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: $\lambda = 3...50 \mu m \pm 6...100$ THz
  - addressing vibrational energy levels of matter
- Macro-/Micro pulse structure:
  - macro-pulse: $\tau_{\text{p}} = 10 \mu s, E_{\text{peak}} \leq 100 \mu J, \tau_{\text{FWHM}} = 10$ Hz
  - micro-pulse: $\tau_{\text{p}} = 0.3...10$ ps, $E_{\text{peak}} \leq 10 \mu J, \tau_{\text{FWHM}} = 1$ GHz (or 27/55 MHz)
- Institute internal use for (non)linear solid-state and molecular spectroscopy

- Synchronized tabletop 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 tabletop laser
- Absolute timing determination between FEL (1) and tabletop laser (2) pulse by balanced optical cross-correlation (BOC) based on SFG

Micro-Pulse Shape
- Control of pulse duration / spectral bandwidth by cavity detuning $\Delta \tilde{L}$
- Transition from Gaussian to asymmetric shape (cf. Knipps et al., PRL 83, 1578 (1999))
  - narrowband radiation (0.3%) for high-resolution spectroscopy

Macro-Pulse Structure
- Micro-pulse evolution within macro-pulse dependent on cavity detuning
- Determined by complex interplay of a ~ bunched and optical pulse round trips

Limit-Cycle Oscillations
- For small cavity detuning: power oscillations within macro-pulse and formation of sub-pulses
- Self-sustained oscillation is a 'limit cycle' solution of nonlinear $\sigma$ / photon interaction system
  (cf. Jaroszynski et al., PRL 70, 3412 (1993))

Timing Jitter + Drift
- Shot-resolved FEL – tabletop balanced optical cross-correlation (BOC)
- Pulse timing jitter as low as $\sigma \sim 100$ 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 $\varepsilon$-bunches

FEL – Table-Top Laser Synchronization
- Table-top laser: Tb$^{3+}$-doped fiber oscillator ($\lambda = 800$ nm, $\lambda = 1055$ nm)
  - Timing distribution by low-jitter reference clock transfer system
  (Libera Sync, rms < 9 fs [10 Hz...10 MHz])