PSI

Demonstration of mode-locked frequency comb for an X-ray free-electron laser

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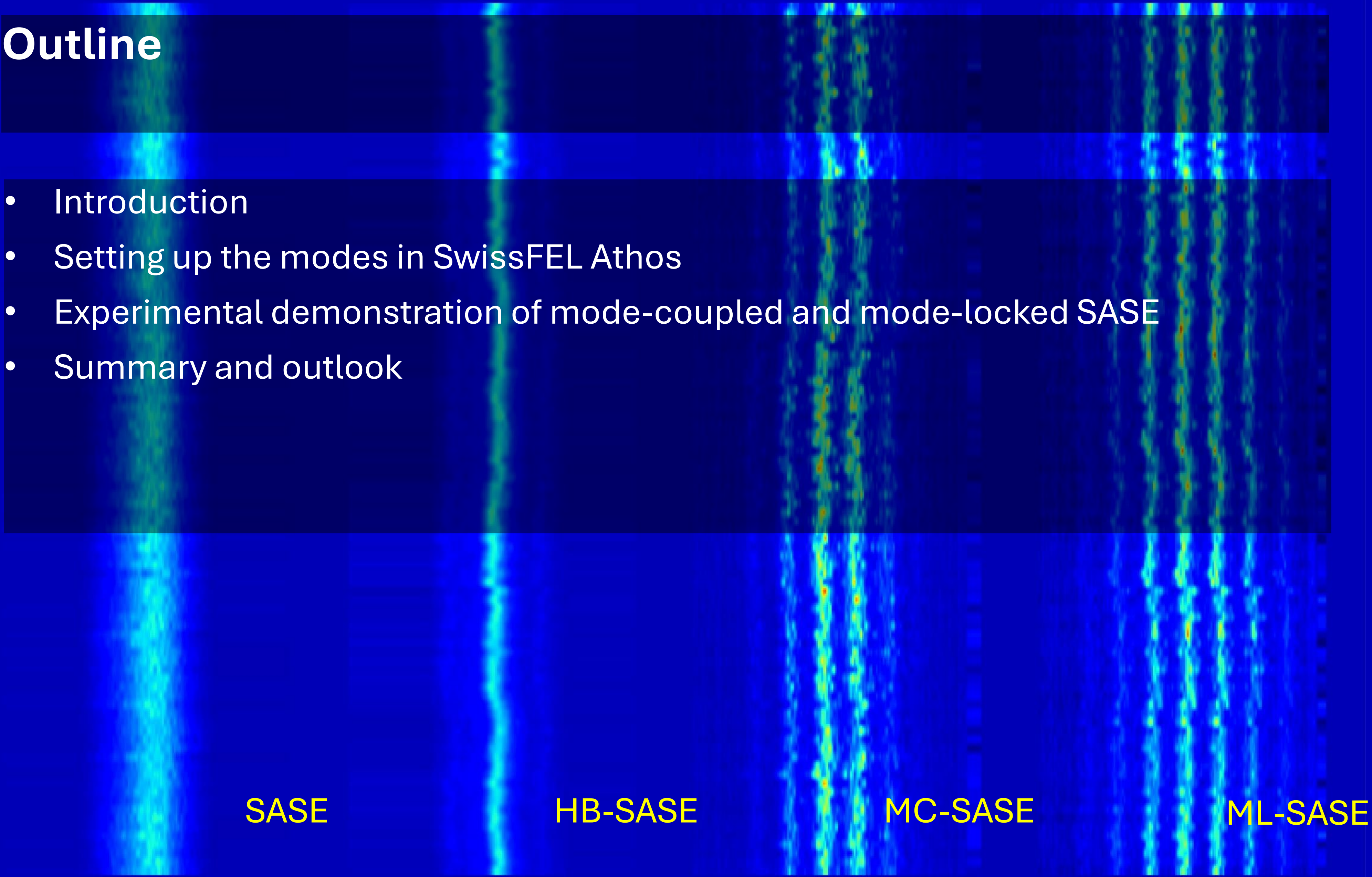
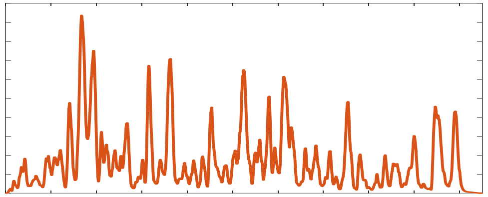
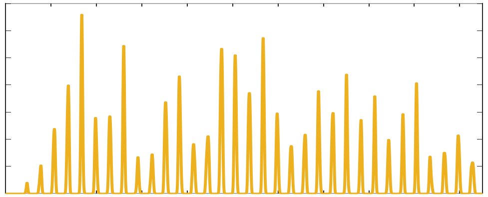
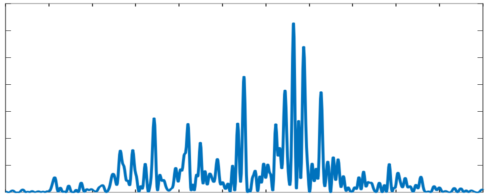
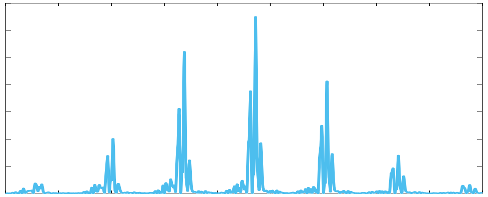
Outline

- Introduction
- Setting up the modes in SwissFEL Athos
- Experimental demonstration of mode-coupled and mode-locked SASE
- Summary and outlook



Concept

- Standard (self-amplified spontaneous emission) SASE: FEL process starts from beam intrinsic noise.
- External seeding: periodic beam energy (or density) modulation regulates the output.
- Chicanes in between undulator modules: improves longitudinal coherence by delaying the electrons.

Time domain / Frequency domain	Uncontrolled 	Controlled, via seed laser 
Uncontrolled 	Standard SASE (SASE)	Enhanced SASE (ESASE)*
Controlled, via chicanes 	Mode-coupled SASE (MC-SASE)**	Mode-locked SASE (ML-SASE)**

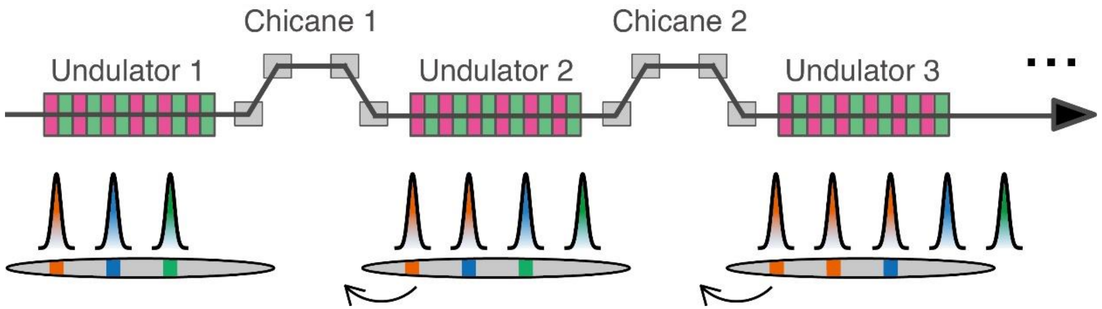
*A. A. Zholents, Phys. Rev. ST Accel. Beams, 8:040701 (2005).

**N. R. Thompson and B. W. J. McNeil, Phys. Rev. Lett., 100:203901 (2008).

Inter-undulator chicanes

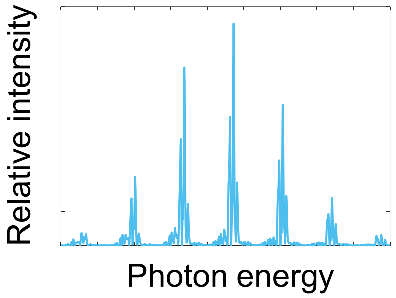
Inter-undulator chicanes are important in these modes:

- Delay e-beam without destroying bunch.
- MC-SASE: Equally delay electron beam with chicanes to build up phase correlation longitudinally.
- ML-SASE: Combine MC-SASE with periodic temporal modulation (seed laser modulation).



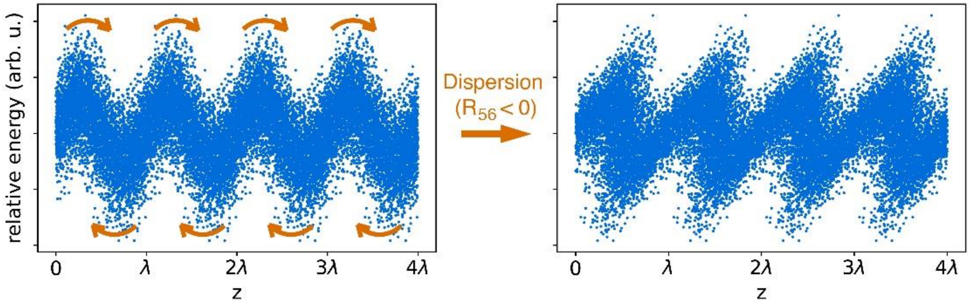
- Requirement: length of each module ≤ FEL gain length.

Simulated MC-SASE spectrum



- Ideally, using isochronous chicanes (only delay)*. Practically, using dispersive chicane instead.
- Optical klystron (OK) effect**: dispersive chicanes convert energy modulation into density modulation, reducing gain length. Less energy spread ➡ More delay before saturation.

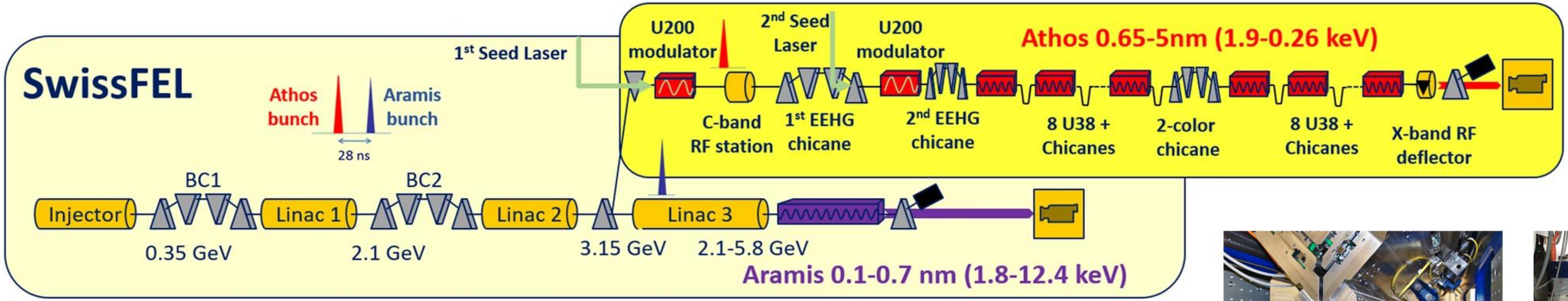
OK effect schematic



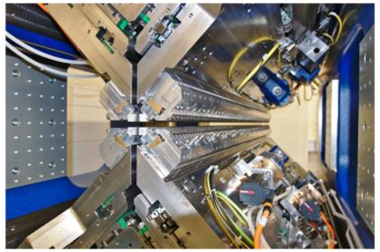
*B. W. J. McNeil *et al*. Phys. Rev. Lett.,110:134802 (2013).

**E. Prat *et al*. Appl. Phys. Lett., 119(15):151102 (2021).

Athos, Soft X-ray beamline designed for these modes



- SwissFEL soft X-ray beamline, Athos*:
  - 16 undulators modules, 52 periods $\times$ 3.8 cm $\approx$ 2 m each.
  - Dispersive chicanes in between undulators (up to $\approx$ 5 fs).
  - Two seeding sections before undulators.
  - A two-color chicane in the middle (delay up to 500 fs).
  - A transverse deflector after the undulator line**.



Undulator

Chicane
(20 cm each)

- These settings allow various modes, including MC-SASE, and ML-SASE (unique to Athos).

*E. Prat *et al*. Nat. Commun. 14, 5069 (2023).
**E. Prat *el al*. Adv. Photonics. 7:026002 (2025).

Setting up MC-SASE mode in Athos

1. Reduce compression (with respect to standard operation):
   - Lower current (~ 3 kA to ~ 0.5 kA): gain length ≈ undulator module length.
   - Lower energy spread: longer delay can be applied before over-bunching.

2. Choose output photon energy to be $500 \sim 600$ eV:
   - For comparison with standard SASE and optimal spectral diagnostics.

3. Apply the inter-undulator chicanes for MC-SASE:
   - Fine tuning the delays (phase-shifters) for better performance.

MC-SASE with different delays

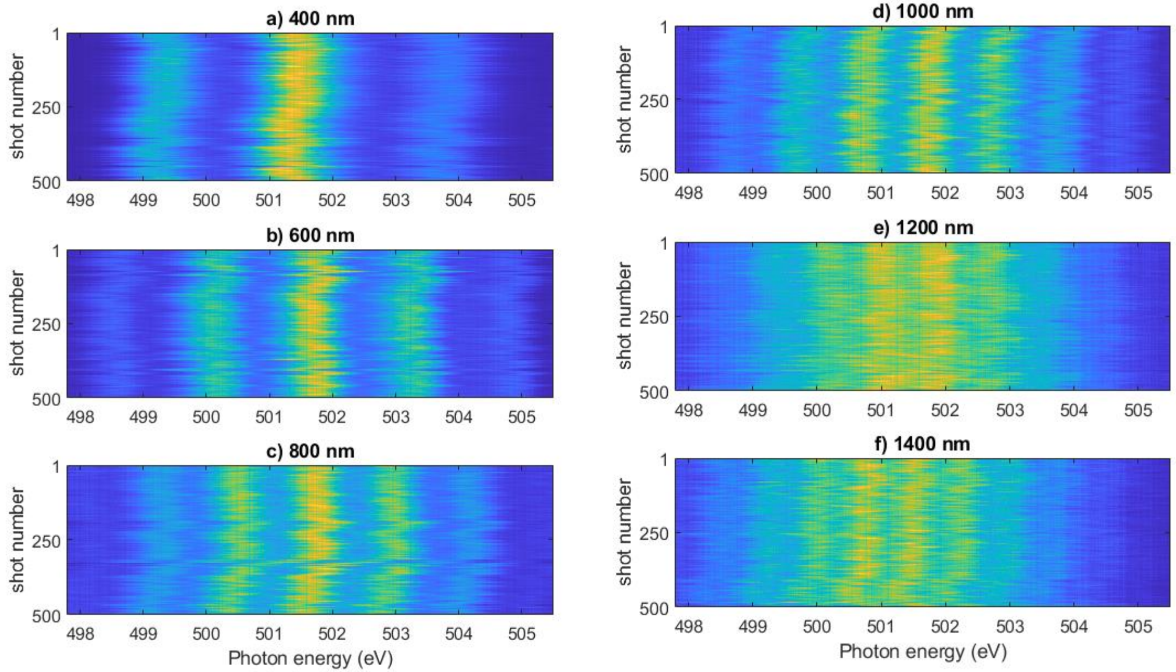
- A frequency comb shows up as expected.
- Larger total bandwidth than standard SASE.

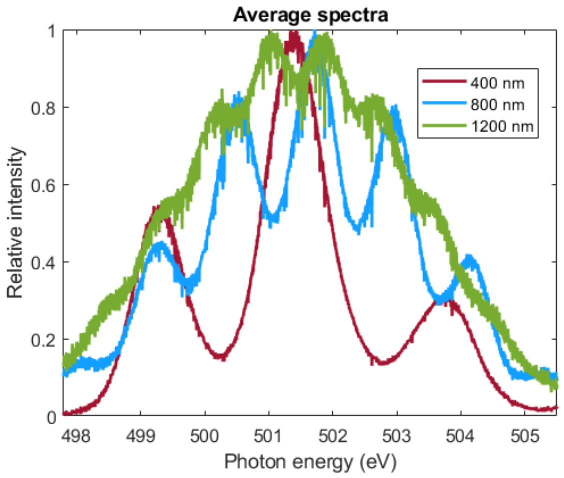
- Apply different delays, ranges from $400\ \mathrm{nm}\ (1.3\ \mathrm{fs})$ to $1400\ \mathrm{nm}\ (4.7\ \mathrm{fs})$.
  - Record 500 consecutive single-shot spectra.

- Stable frequency comb structure.
- Line separation agrees with expectation:

  mode delay = chicane delay + slippage per module

Single-shot & averaged spectra with different delays





Experimental demonstration mode-locked SASE

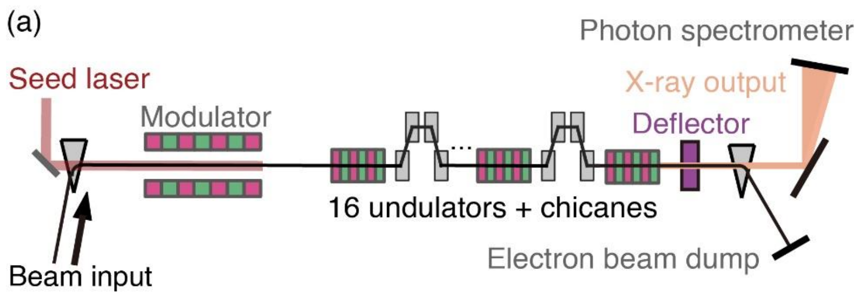
Combining MC-SASE with seed laser:

- Local energy chirp variation selects the lasing region.
- 790 nm laser: ≈ 425 fs FWHM, ≈ 4.2 mJ pulse energy.
  263 nm laser: ≈ 195 fs FWHM, ≈ 0.1 mJ pulse energy.
- Optimize overlap (spatial & temporal) with phase space measurements.

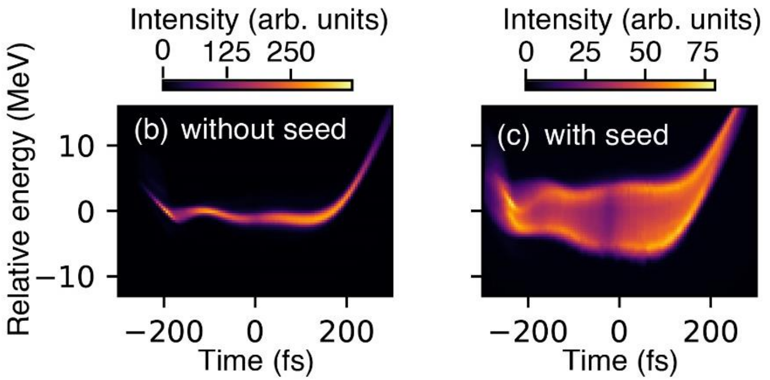
- Laser induced energy spread > 4 MeV for 790 nm seed laser (and > 1 MeV for 263 nm seed laser).

Diagnostics:

- Measuring single-shot spectra with photon spectrometer (grating monochromator).
- Measuring electron beam phase space.



Phase space for 790 nm seed laser



Spectral evidences of mode-locked SASE

Spectral evidences of ML-SASE:

1. Lower energy, bigger spectral bandwidth (corresponds to shorter spikes) and better interference contrast.

2. Comparing auto-correlation plots.

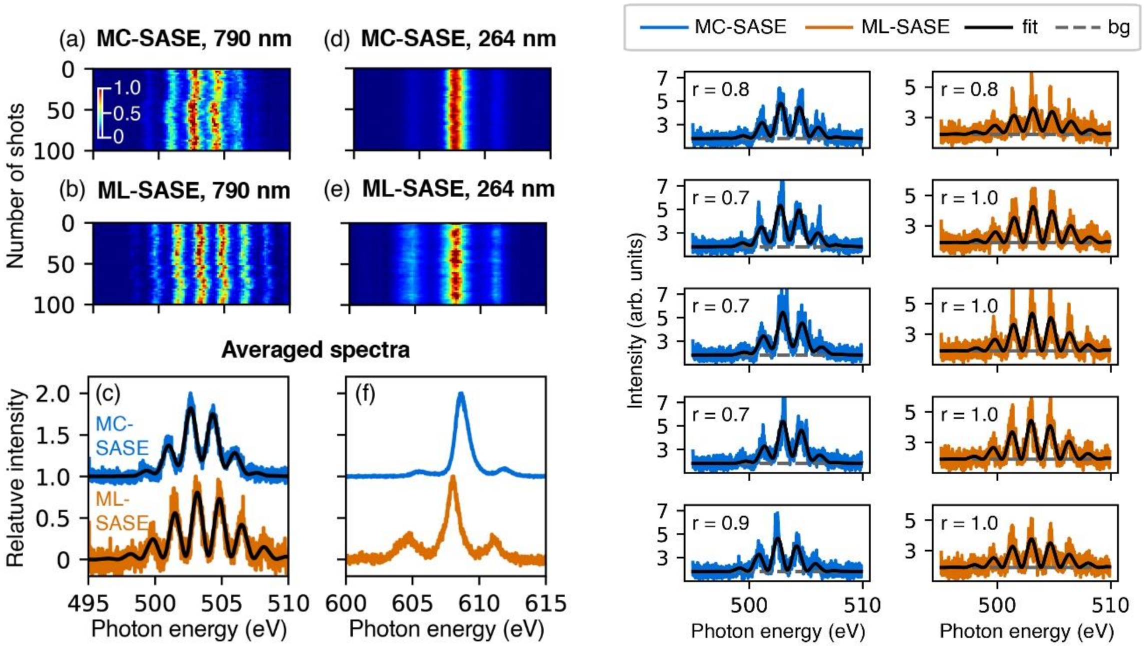
3. Resonant behaviour during chicane delay scan
   - Optimal working point correspond to:
     chicane delay + slippage = seed laser wavelength

4. Spectrum center change during seed laser energy scan.
   - Suggesting the favoured lasing region loses energy in the laser modulation.

Spectral analysis

Average

Single-shot (790 nm case)



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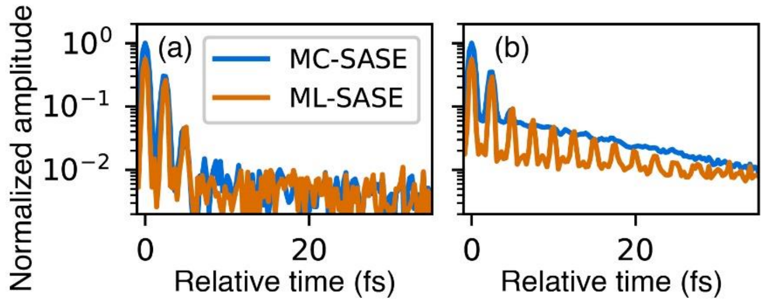
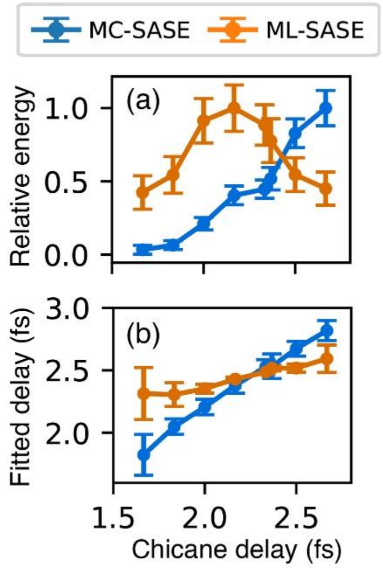
Spectral analysis

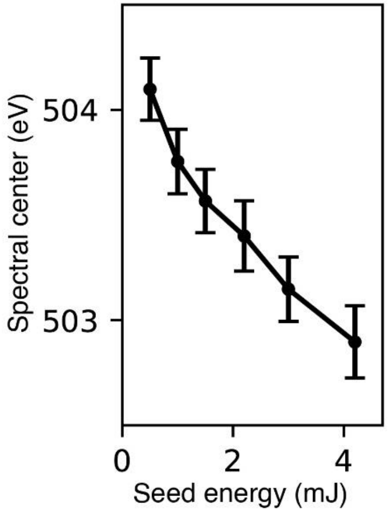
Auto-correlation averages
with/without phase information



Chicane delay scan



Seed laser energy scan

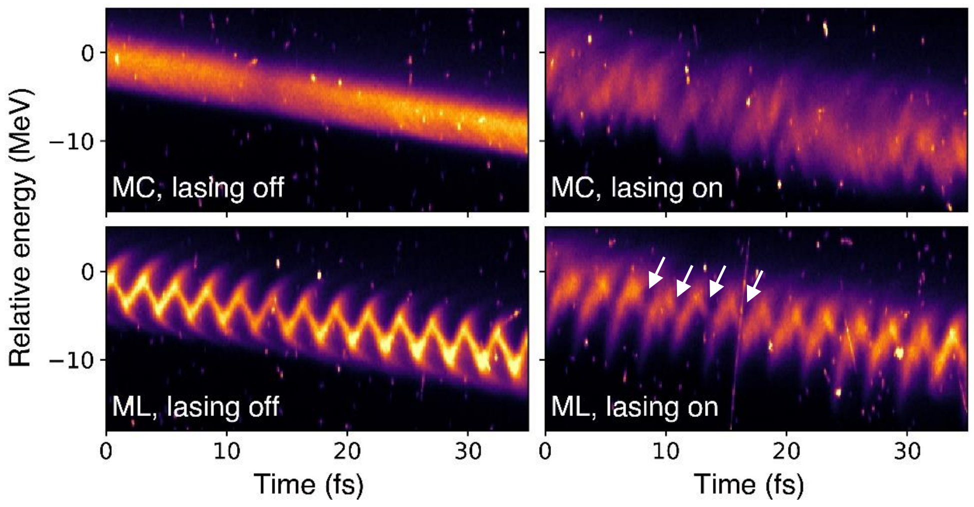


Temporal evidences of mode-locked SASE

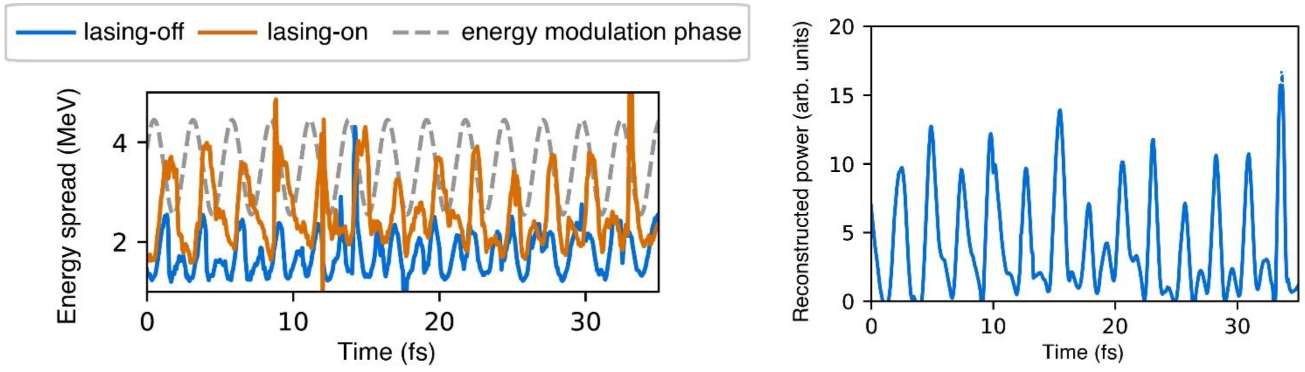
Temporal evidences of ML-SASE:

- Increase the streaking field and optimize the measuring optics to reach sub-femtosecond resolution.
- The energy modulation induced by 790 nm seed laser is observable.

High-resolution phase space measurements



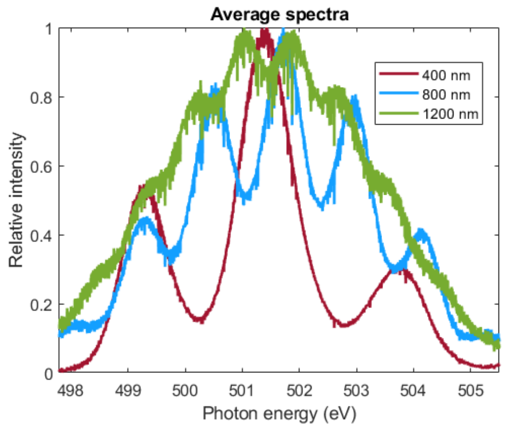
Fitted energy spread & reconstructed power for ML-SASE cases (spike width resolution limited)

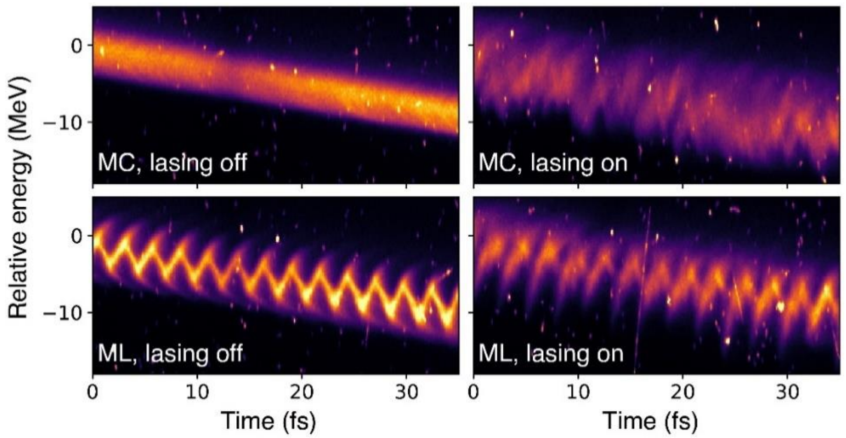


The lasing is preferred at the falling edge of the energy modulation, consistent with the simulations & spectral results.

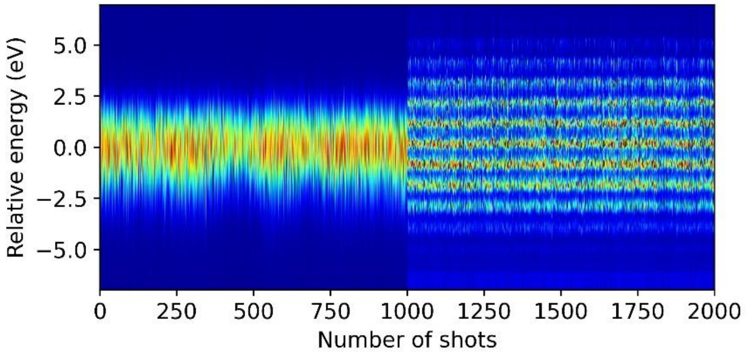
Summary and outlook

- Summary
  - SwissFEL Athos beamline features intra-undulator chicanes, seeding-stages, and high-resolution electron beam diagnostics.
  - We demonstrate the proposed MC-* and ML-SASE** schemes.
  - MC-SASE: tuneable frequency combs.
  - ML-SASE: multiple evidences support the demonstration.





- Outlook
  - Further improve ML-SASE: improving electron bunch and/or apply more chicane delays to enhance temporal coherence.
  - Apply ML modes in experiments: time-resolved RIXS, time-domain/nonlinear spectroscopy, etc. (There has been a first RIXS experiment trial @ Athos using MC-SASE)



*For more details: E. Prat *et al.*, Phys. Rev. Lett., 133:205001 (2024).
**For more details: W. Hu *et al.*, Phys. Rev. Lett., 135:265001 (2025).

Thanks for your attention!

Thanks to all technical groups involved in the operation of SwissFEL.

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