Laser-Based Bunch Shaping for Short Pulses at FLASH

Philipp Amstutz[1]

for my colleagues of the FLARE project

Christopher Gerth[2], Wolfram Helml[1], Shaukat Khan[1], Carsten Mai[1]

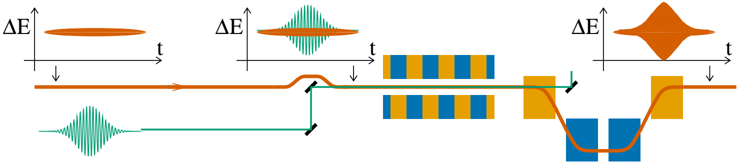
[1] TU Dortmund University, [2] Deutsches Elektronen-Synchrotron DESY

2024-09-18

LEDS'24 Bern

v1

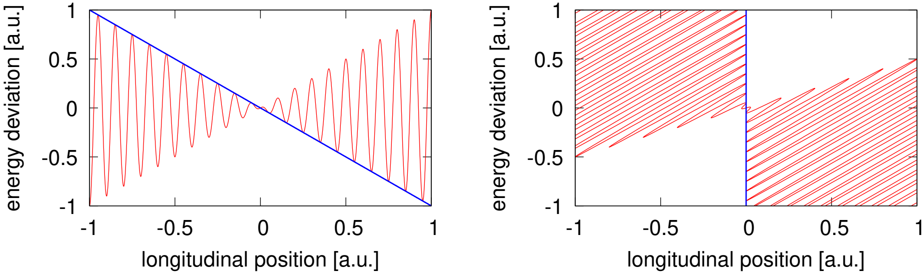
Laser Heater enables longitudinal phase-space manipulation



- Electron bunch inherits energy-modulation profile from LH laser-pulse
  - results effectively in energy-spread profile, after subsequent chicane
- A non-uniform E-spread profile enables bunch- and FEL-pulse shaping
  - local FEL suppression
    - Marinelli et al., "Optical Shaping of X-Ray Free-Electron Lasers", PRL 116, 254801 (2016)
    - Amstutz et al., in proc. IPAC'24, MOPG65
  - non-uniform bunch compression
    - Cesar et al., "Electron beam shaping via laser heater temporal shaping", PRAB 24, 110703 (2021)
    - this talk

At FLASH, a LH-based method for local compression is studied

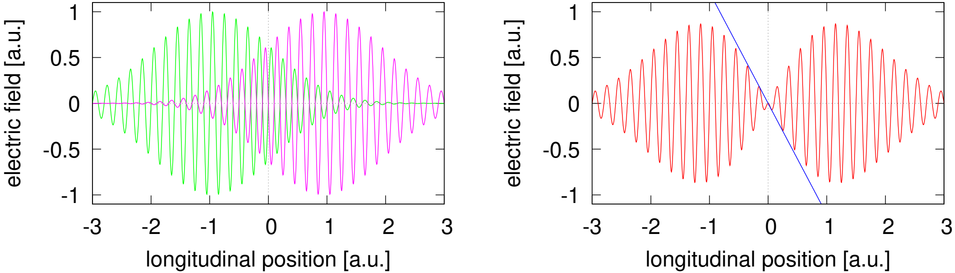
- A linear laser-pulse envelope, with appropriate longitudinal dispersion, results in a local compression of the bunch
- Proposed in T. Tanaka, "Electron bunch compression with an optical laser", PRAB 22, 110704 (2019)
- Schematic for a cold beam $\sigma_E = 0$:



- w.r.t. bunch compression: substructure is generated w/ "effective" chirp equal to slope of laser-pulse envelope

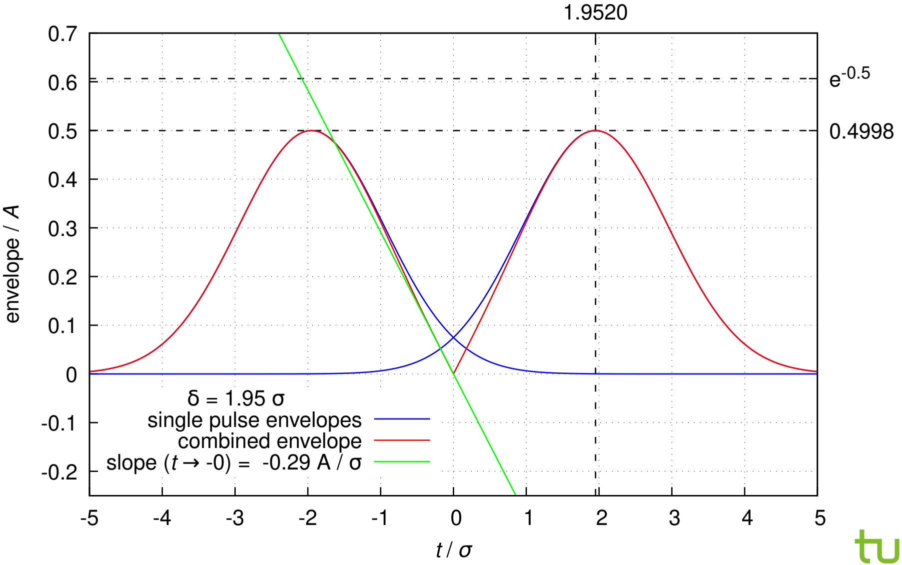
Destructively interfering Gaussian pulses feature large "linear" region

- Overlapping Gaussian laser pulses, schematic (actually $\lambda \ll \sigma$):



- Destructive interference creates "linear" envelope in a region around the center

Two-Pulse envelope animated



Two-Pulse envelope is controlled by the pulse separation

- Pulse separation 2δ, pulse length σ, peak E-field A, and laser freq. $\omega_0 \gg \sigma^{-1}$:

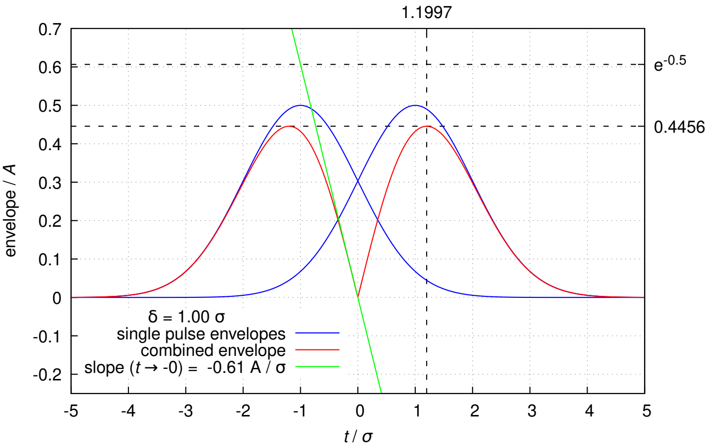
$$\text{envelope} \approx |S_a(t)| \equiv \frac{1}{\sqrt{2}} A\, \mathrm{e}^{-\frac{1}{2}\frac{\delta^2}{\sigma^2}} \mathrm{e}^{-\frac{1}{2}\frac{t^2}{\sigma^2}} \sqrt{\cosh(\tfrac{2\delta}{\sigma^2} t) + \cos(2\omega_0 \delta)}$$

  - Destructive interference when $\delta = \delta_- \equiv (m + \frac{1}{2})\frac{\pi}{\omega_0}$, $m \in \mathbb{Z}$
- With normalized separation $\nu \equiv \delta_-/\sigma$:

$$\lim_{t \to \pm 0} \frac{\mathrm{d}^n}{\mathrm{d}t^n} |S_a|_{\delta=\delta_-}(t) = \begin{cases} 0 & \text{n is even} \\ \mp \frac{A}{\sigma^n} \frac{\mathrm{d}^n}{\mathrm{d}\nu^n} \mathrm{e}^{-\frac{1}{2}\nu^2} & \text{n is odd} \end{cases}$$

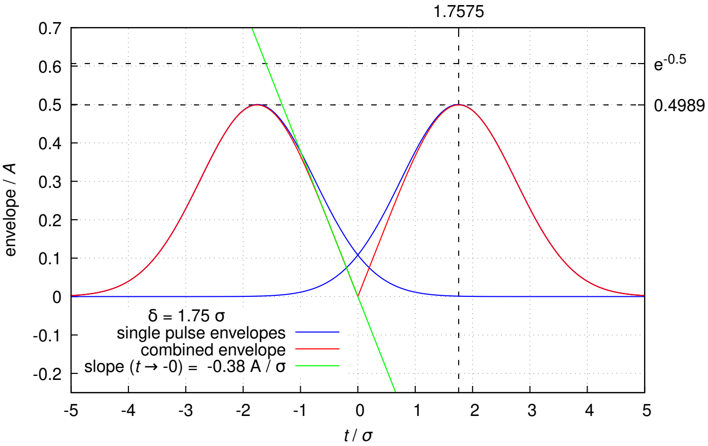
  - $\nu = 1 \implies$ maximum slope
  - $\nu = \sqrt{3} \implies \lim_{t \to \pm 0} \frac{\mathrm{d}^i}{\mathrm{d}t^i} |S_a|_{\delta=\delta_-}(t) = 0, \quad i \in \{0, 2, \mathbf{3}, 4, 6, 8, \dots\}$

Two-Pulse envelope, $\nu = 1$ (maximum slope)



- $|S_a|_{\nu=1}(t) = \frac{A}{\sigma} e^{-\frac{1}{2}} |t| + O(|t|^3)$

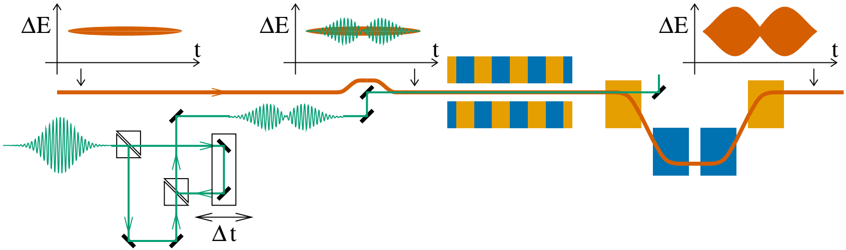
Two-Pulse envelope, $\nu \approx \sqrt{3}$ (minimal non-linearity)



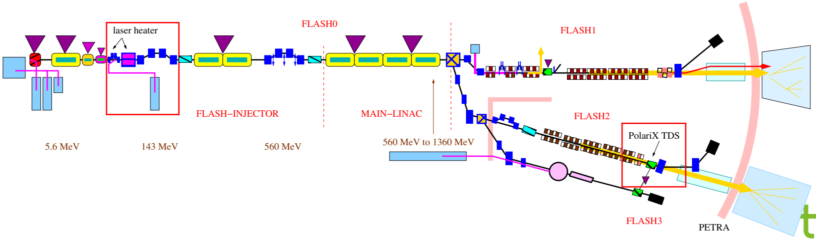
- $|S_a|_{\nu=\sqrt{3}}(t) = \frac{A}{\sigma}\sqrt{3}\mathrm{e}^{-\frac{3}{2}}|t| + O(|t|^5)$

technische universität dortmund

Implemented at FLASH via an interferometer in the LH laser beamline

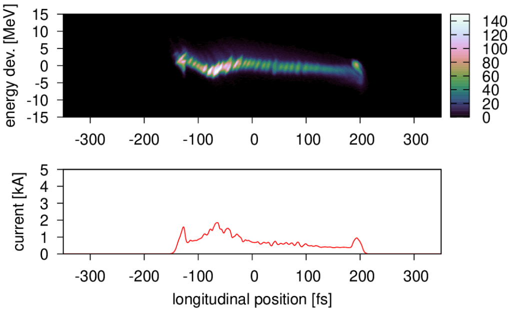


- Following phase-space measurements taken w/ PolariX TDS (end of FLASH2)

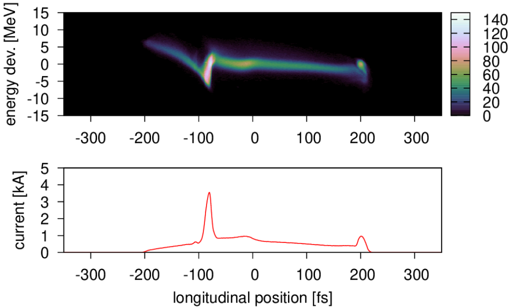


Local compression effect is visible in PolariX TDS measurements

Entire bunch w/o LH



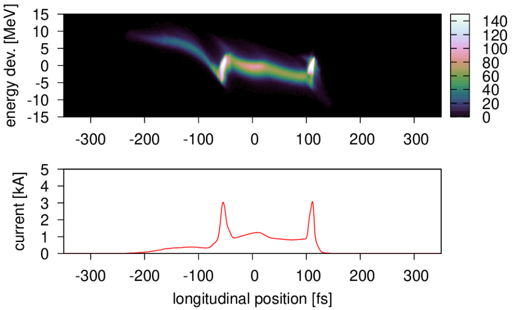
Local compression induced by LH

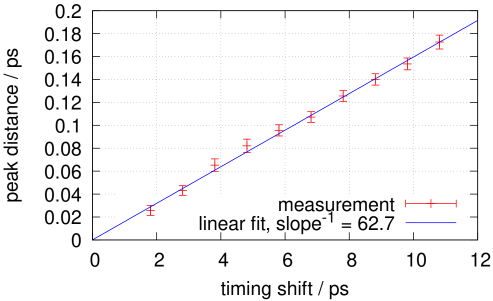


- LH pulse separation $\nu = \delta/\sigma = 1$
  - from laser parameters: expected local compression chirp $\approx -10\,\mathrm{keV/ps}$
- PolariX TDS time resolution here $\sigma_{\mathrm{res}} \approx 6.5\,\mathrm{fs}$
- Spike width & current measurement is resolution limited

technische universität dortmund

Spike position can be controlled by laser timing





- Spike in the head (at $t \approx 100\,\text{fs}$) generated by non-linear bunch compression
- Second spike is generated by local compression
  - position controllable by laser timing
  - (timing shift) / (peak distance) $\approx$ compression factor

technische universität dortmund

Convenient parameterization of linear bunch compression dynamics

- Coordinates: Time/Energy Deviation $q \equiv t - t_0(s)$, $p \equiv E - E_0(s)$, $\vec{z} \equiv (q, p)^{\mathrm{T}}$.
- 1D, linear, ultrarelativistic, single-particle Model:
  - Cavities: $\vec{z} \mapsto \underline{K}(h)\vec{z} \equiv \begin{pmatrix} 1 & 0 \\ h & 1 \end{pmatrix} \vec{z}$
  - Chicanes: $\vec{z} \mapsto \underline{D}(\beta)\vec{z} \equiv \begin{pmatrix} 1 & \beta \\ 0 & 1 \end{pmatrix} \vec{z}$ with $\beta \equiv \frac{R_{56}}{c\,E_0}$
  - Drift spaces: $\vec{z} \mapsto \vec{z}$
- For any number N of compression stages it is

$$\underline{M} = \underline{D}(\beta_N)\underline{K}(h_N) \cdots \underline{D}(\beta_1)\,\underline{K}(h_1) = \underline{K}(h^\dagger) \begin{pmatrix} C^{\dagger -1} & 0 \\ 0 & C^\dagger \end{pmatrix} \underline{D}(\beta^\dagger)$$

  - $h^\dagger$, $C^\dagger$ and $\beta^\dagger$: *total* chirp, compression and longitudinal dispersion
  - explicit solutions for $h^\dagger$, $C^\dagger$ and $\beta^\dagger$ in dependence on $h_1, \beta_1, \ldots, h_N, \beta_N$ exist
  - For $N = 2$: $\beta^\dagger = C^\dagger\,\bar{\beta}$, $C^\dagger = \left[(h_1 + \bar{h})\bar{\beta}\right]^{-1}$
    with $\bar{\beta} \equiv \beta_1 + \beta_2 + \beta_1\beta_2 h_2$, $\bar{h} \equiv (1 + h_2\beta_2)/\bar{\beta}$.

Final temporal variance depends quadratically on first RF-chirp

- Covariance matrix of a longitudinal phase-space density Ψ:

$$\underline{\Sigma}[\Psi] \equiv \begin{pmatrix} \langle q^2 \rangle_\Psi & \langle qp \rangle_\Psi \\ \langle qp \rangle_\Psi & \langle p^2 \rangle_\Psi \end{pmatrix},$$

  with $\langle f(\vec{z}) \rangle_\Psi \equiv \int_{\mathbb{R}^2} f(\vec{z} - \vec{\mu}_{\vec{z}}) \Psi(\vec{z}) \, \mathrm{d}\vec{z}$ and $\vec{\mu}_z \equiv \int_{\mathbb{R}^2} \vec{z} \Psi(\vec{z}) \, \mathrm{d}\vec{z}$.

- $\underline{\Sigma}[\Psi_i]$ upstream of first RF-section maps to $\underline{\Sigma}[\Psi_f] = \underline{M} \, \underline{\Sigma}[\Psi_i] \, \underline{M}^{\mathrm{T}} =$

$$\underline{K}(h^\dagger) \begin{pmatrix} \frac{\beta^{\dagger 2} \langle p^2 \rangle_{\Psi_i} + 2\beta^\dagger \langle qp \rangle_{\Psi_i} + \langle q^2 \rangle_{\Psi_i}}{C^{\dagger 2}} & \beta^\dagger \langle p^2 \rangle_{\Psi_i} + \langle qp \rangle_{\Psi_i} \\ \beta^\dagger \langle p^2 \rangle_{\Psi_i} + \langle qp \rangle_{\Psi_i} & C^{\dagger 2} \langle p^2 \rangle_{\Psi_i} \end{pmatrix} \underline{K}(h^\dagger)^{\mathrm{T}}$$

  at PolariX.

- We can write $\langle q^2 \rangle_{\Psi_f} = a_2 \left(h_1 - a_1\right)^2 + a_0$,

  with $a_2 \equiv \bar{\beta}^2 \langle q^2 \rangle_{\Psi_i}$, $a_1 \equiv -\left(\bar{h} + \frac{\langle qp \rangle_{\Psi_i}}{\langle q^2 \rangle_{\Psi_i}}\right)$, and $a_0 \equiv \bar{\beta}^2 \left(\langle p^2 \rangle_{\Psi_i} - \frac{\langle qp \rangle^2_{\Psi_i}}{\langle q^2 \rangle_{\Psi_i}}\right)$.

Initial covariance matrix can be reconstructed from RF-scan

- Determine a_2, a_1, a_0 from a quadratic fit to measurements of $\langle q^2 \rangle_{\Psi_f}(h_1)$.
- Initial covariance matrix is then given by

$$\langle q^2 \rangle_{\Psi_i} = \frac{a_2}{\bar{\beta}^2}, \quad \langle qp \rangle_{\Psi_i} = -\left(a_1 + \bar{h}\right) \langle q^2 \rangle_{\Psi_i}, \quad \langle p^2 \rangle_{\Psi_i} = \frac{a_0}{\bar{\beta}^2} + \frac{\langle qp \rangle_{\Psi_i}^2}{\langle q^2 \rangle_{\Psi_i}}.$$

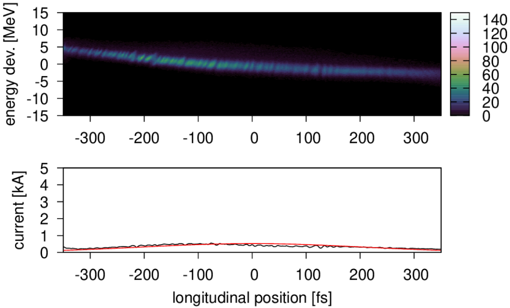
- Remarkable: for two initial PSDs $\Psi_{i,A}$ and $\Psi_{i,B}$ the relative quantities

$$\frac{\langle q^2 \rangle_{\Psi_{i,A}}}{\langle q^2 \rangle_{\Psi_{i,B}}} = \frac{a_{2,A}}{a_{2,B}} \quad \text{and} \quad \frac{\langle qp \rangle_{\Psi_{i,A}}}{\langle q^2 \rangle_{\Psi_{i,A}}} - \frac{\langle qp \rangle_{\Psi_{i,B}}}{\langle q^2 \rangle_{\Psi_{i,B}}} = a_{1,B} - a_{1,A},$$

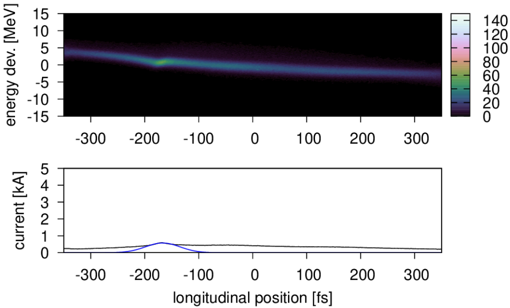
can be determined w/o knowledge of the machine parameters $\bar{h}$, $\bar{\beta}$.

Method can be applied to both, entire bunch and isolated spike

Entire bunch w/o LH



Local compression induced by LH

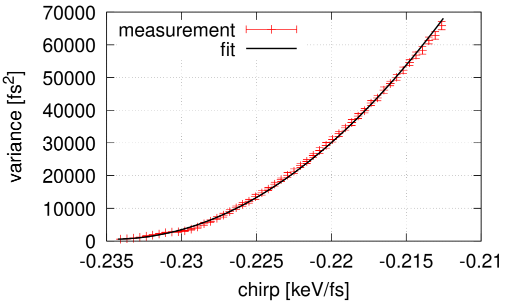


- Entire bunch: use $\langle q^2 \rangle_{\text{bunch}}$
- Local compression: fit Gaussian, approximate $\langle q^2 \rangle_{\text{spike,meas}} \approx \sigma^2_{\text{spike}}$
- Due to limited resolution: $\langle q^2 \rangle_{\text{spike,meas}} \approx \langle q^2 \rangle_{\text{spike,actual}} + \sigma^2_{\text{res}}$

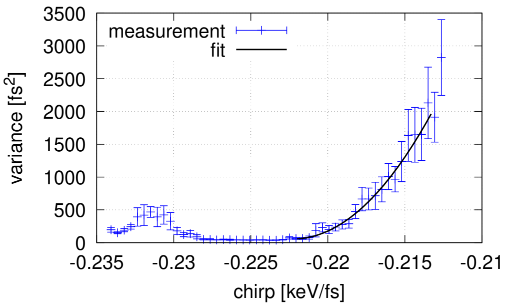
Method can be applied to both, entire bunch and isolated spike

preliminary!

Entire bunch w/o LH



Local compression induced by LH

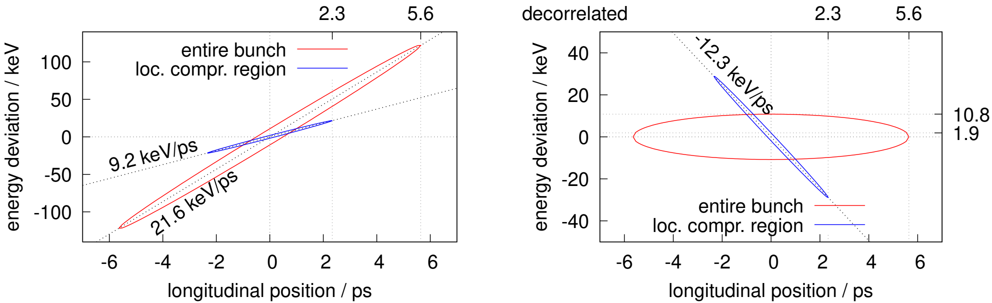


- Entire bunch: over the whole scan region well represented by parabola
- Local compression: Fit only meaningful before resolution "plateau"
  - resolution impedes determination of a_0, a_1 (not so much a_2)

technische universität dortmund

Initial covariance matrices

preliminary!



- Chirp difference:
  - fully determined by fit coefficients (independent of machine parameters)
  - close to expected chirp determined from laser-pulse parameters $\approx -10\,\mathrm{keV/ps}$
- this shows: loc. compr. mechanism is well-described by linear model
- Detailed error analysis/calculation is ongoing!

Summary & Outlook

- Laser-based local compression scheme successfully tested
  - results understandable w/ linear longitudinal dynamics
  - reconstructed chirp of local compression region in good agreement w/ estimation from laser parameters
- Next experimental step: get lasing from the spike(s)
  - sub-femtosecond X-ray pulse length targeted
  - single-color, double-pulse scheme to be tested
  - ... however, FLASH is in shutdown until Aug '25

Thank you for your attention!