HERO beamtime

SwissFEL Exchange Meeting

Wenxiang Hu on behalf of the HERO team
23/02/2026

Outline

- Overview of the beamtime
- Introduction to EEHG and ML-SASE
- Progress on EEHG
- Progress on ML-SASE
- Conclusions and outlook

Overview

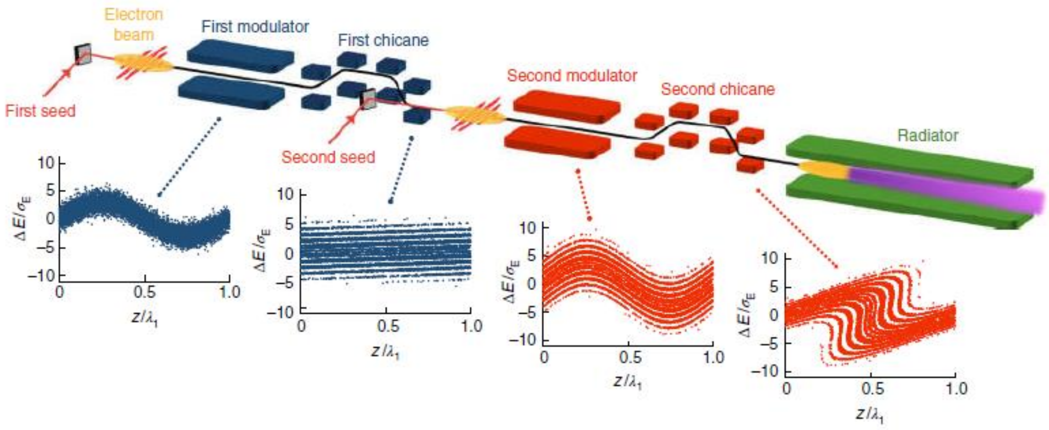
- Tuesday to Friday: EEHG commissioning.
  - Beam setup
  - Optimize EEHG at different photon energies
  - Measure spectra using different apparatus
- Saturday and Sunday: MC- / ML-SASE commissioning.
  - MC- / ML-SASE at different photon energies.
  - Measure spectra using spectrometers at Furka.

Introduction to EEHG

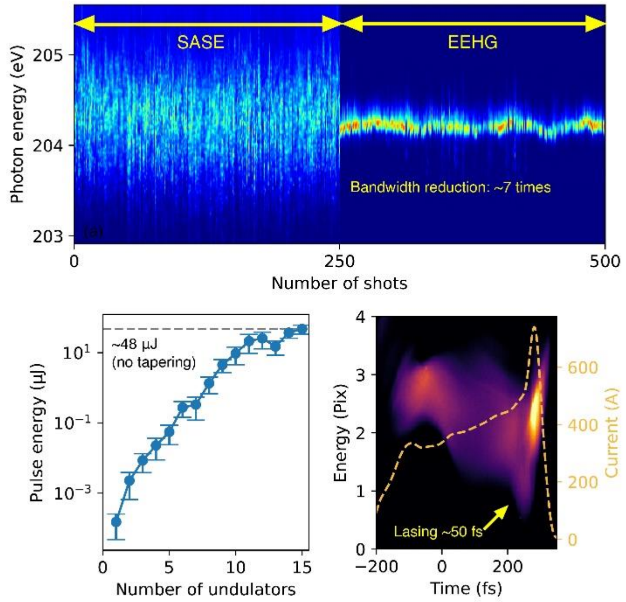
Echo-enabled harmonics generation (EEHG):

- Modulating the electron beam to improve the longitudinal coherence of the XFEL output.
- Up-conversion of the external (seed) laser (~265 nm): For example, 70 harmonics = 265 nm / 70 = 3.8 nm, or 327 eV.
- Full coherent output in principle.

Schematic*



Performance from previous EEHG beamtime (~50 uJ, 200 eV).



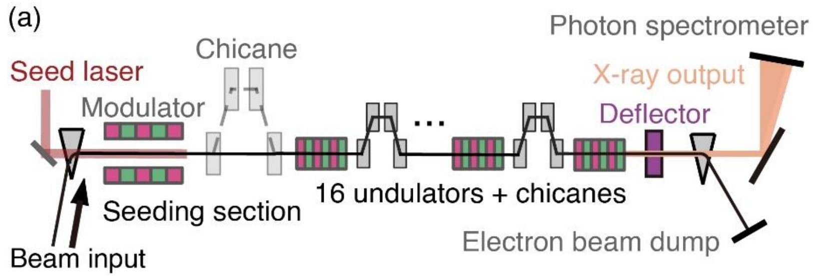
*R. Ribič *et al.* Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser. *Nat. Photonics* **13**, 555–561 (2019).

Introduction to MC- / ML-SASE

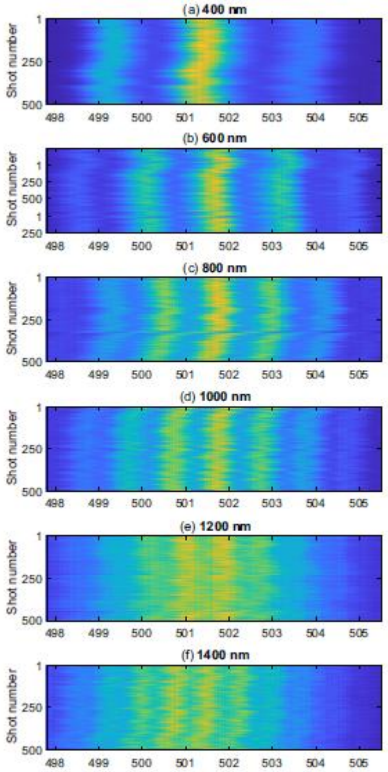
Mode-coupled / Mode-locked SASE (MC- / ML-SASE):

- MC-SASE: Use the inter-undulator chicane delays to improve the (temporal) coherence of the output. Results in a frequency comb.
- ML-SASE: additionally use a seed laser to confine the lasing region. Results in a pulse train in time and a frequency comb.

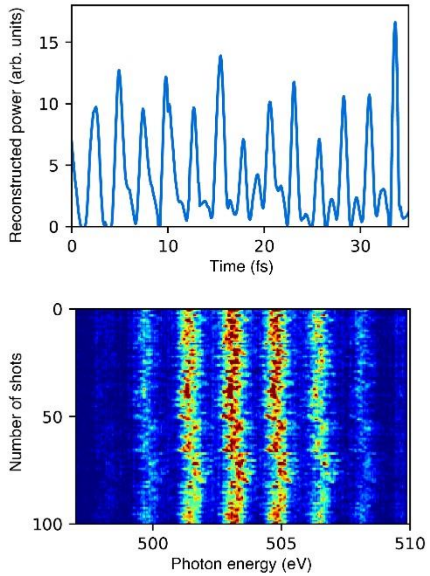
Schematic*



MC-SASE**



ML-SASE*



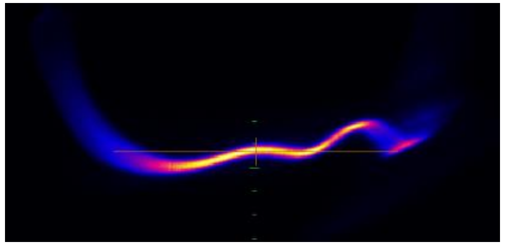
*W. Hu *et al.* Demonstration of Mode-Locked Frequency Comb for an X-Ray Free-Electron Laser. *Phys. Rev. Lett.* **135,** 265001 (2025).
E. Prat *et al.* Experimental Demonstration of Mode-Coupled and High-Brightness Self-Amplified Spontaneous Emission in an X-Ray Free-Electron Laser. *Phys. Rev. Lett*. **133, 205001 (2024).

EEHG commissioning

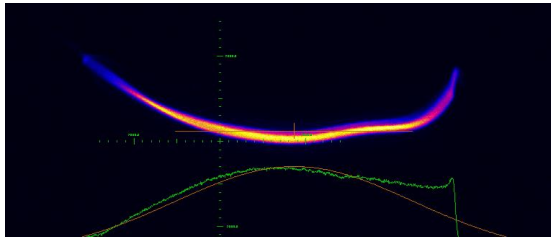
Beam setup

- Combining single-stage compression (current ~500 A), **horn-cutting**, and a **closed dispersion** Switchyard optics setup allows a **flat** and **reproducible** electron beam phase space.

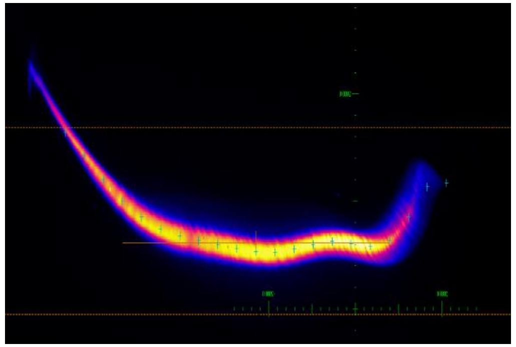
Typical phase space during previous EEHG beamtimes

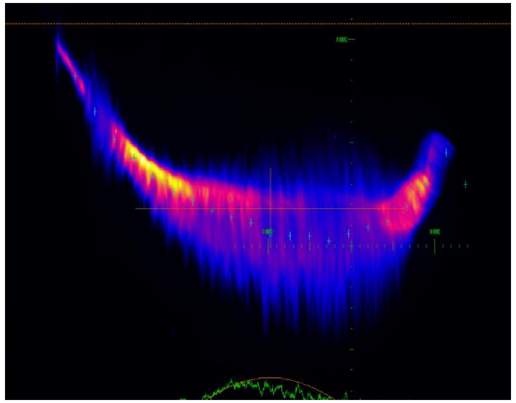


Measured October 2025 (with a similar setup as this beamtime)



Measured during this beamtime

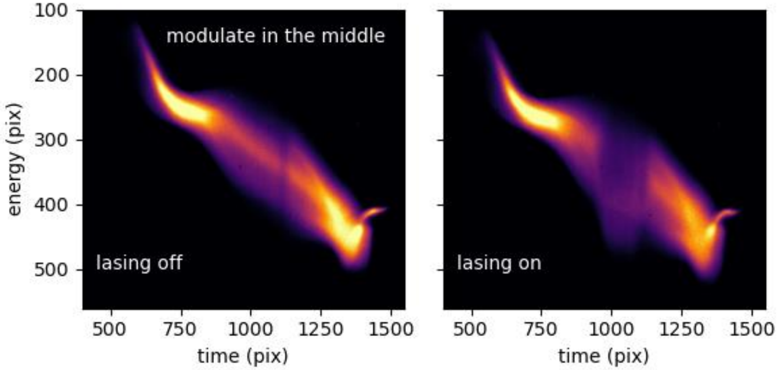




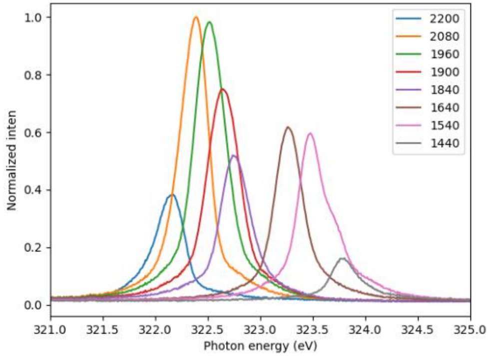
Optimize EEHG performance at different photon energies

- With the new beam setup, we demonstrated gain & saturation up to 450 eV (~97 harmonics).
  - Pulse energy: ~ 26 / 17 / 12 uJ at 320 / 405 / 450 eV; Pulse duration ~60 fs.
- With the change of second seed laser wavelength, demonstrated wavelength tunability of ~ 2 eV at 320 eV (almost covering the full range).

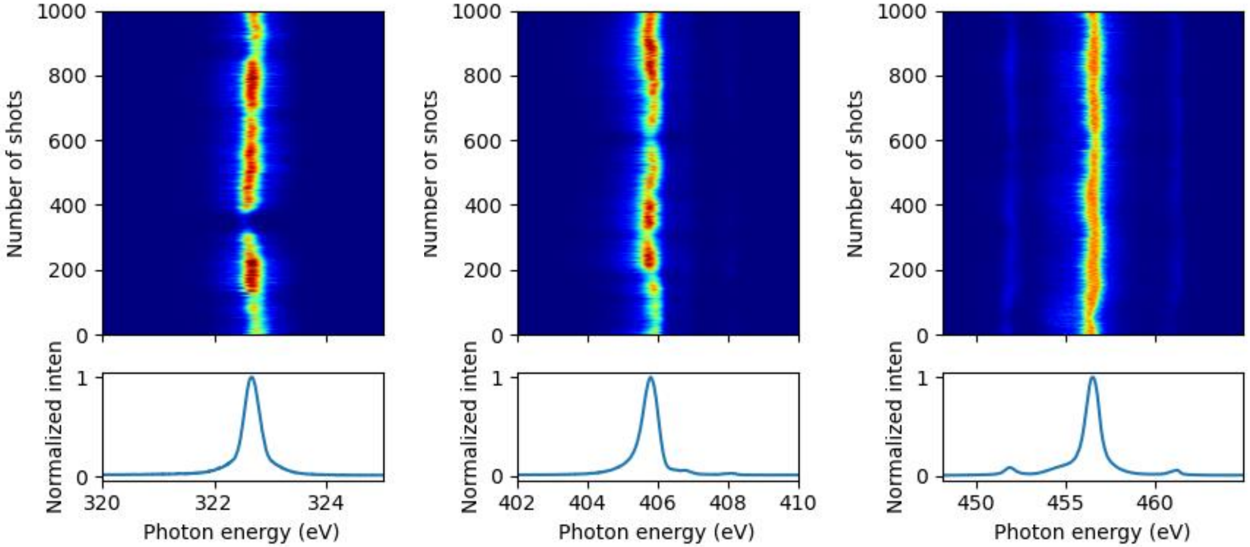
Beam phase space



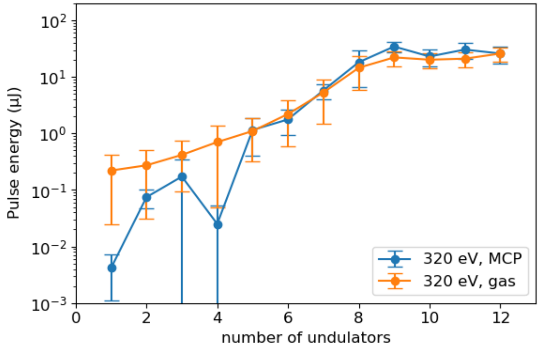
Wavelength tunability



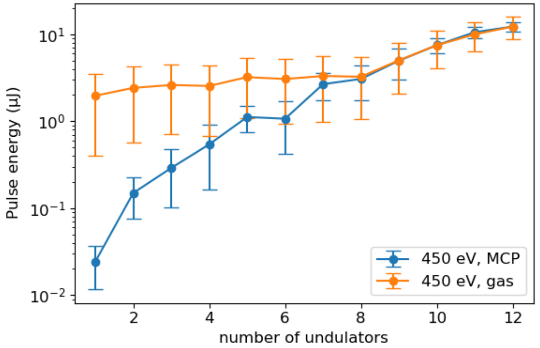
Spectra



Gain @ 320 eV

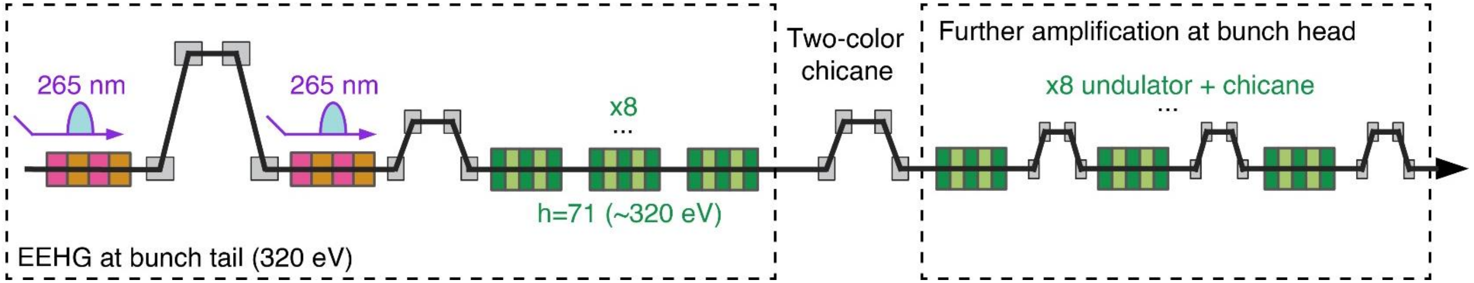


Gain @ 450 eV

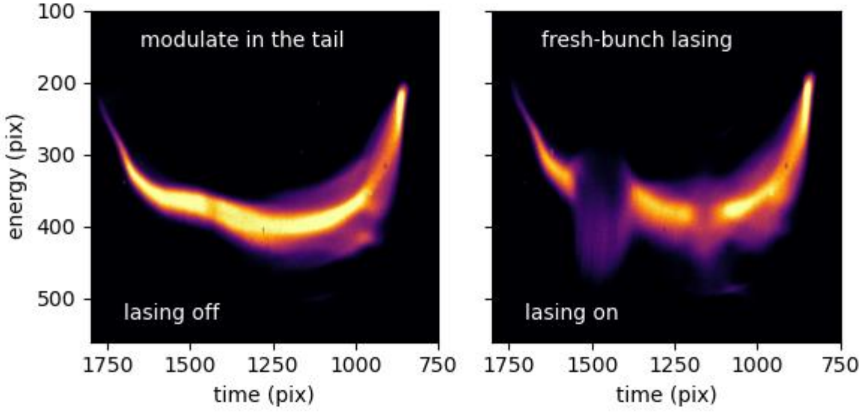


Advanced schemes to further improve performance

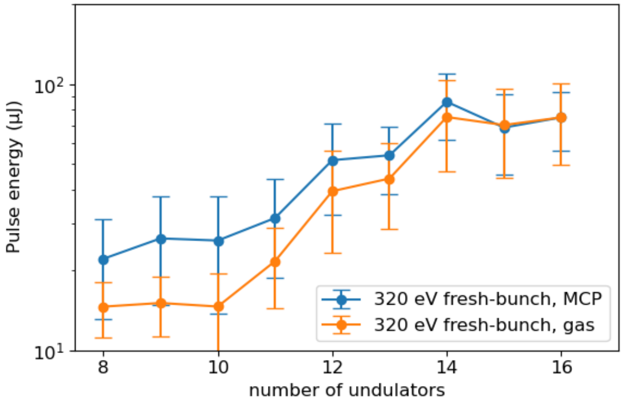
- Beam much longer than lasing region & close to saturation with 8 modules: fresh-bunch schemes.
- Scheme 1: multi-stage amplification (~75 uJ at 320 eV, spectral FWHM increased to ~0.5 eV).



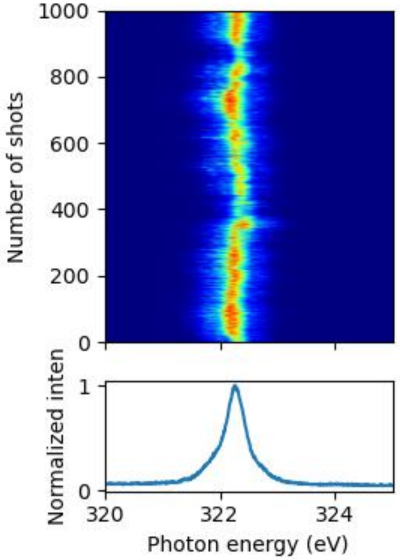
Beam phase space



Gain

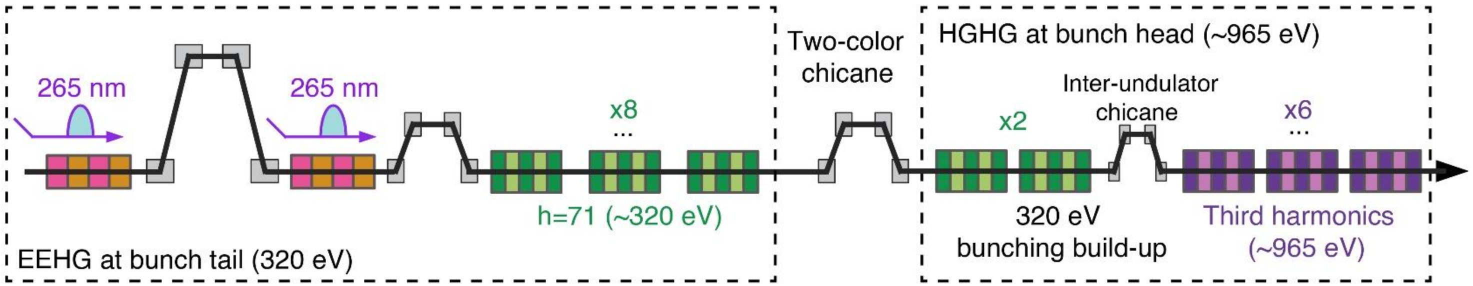


Spectra

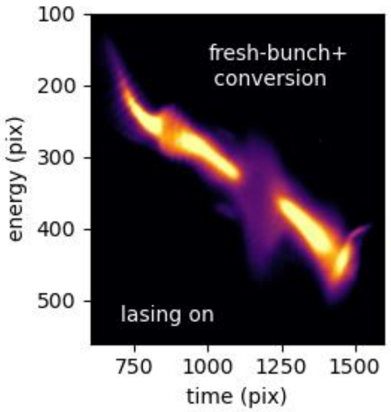


Advanced schemes to further improve performance

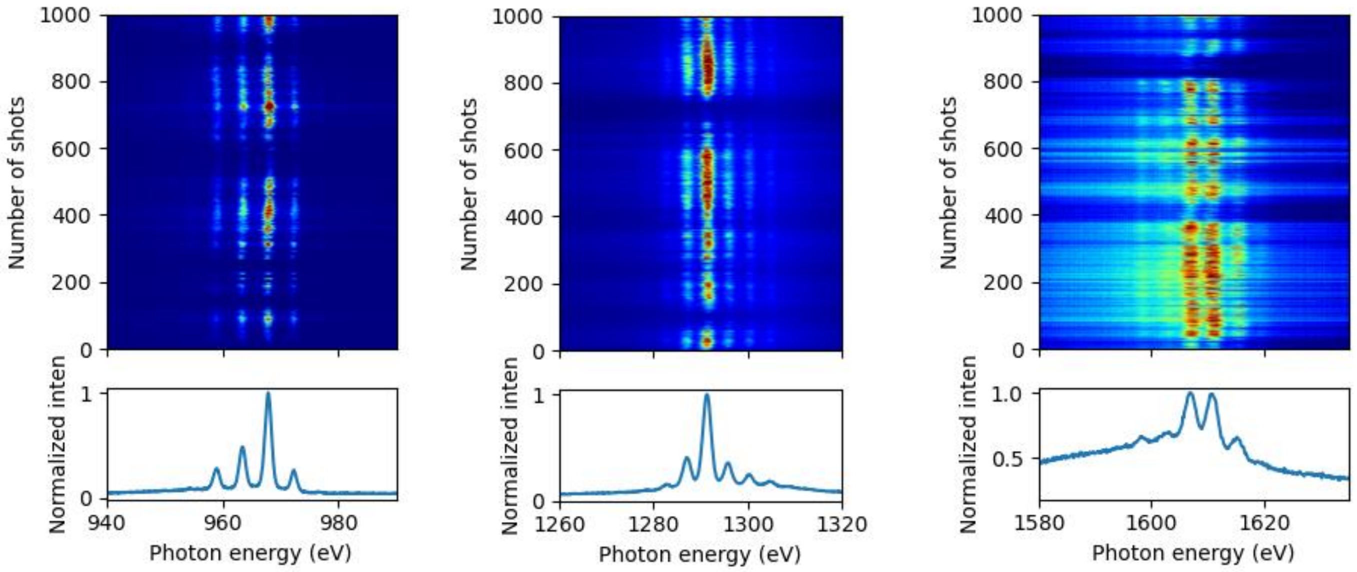
- Beam much longer than lasing region & close to saturation with 8 modules: fresh-bunch schemes.
- Scheme 2: further harmonic up-conversion (coherent signal up to 1.6 keV with low gain < uJ level)



Beam phase space



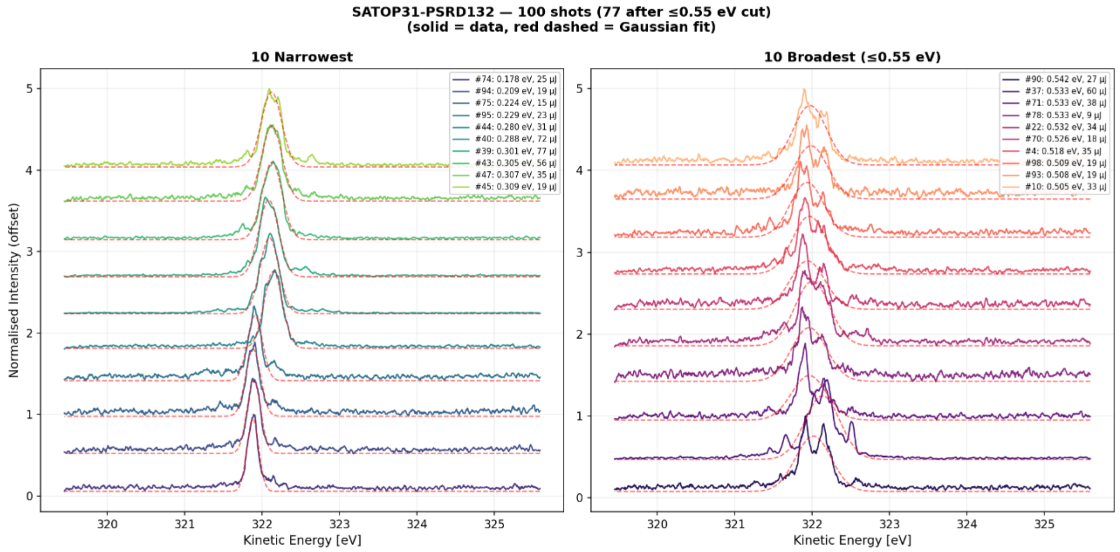
Spectra (taken at 320*3 / 320*4 / 320*5 eV)



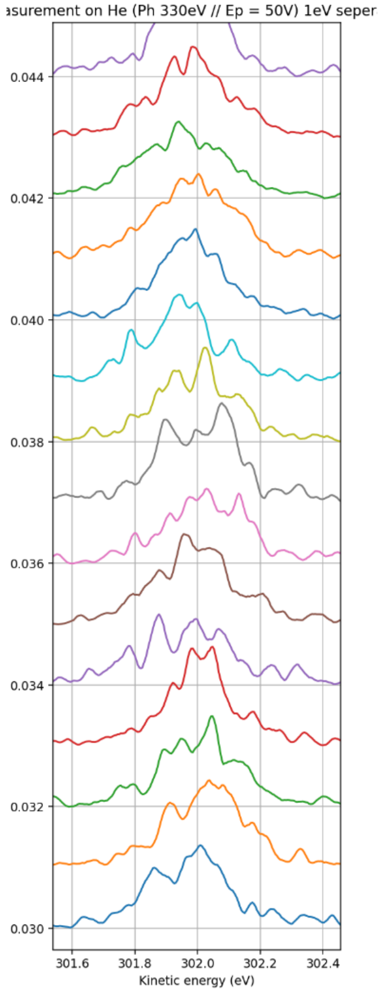
Measure spectra using different apparatus

- Acknowledgements to the photon diagnostics team and to the Maloja team!
- 320 eV EEHG spectra: both measurements shows ~0.3 eV FWHM (~3 eV for SASE). Time-BW product estimated to be ~4.4 with a pulse duration of ~60 fs.
- There is some sub-structures in the line.

Spectra taken using mono + MCP detector



Spectra taken from Maloja
(Hemispherical analyser)

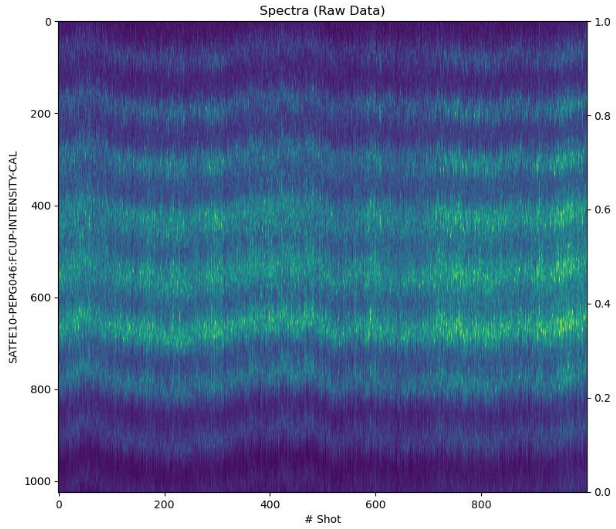


MC- / ML-SASE commissioning

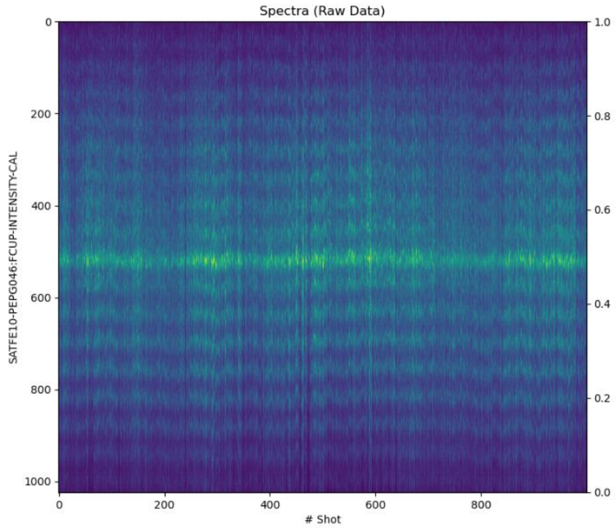
MC- / ML-SASE spectra at different photon energies

- Measuring MC- / ML-SASE at higher photon energies.
  (correspond to larger total bandwidth, or shorter single pulse durations)
- Setting undulators to different frequency modes to further extend the FEL gain bandwidth.
  (better contrast & more sidebands)

ML-SASE at 520 eV
(pulse delay 800 nm)



ML-SASE at 995 eV
(pulse delay 800 nm)



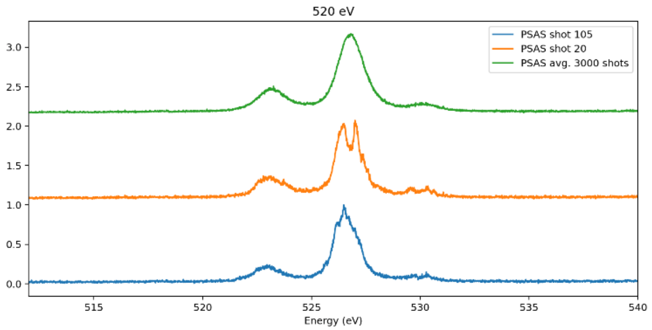
Mode commissioning at Furka end station

PSI

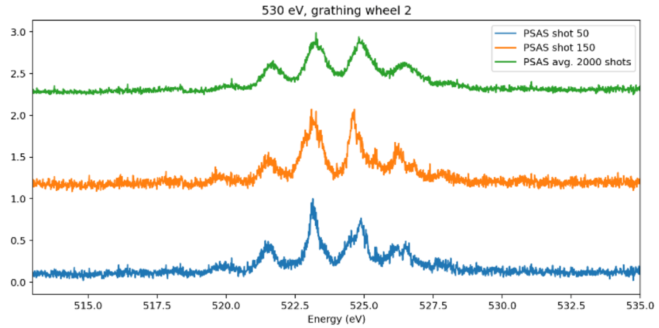
- Acknowledgements to the Furka team!
- Single-shot MC-SASE spectra is observable using SASE spectrometer.
- Average (and in some cases single-shot) spectra also work for RXIS spectrometer.
- Data taken both with elastic scattering and RXIS sample.

Furka SASE spectrometer

520 eV,
250 nm delay

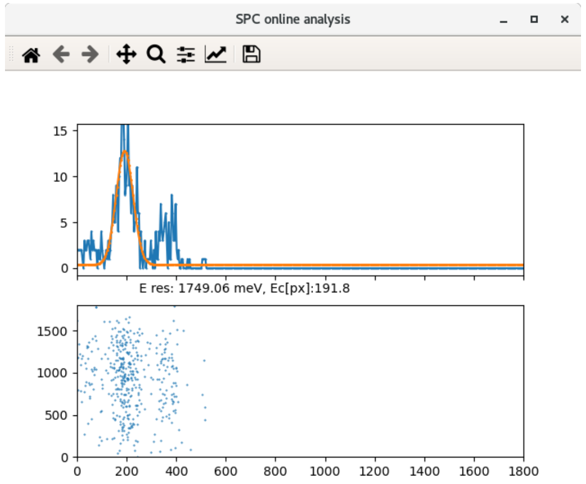


520 eV,
500 nm delay



Furka RXIS spectrometer

520 eV,
250 nm delay



Conclusion and outlook

EEHG:

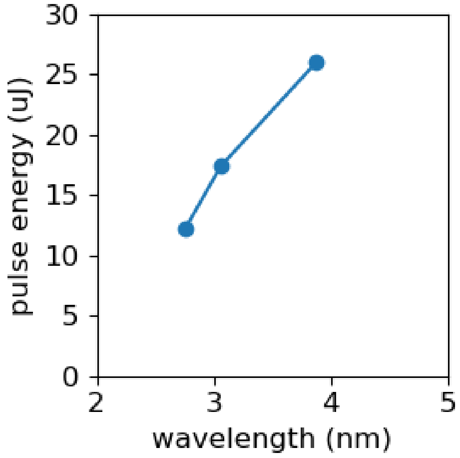
- Demonstrated EEHG up to 450 eV (pulse energy comparable to FERMI's results).
- Reach ~75 uJ coherent radiation at 320 eV by multi-stage amplification.
- Observed coherent signal up to 1.6 keV, using EEHG-HGHG configuration. Unable to measure the pulse energies as the fundamental pulse energy is much larger. Will work on with it in future studies.
- There is a strong intensity fluctuation on a time scale of 15 s. Next EEHG MD time will be dedicated to find the reason and to stabilize combined with data mining to find correlations to the fluctuation.
- Currently, EEHG performance is limited by the energy spread and the seed power. This limits the beam current to ~500 A. Higher current could improve the performance, but it isn't foreseeable in the near future.

MC- / ML-SASE:

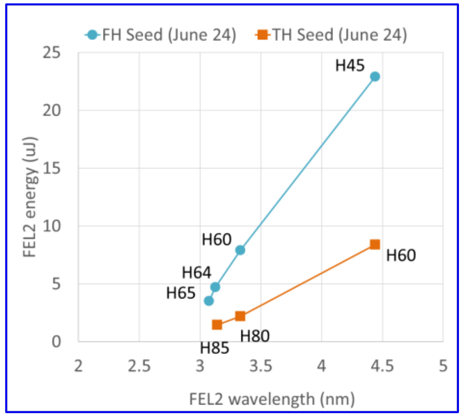
- Demonstrated larger spectral bandwidth at higher photon energies.
- Single-shot measurement of MC-SASE mode using spectrometer at Furka.
- Using MC-SASE, data is taken both with elastic scattering and RIXS sample.

More detailed analysis envisioned.

Single stage EEHG from this beamtime



FERMI EEHG results (2025)



Acknowledgements

- Beam Dynamics
    - Sven Reiche, Eduard Prat, Philipp Dijkstal
- Laser
    - Alexandre Trisorio, Andreas Dax, Carlo Vicario, Martin Huppert
- Diagnostics
    - Christopher Arrell, Rolf Follath, Pavle Juranic
- Maloja
    - Andre Al Haddad, Kirsten Schnorr, Antoine Sarracini, Gregor Knopp
- Furka
    - Elia Razzoli, Elizabeth Skoropata, Hiroki Ueda, Eugenio Paris

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