Synchronized Mid-Infrared Pulses at the Fritz Haber Institute IR-FEL

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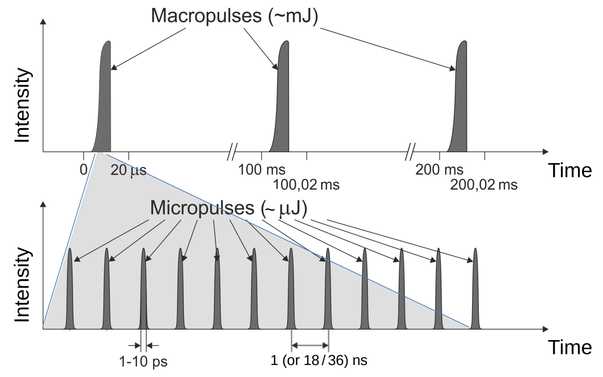
Fritz Haber Institute IR-FEL Oscillator

- Tunable mid-IR/THz radiation: λ = 3 … 50 µm ≙ 6 … 100 THz
  → addressing vibrational energy levels of matter
- Macro-/Micro-pulse structure:
  - macro-pulses: τ_p ~ 10 µs, E_p ≤ 100 mJ, f_{rep} = 10 Hz
  - micro-pulses: τ_p ~ 0.3 … 10 ps, E_p < 10 µJ, f_{rep} = 1 GHz (or 27/55 MHz)
- Institute-internal use for (non-)linear solid-state and molecular spectroscopy

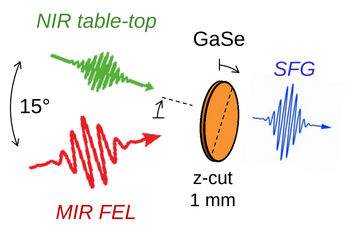
*Schöllkopf et al., Proc. SPIE **9512**, 95121L (2015)*

- Synchronized table-top laser for two-color non-linear / time-resolved spectroscopy



Balanced Optical Cross-Correlation

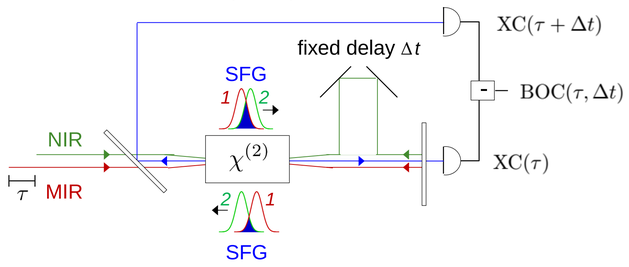
- FEL pulse shape by sum-frequency generation (SFG) cross-correlation with synchronized table-top laser



$$I_{SFG} \propto |\chi^{(2)}_{eff}|^2 \, I_{NIR} \, I_{MIR}$$

*Schulz et al., Nat. Commun. **6**, 5938 (2015)*

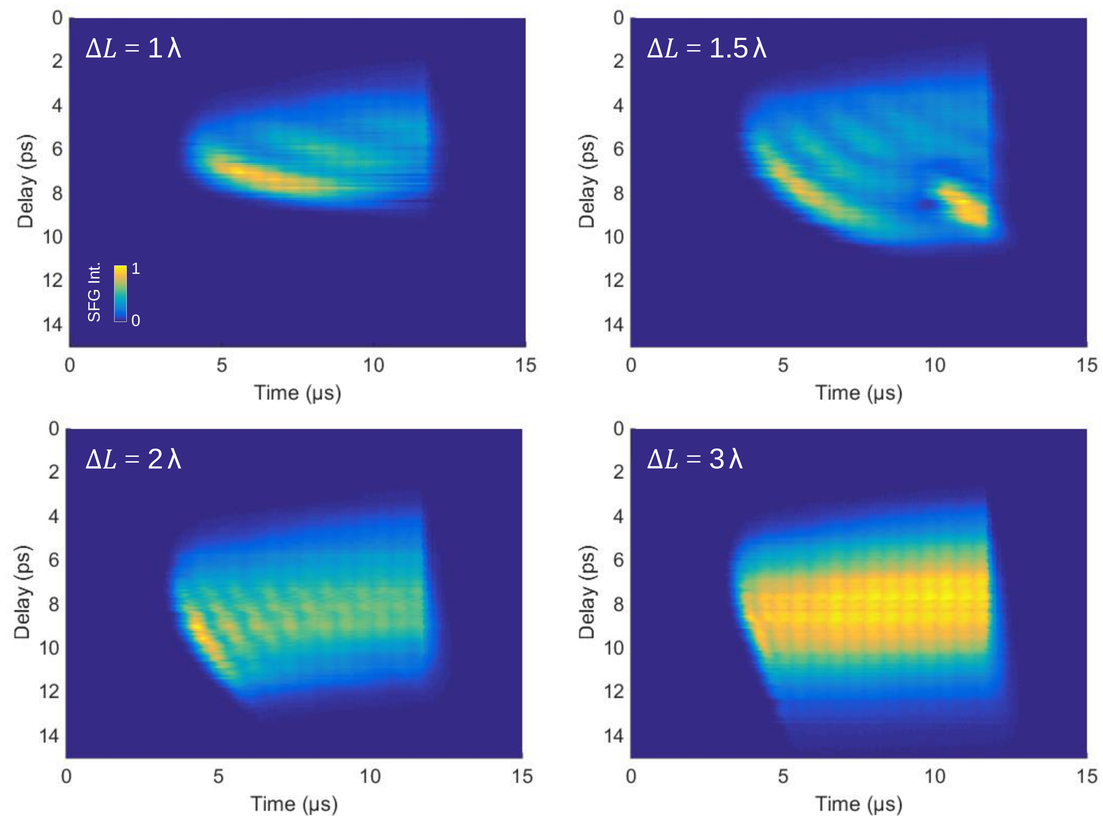
- absolute timing determination between FEL (***1***) and table-top laser (***2***) pulse by balanced optical cross-correlation (BOC) based on SFG



$$BOC(\tau,\Delta t) = \frac{XC(\tau)}{\max(XC(\tau))} - \frac{XC(\tau+\Delta t)}{\max(XC(\tau+\Delta t))}$$

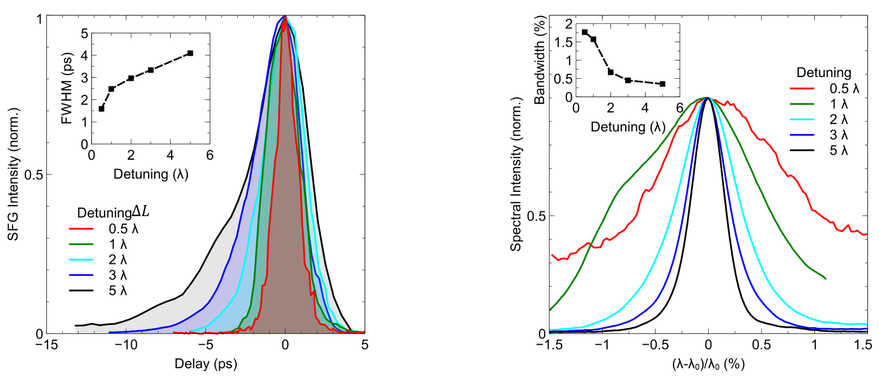
Macro-Pulse Structure

- Micro-pulse evolution within macro-pulse dependent on cavity detuning
- Determined by complex interplay of e⁻ bunches and optical pulse round trips



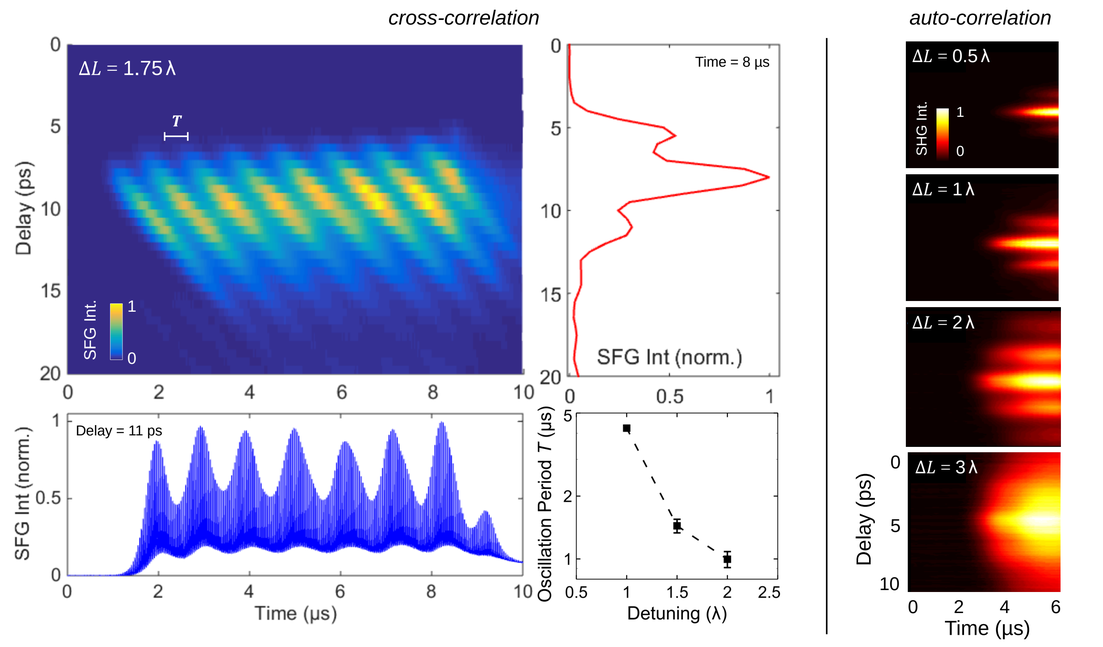
Micro-Pulse Shape

- Control of pulse duration / spectral bandwidth by cavity detuning ΔL
- Transition from Gaussian to asymmetric shape (cf. *Knippels et al., PRL **83**, 1578 (1999)*)
  → narrowband radiation (0.3 %) for high-resolution spectroscopy



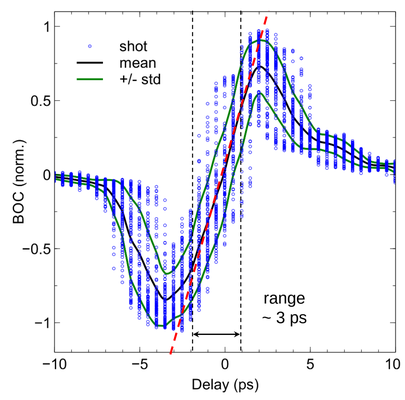
Limit-Cycle Oscillations

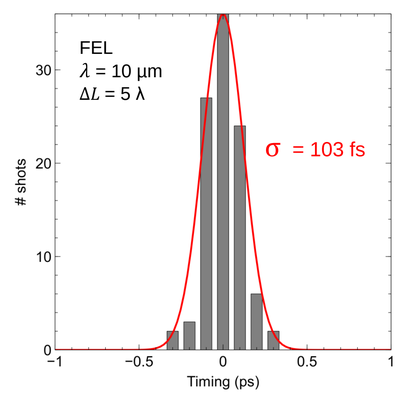
- For small cavity detuning: power oscillations within macro-pulse and formation of sub-pulses
- self-sustained oscillation is stable 'limit cycle' solution of nonlinear e⁻ / photon interaction system (cf. *Jaroszynski et al., PRL **70**, 3412 (1993)*)



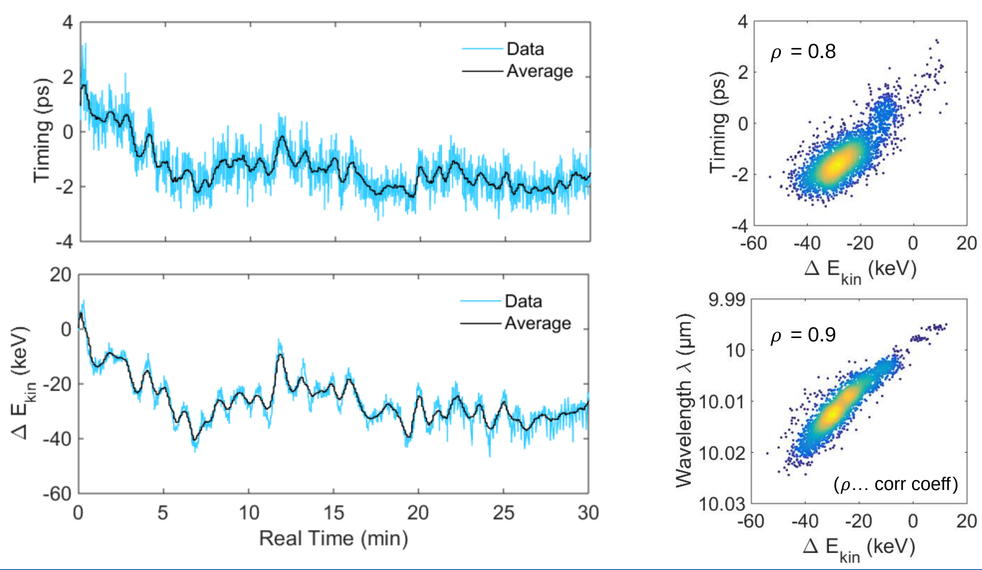
Timing Jitter + Drift

- Shot-resolved FEL – table-top balanced optical cross-correlation (BOC)
- Pulse timing jitter as low as σ ~ 100 fs (rms) at 27 MHz repetition mode
  → sub-ps time-resolution pump-probe experiments

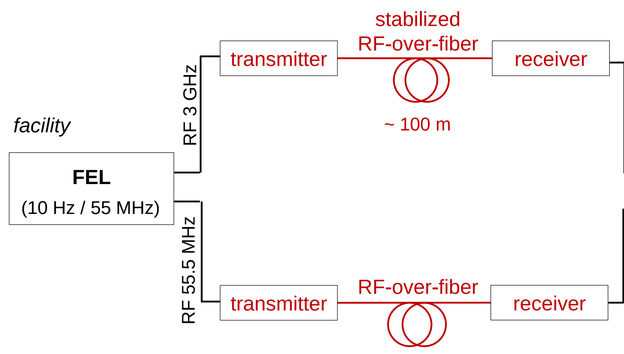




- Linear correlation of long-term drift with kinetic energy fluctuations of accelerated e⁻ bunches



FEL – Table-Top Laser Synchronization



- Table-top laser: Tb^{3+}-doped fiber oscillator (τ_P ~ 100 fs, λ ~ 1055 nm)
- Timing distribution by low-jitter reference clock transfer system (Libera Sync, rms < 9 fs [10 Hz … 10 MHz])

*Zorzut et al., Proc. FEL**2015**, 126 (2015)*