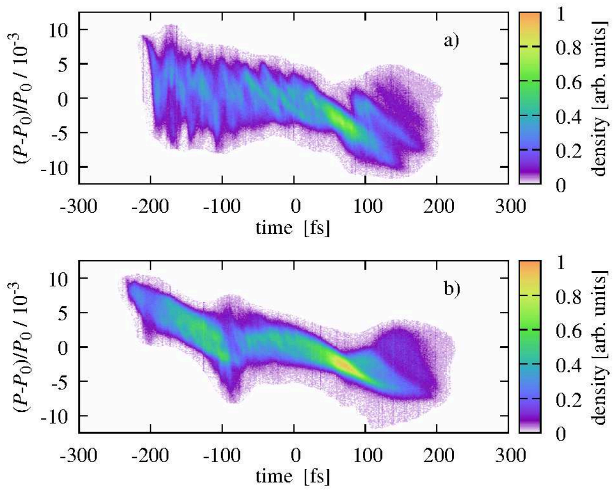

Figure 4: TDS measurements of the longitudinal phase-space density as a function of the time coordinate within the bunch and the relative momentum deviation $(P - P_0)/P_0$ downstream of the FLASH2 undulator beamline of (a) an unheated bunch, (b) a partially overheated bunch.

smaller region, visible around $t \approx -80$ fs in Fig. 4b, providing clear evidence for successful partial overheating.

Splitting the laser pulse in the FLARE interferometer decreases the effective laser pulse energy driving the heating process to around 15 µJ per single pulse. It became evident that when FLASH2 is tuned for maximum FEL pulse energy in this energy and wavelength regime, the FEL process is too resilient to the overheating effect to be fully suppressed by the reduced amount of added energy spread. For the above measurements, to achieve total FEL suppression in the overheated regions, the FEL process was made more susceptible to overheating by detuning the gun solenoid. To make this technique applicable in a broad range of typical user operation modes of FLASH, a greater initial laser heater pulse energy would be required.

Another method to use the pulse-shaping capabilities of the FLARE setup for the generation of short FEL pulses is to locally compress a small part of the bunch, so that a short current spike is formed [10]. In the destructive mode of the FLARE setup, the imprinted energy spread around the center of the shaped pulse is proportional to the absolute value of the distance from the center. With appropriate bunch compression settings, this energy spread profile results in an additional localized compression of the bunch around the center of the shaped laser pulse.

Figure 5 shows TDS measurements of a ≈ 300 pC bunch with a central energy of 1.2 GeV radiating at 12 nm, which was compressed more strongly compared to Fig. 4. Without heating (Fig. 5a) signs of the FEL process are evident in the region < 0 fs. In Fig. 5b, one arm of the FLARE interferometer is blocked, so that the bunch is heated only by a single pulse. It becomes apparent that at this wavelength the FEL process is less robust and can be suppressed to a large extend by the laser heater. In Fig. 5c, the interferometer is in

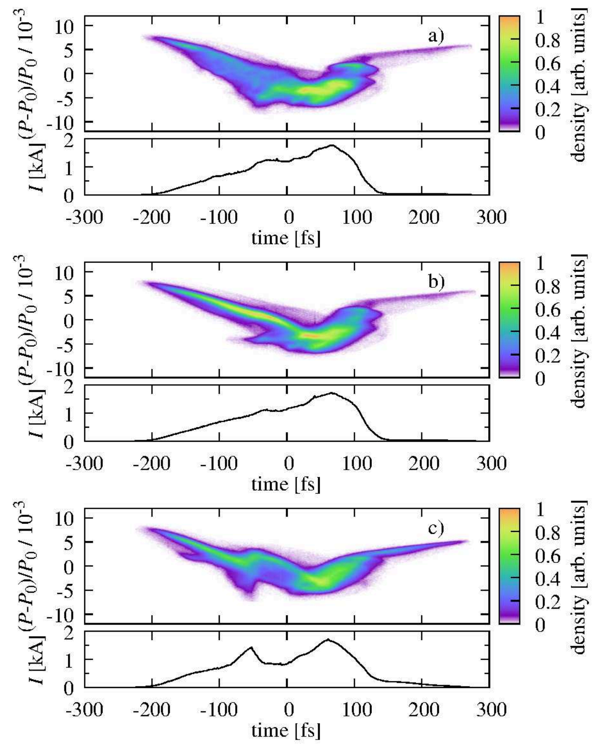

Figure 5: Longitudinal phase-space density and current profile of a bunch that is (a) unheated, (b) heated by a single laser pulse, (c) heated by two partially destructively interfering laser pulses.

destructive mode with both arms open: in a region around −60 fs, a pronounced spike appears in the current profile as a result of local compression by the aforementioned mechanism. In the PSD, at the same position a local energy chirp emerges which results from collective energy kicks generated by the current spike. In this region, both the locally increased charge density as well as the overheating of the neighboring regions aid the generation of a short FEL pulse. Indeed, the PSD shows characteristic structures of the FEL process around the current spike.

Overall, these first results show that, despite its conceptual simplicity, an interferometer adds useful bunch shaping capabilities to a laser heater that can be utilized for the generation of short FEL pulses. Via TDS measurements, the viability of both the partial overheating method and the local compression approach has been verified. Determining FEL pulse durations from the TDS data [15] and comparison with THz-streaking measurements [16, 17] is the subject of ongoing work. In future studies, optimized compression settings will be investigated to achieve a more pronounced local compression and potentially generate even shorter FEL pulses.

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