PAUL SCHERRER INSTITUT
PSI

Thomas Schietinger :: Paul Scherrer Institute

for the SwissFEL team

SwissFEL Status and Plans

67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources, 28 August 2023

Contents

- SwissFEL in a nutshell
  - Key systems
  - Experimental stations
  - Timeline
- Operation and performance in 2022/23
- Recent experimental highlight
- Status of special FEL modes
- Athos seed laser upgrade (EEHG)
- Outlook:
  - Mid-term improvements
  - Long-term upgrade: Porthos beamline

SwissFEL:
The Big Picture

Athos upgrades:

ESASE: λ_{seed} = 267/400/800 nm

EEHG: λ_{seed} = 267 nm

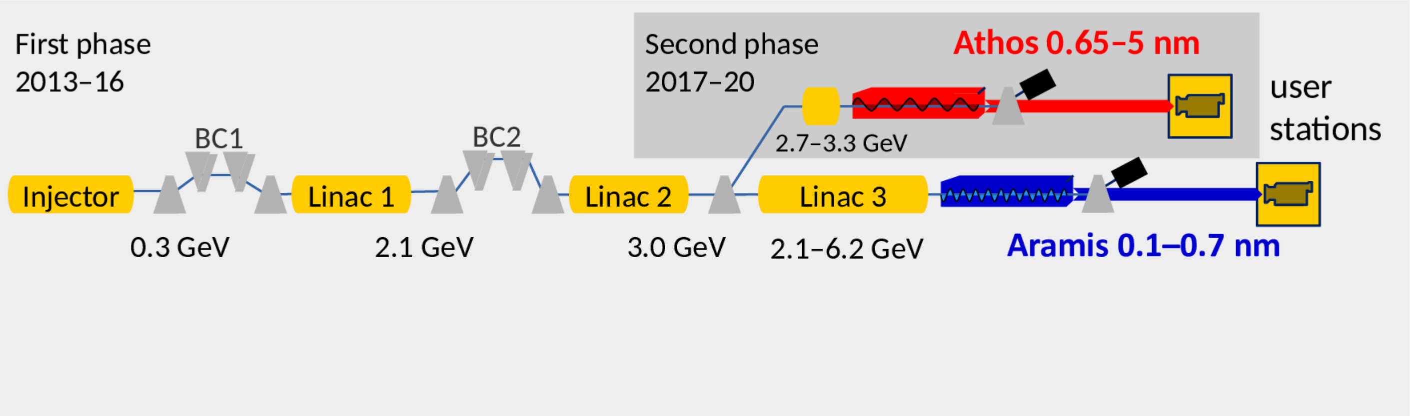
Commissioning 2022–24

Athos:

Soft X-ray FEL, λ = 0.65–5.0 nm

Variable polarization, APPLE-X undulators

First users 2021



Linac:

Pulse duration : 1–20 fs

Electron energy : up to 6.2 GeV

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz, 2 bunches

Aramis:

Hard X-ray FEL, λ = 0.1–0.7 nm

Linear polarization, in-vacuum, variable-gap undulators

First users 2018

SwissFEL:
The Big Picture

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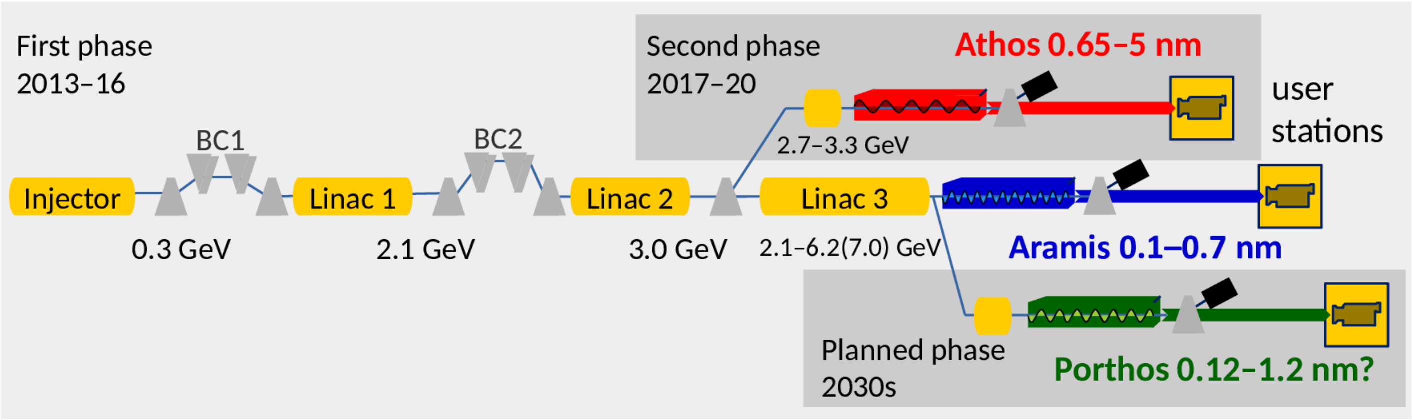


Linac:

Pulse duration : 1–20 fs

Electron energy : up to 6.2 GeV
(7 GeV after upgrade)

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz, 2 bunches
(3 bunches after upgrade)

Aramis:

Hard X-ray FEL, λ = 0.1–0.7 nm

Linear polarization, in-vacuum, variable-gap undulators

First users 2018

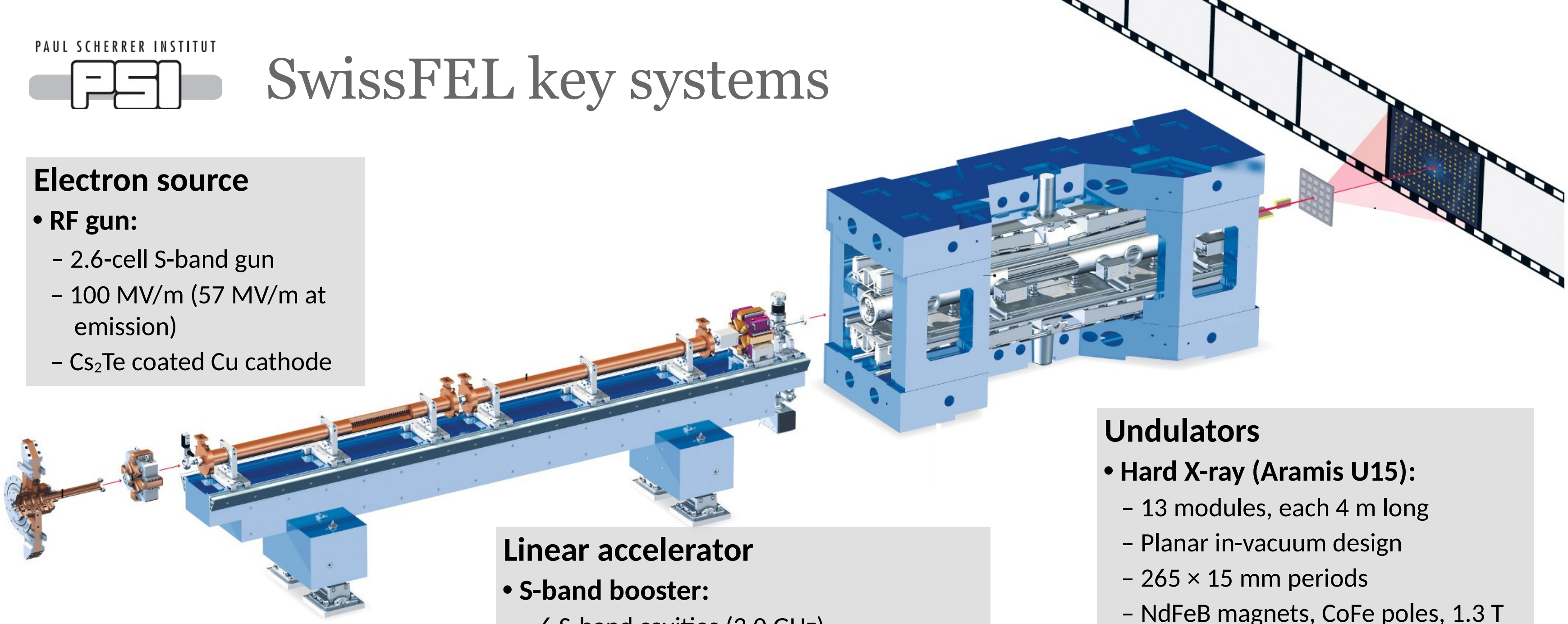
Porthos:

Hard X-ray FEL, λ = 0.12–1.2 nm?

Variable-polarization undulators (technology to be decided)

Construction: 2030s

SwissFEL key systems



Electron source

- **RF gun:**
  - 2.6-cell S-band gun
  - 100 MV/m (57 MV/m at emission)
  - Cs_2Te coated Cu cathode

- **Gun laser systems:**
  - Two identical solid state Yb:CaF_2 chirped pulsed amplifier with excellent stability and uptime.
  - Cs_2Te cathode installed since 2019 with stable performance

Linear accelerator

- **S-band booster:**
  - 6 S-band cavities (3.0 GHz)
  - 80 MeV per cavity (20 MV/m)

- **C-band linac:**
  - 27 C-band modules (5.7 GHz)
  - Four 2-m cavities per module
  - Barrel Open Cavity (BOC) RF pulse compressors
  - 240 MeV per station (30 MV/m)

Undulators

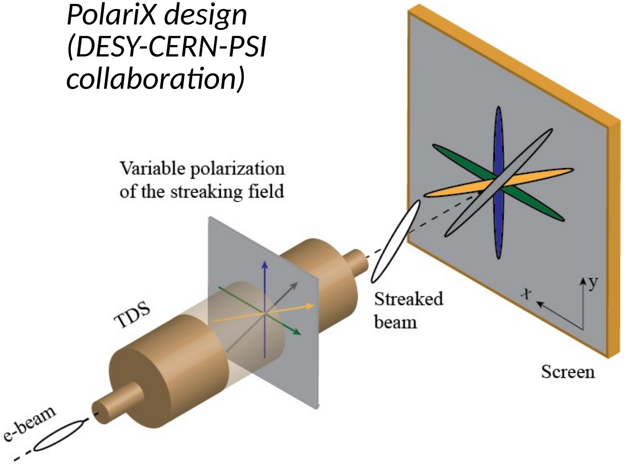
- **Hard X-ray (Aramis U15):**
  - 13 modules, each 4 m long
  - Planar in-vacuum design
  - 265 × 15 mm periods
  - NdFeB magnets, CoFe poles, 1.3 T

- **Soft X-ray (Athos U38):**
  - 16 modules, each 2 m long
  - Apple-X design
  - 50 × 38 mm periods
  - SmCo magnets, 1.1 T
  - Magnetic chicanes between modules (“CHIC”)

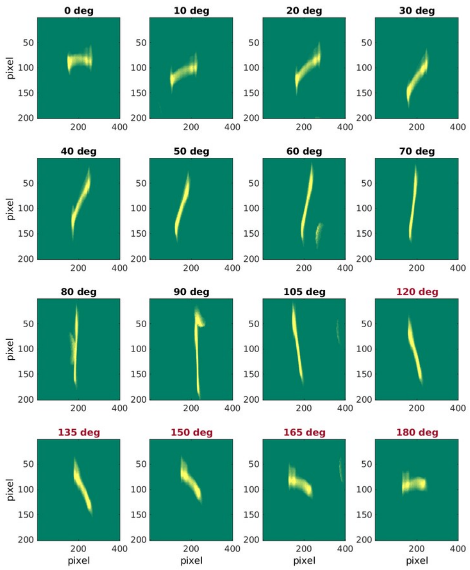
Transverse deflecting cavities for Athos

- Two X-band transverse deflecting RF cavities installed for post-undulator diagnostics in Athos
- Available since June 2022 (last major component of the SwissFEL baseline design!)
- Resolution below 1 fs demonstrated.
- Essential for setup of many Athos modes!

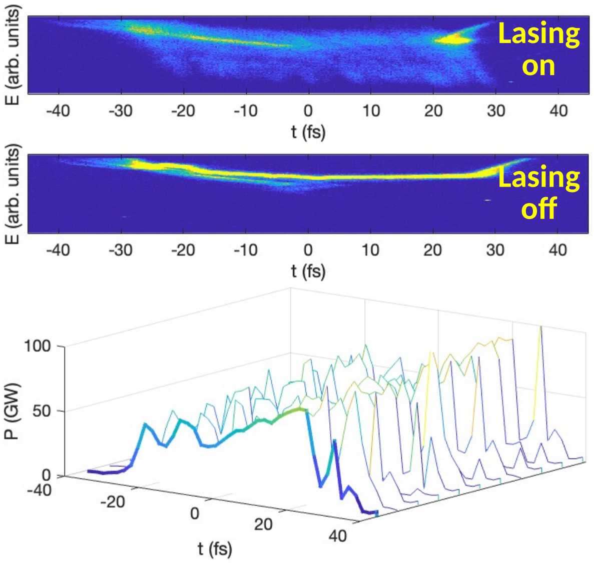
PolariX design (DESY-CERN-PSI collaboration)

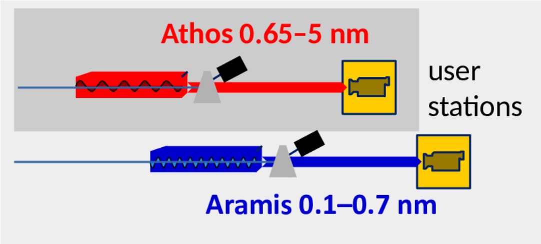


Streaking at arbitrary angles



Horizontally streaked beam in vertically dispersive beam dump section:
FEL power profile reconstruction!

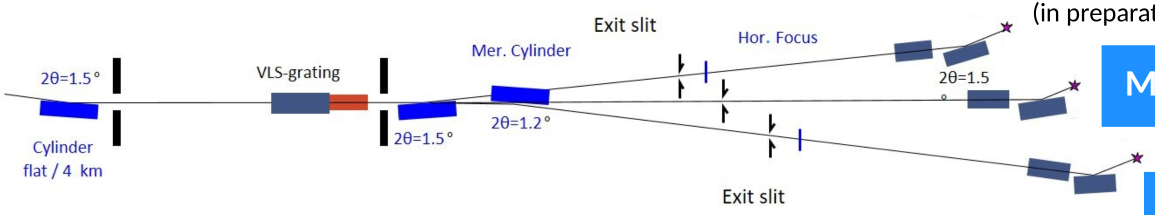




SwissFEL experimental stations

Experimental stations are named after Swiss passes

Athos

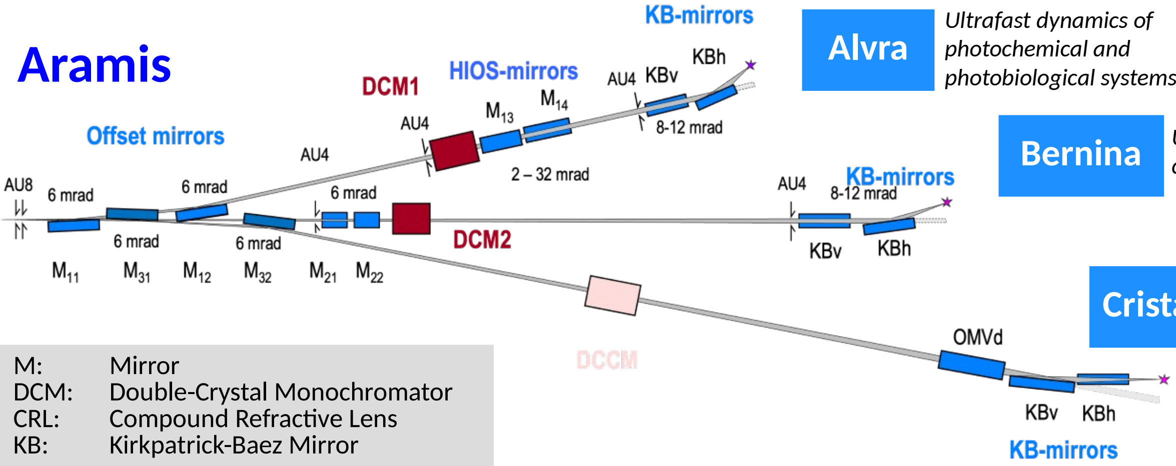


Diavolezza (in preparation) *Attosecond and nonlinear X-ray science*

Maloja *Atomic, molecular and nonlinear X-ray physics and chemical dynamics*

Furka *Ultrafast dynamics in quantum matter*

Aramis



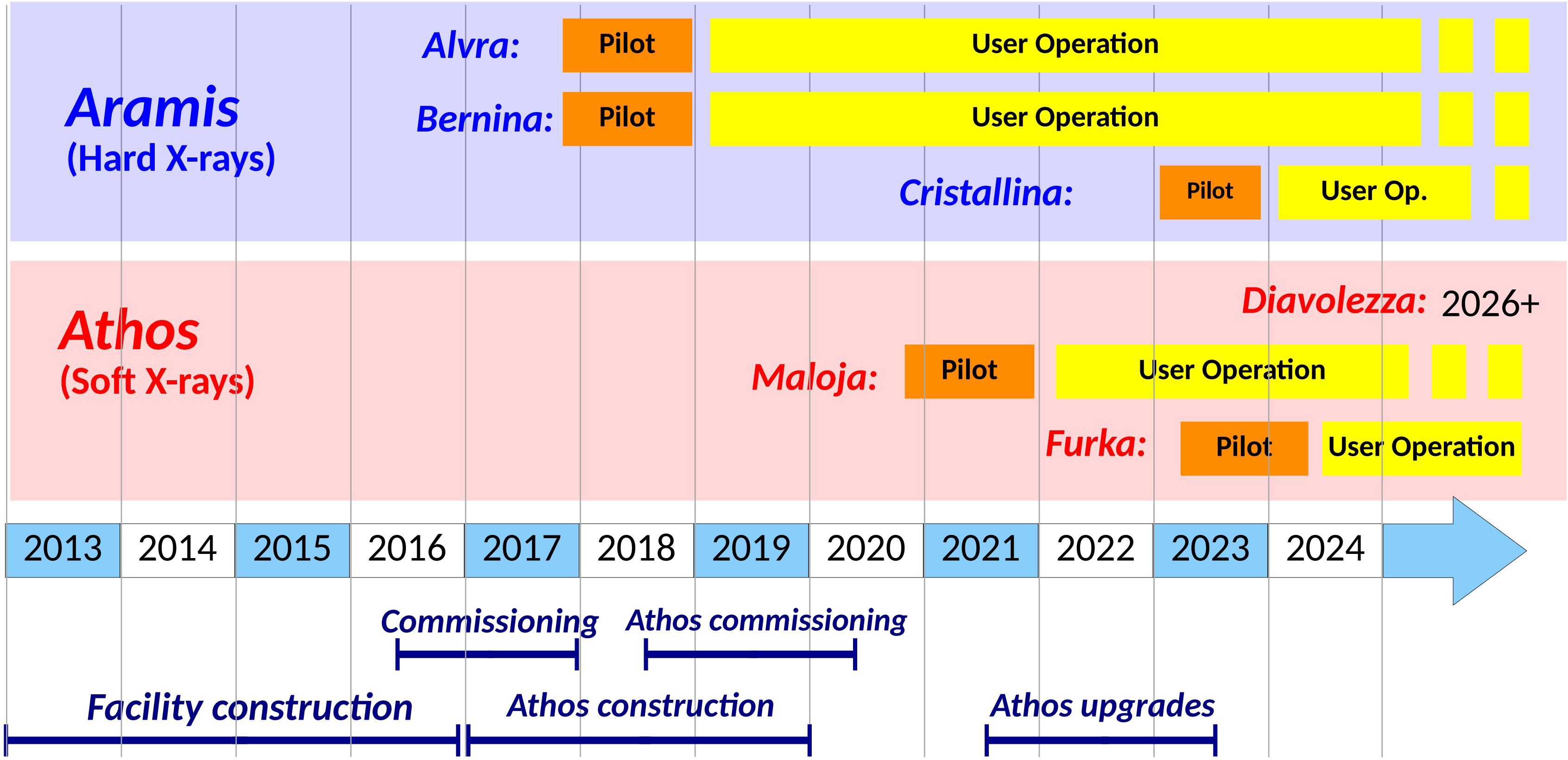
Alvra *Ultrafast dynamics of photochemical and photobiological systems*

Bernina *Ultrafast phenomena in condensed matter systems*

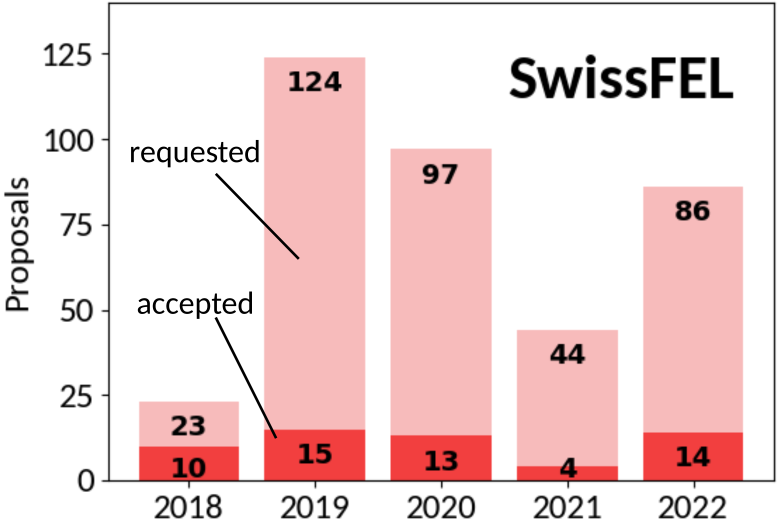
Cristallina *Quantum science and structural biology*

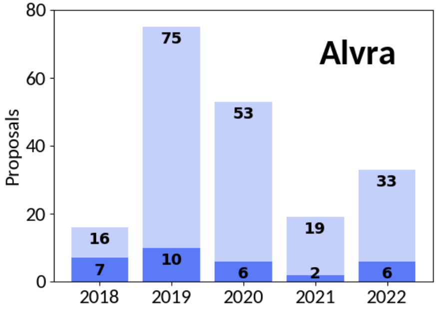
M:	Mirror
DCM:	Double-Crystal Monochromator
CRL:	Compound Refractive Lens
KB:	Kirkpatrick-Baez Mirror

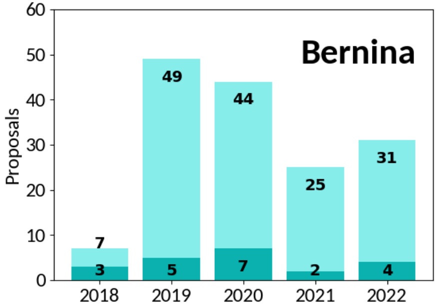
SwissFEL timeline



SwissFEL proposals







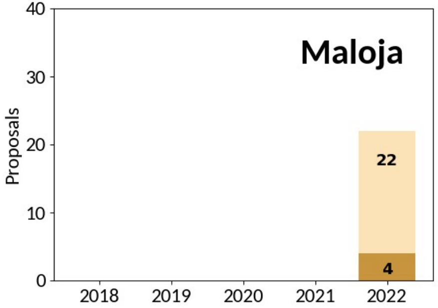
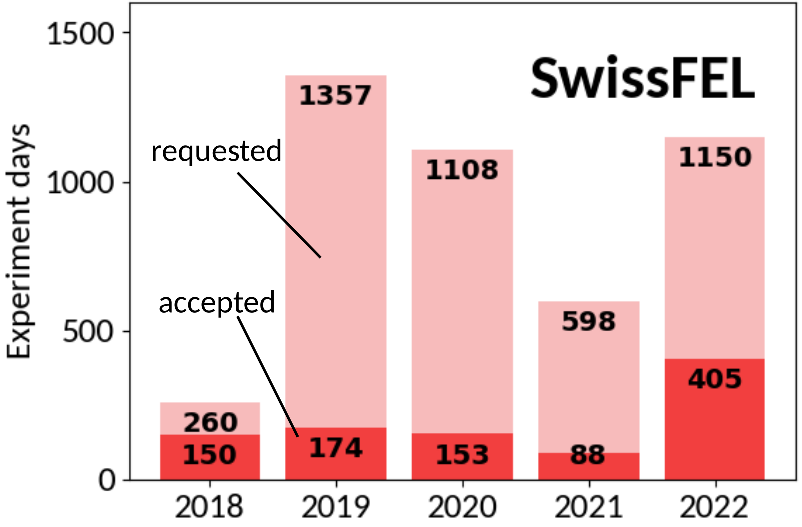
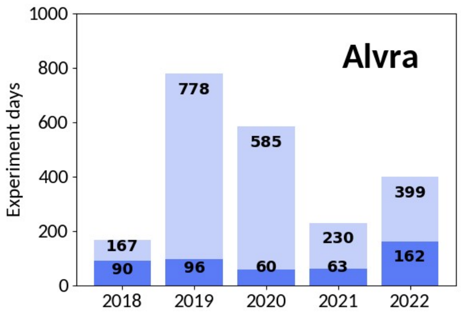
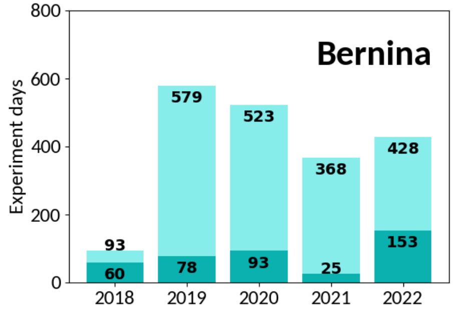


Illustration: https://www.alpen-panoramen.de

SwissFEL experiment days







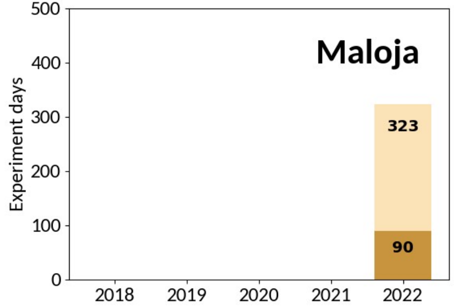
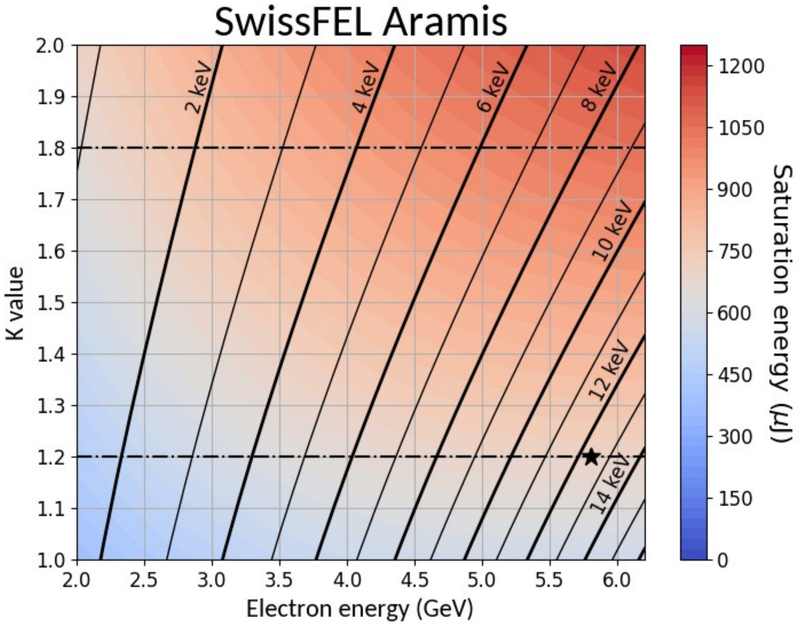
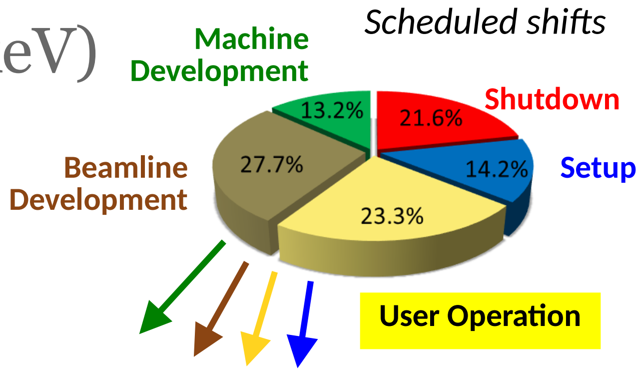


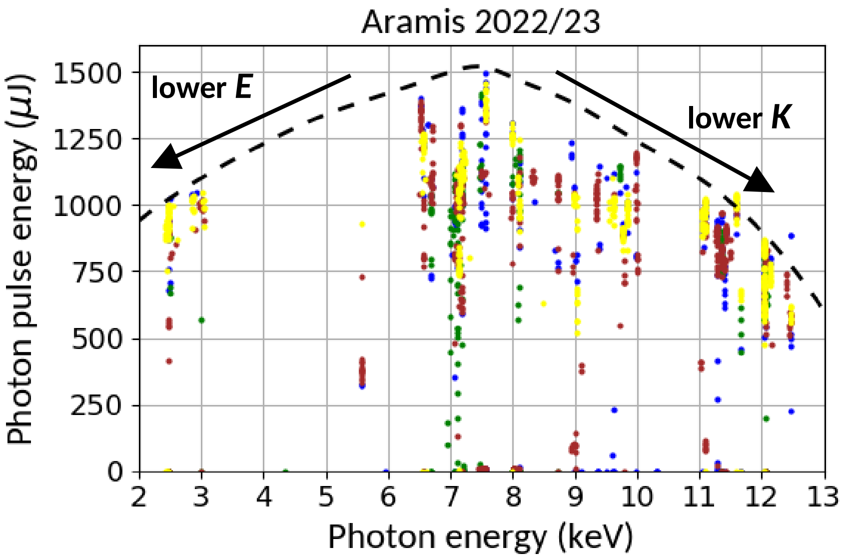
Illustration: https://www.alpen-panoramen.de

Aramis operation (1.8–12.4 keV)

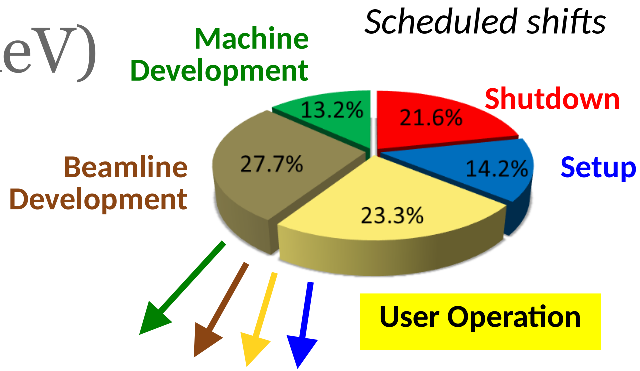


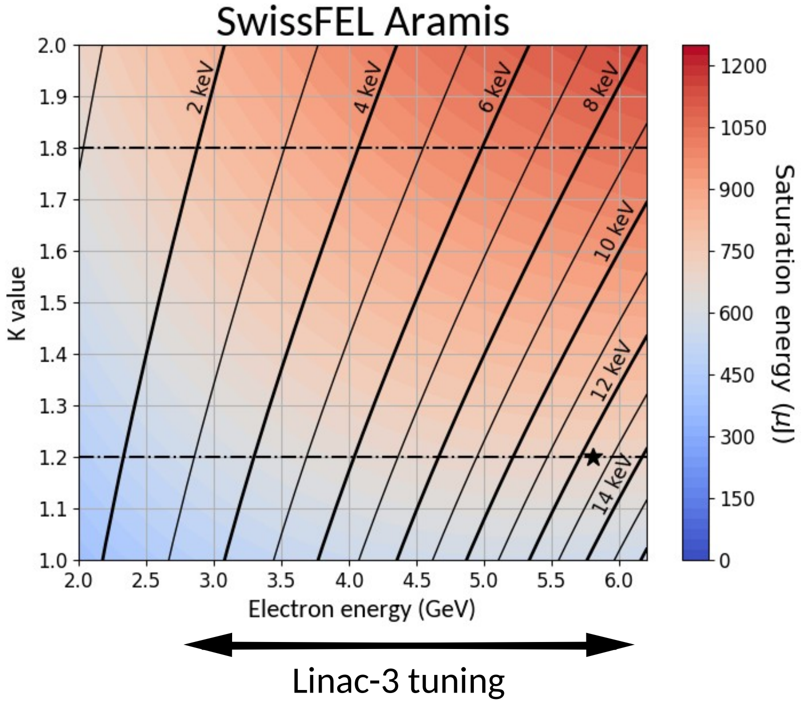
Linac-3 tuning

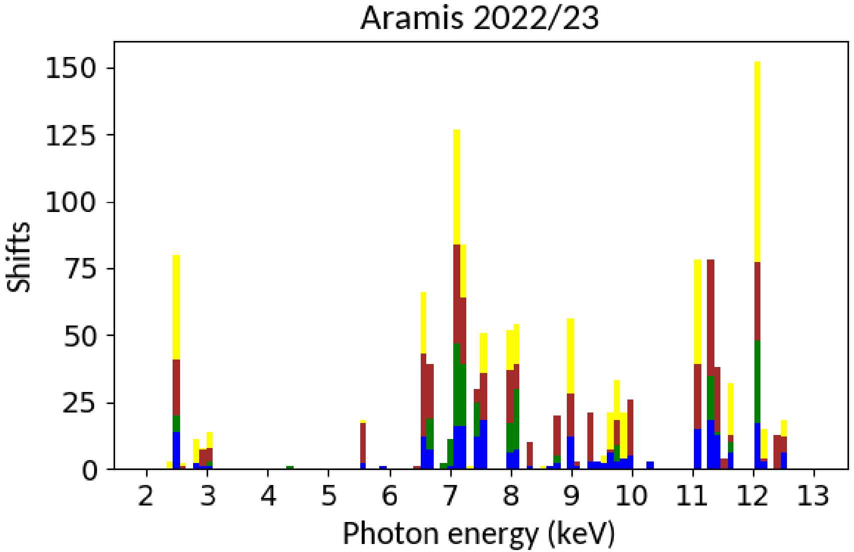




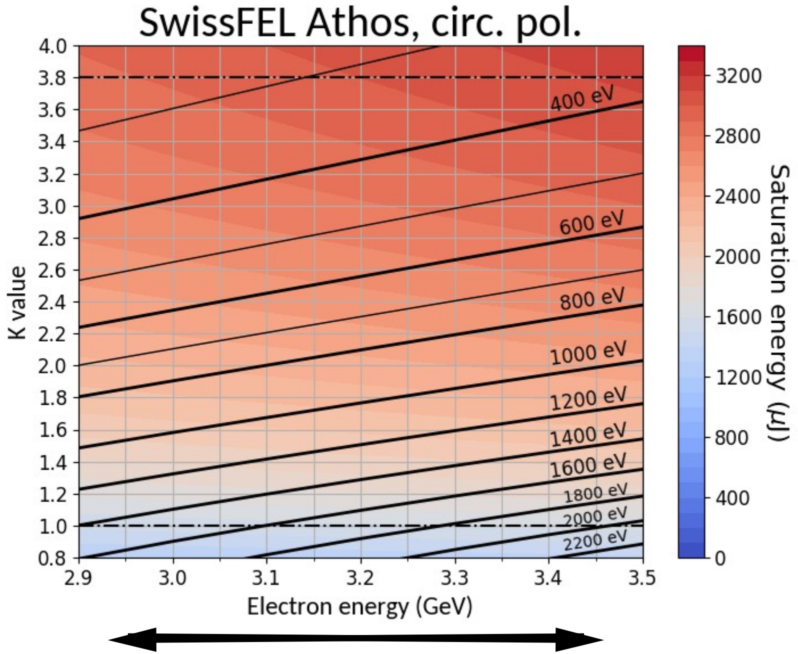
Aramis operation (1.8–12.4 keV)





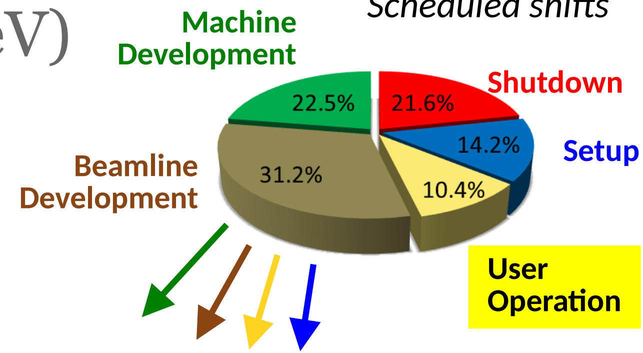


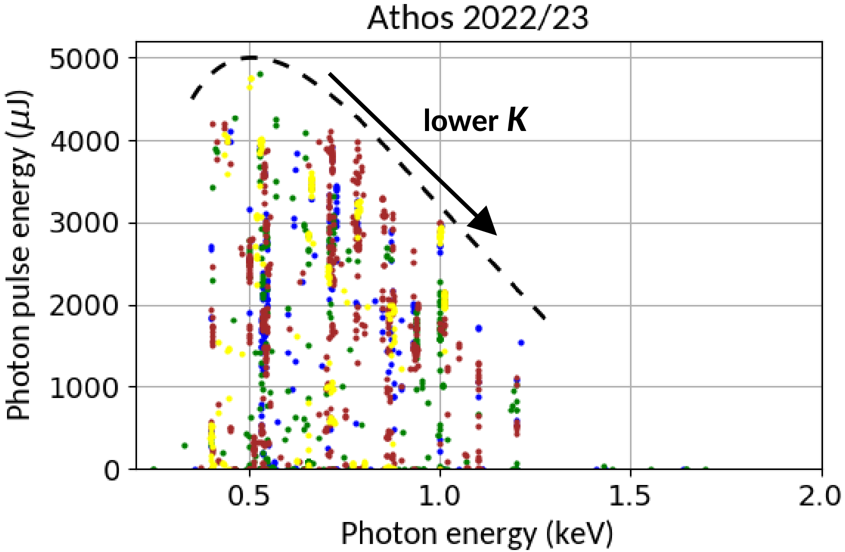
Athos operation (0.26–1.9 keV)



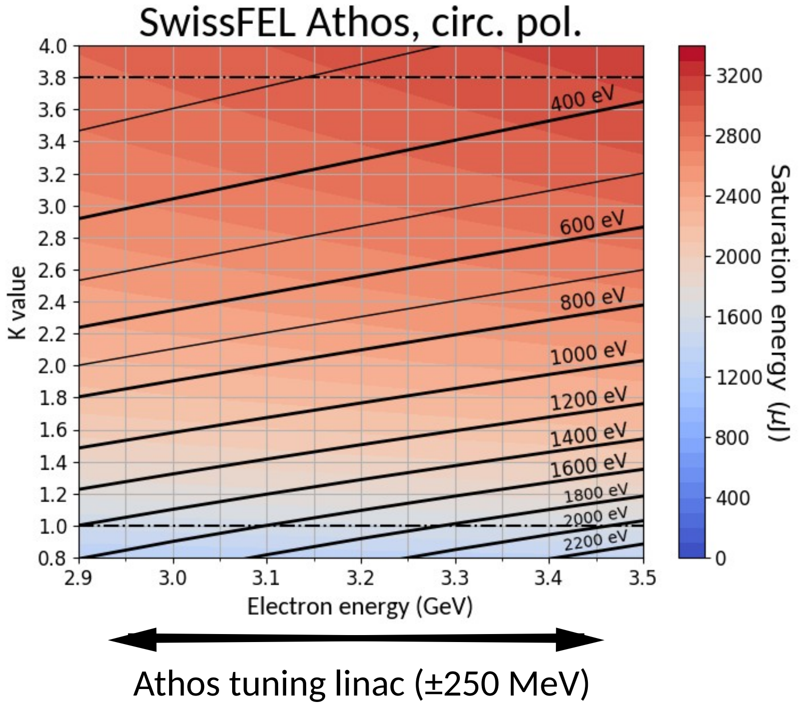
Athos tuning linac (±250 MeV)

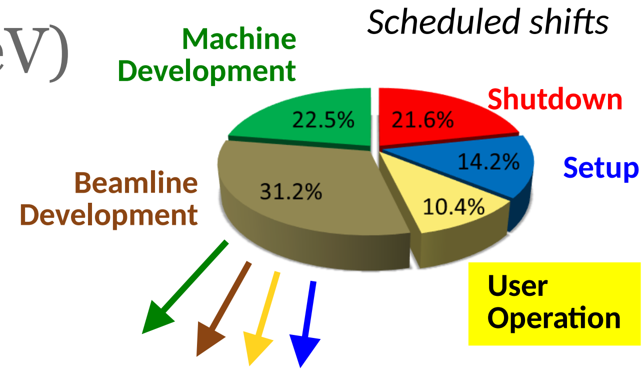
Scheduled shifts

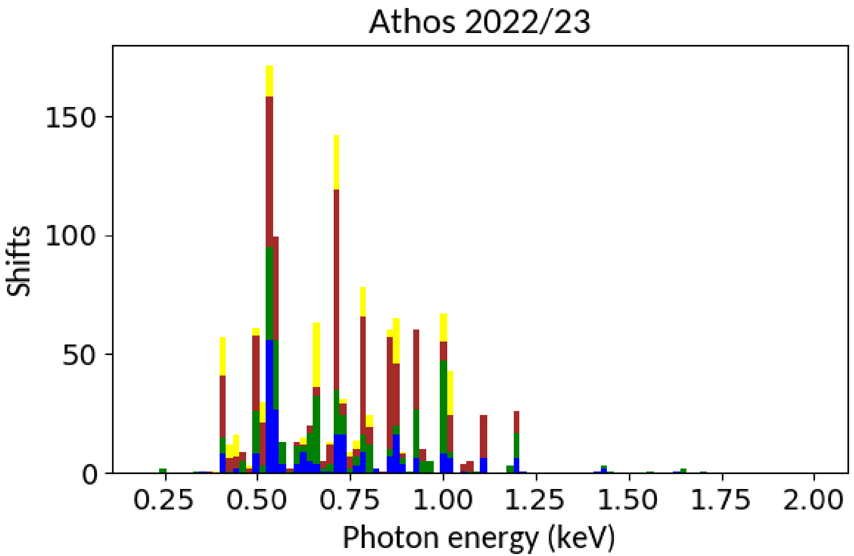




Athos operation (0.26–1.9 keV)

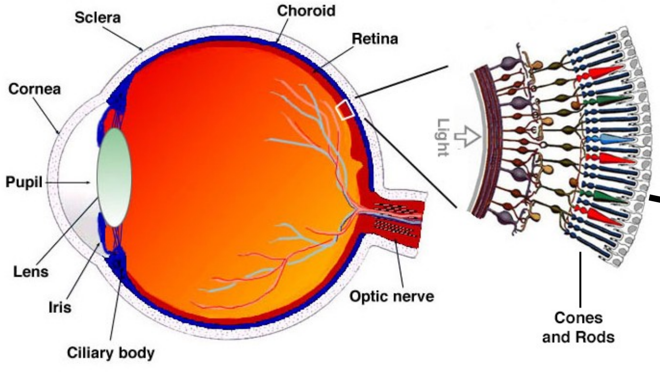




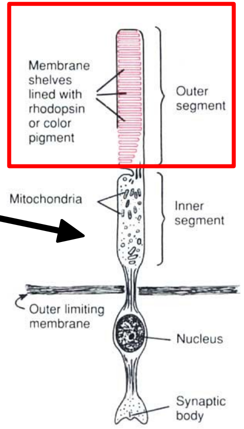


SwissFEL experiment highlight (also SACLA)

Alvra



www.blueconemonochromacy.org/how-the-eye-functions/



nature

Article

Ultrafast structural changes direct the first molecular events of vision

https://doi.org/10.1038/s41586-023-05863-6

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Check for updates

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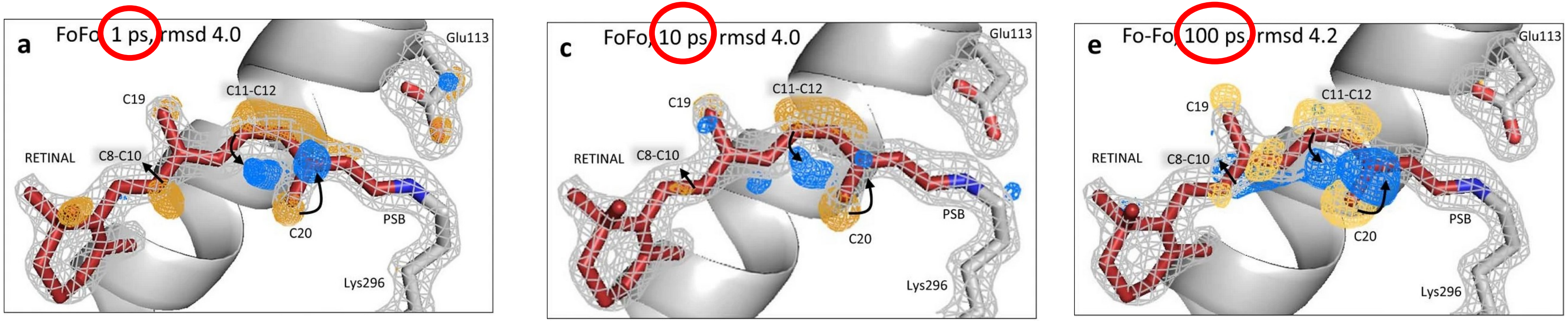
Inside the rod cells (outer segment):



T. Gruhl et al., Nature 615 (2023) 939–944

Aramis advanced modes – overview

Short pulses ✔
(beam tilt)

Large bandwidth mode ✔
(large energy chirp from linac wakefields)

“Attosecond” pulses ✔
(three-stage compression)

Large bandwidth mode with spatial chirp ✔
(additional spatial chirp from dispersion in undulator)

✔ ready for experiments!

https://www.victorinox.com/ch/en/Products/Swiss-Army-Knives/Small-Pocket-Knives/Classic-SD-Classic-Colors/p/0.6223.G

Athos advanced modes – overview

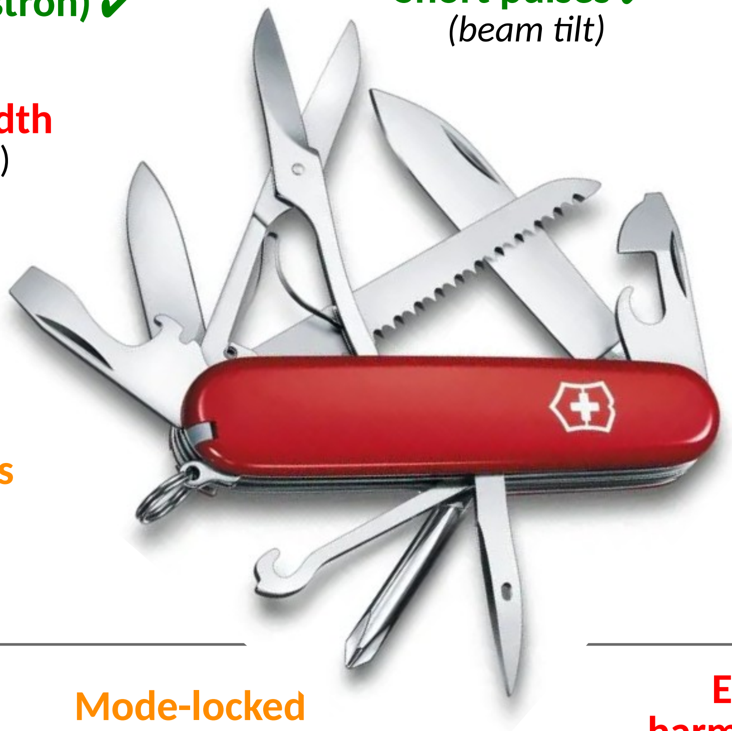
not yet attempted
in commissioning
✔ ready for experiments!

(Optical klystron) ✔

Short pulses ✔
(beam tilt)

Variable polarization ✔

Large bandwidth
(energy chirp)



Two-color with fresh slices ✔

Ultralarge bandwidth
(TGU)

Short-pulse high-power ✔
(superradiance)

High-brightness SASE

“Attosecond” pulses ✔
(three-stage compression)

Laser seeded modes:

Enhanced SASE ✔

Mode-locked lasing

Echo-enabled harmonic generation (EEHG)

https://www.victorinox.com/ch/en/Products/Swiss-Army-Knives/Medium-Pocket-Knives/Fieldmaster/p/1.4713

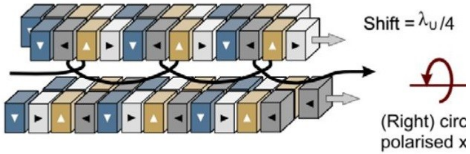
Porthos user wish list…

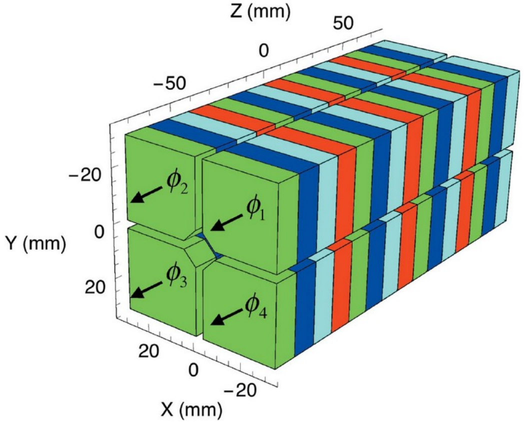
https://www.victorinox.com/ch/en/Products/Swiss-Army-Knives/Medium-Pocket-Knives/Swiss-Champ-XXL/p/1.6795.XXL

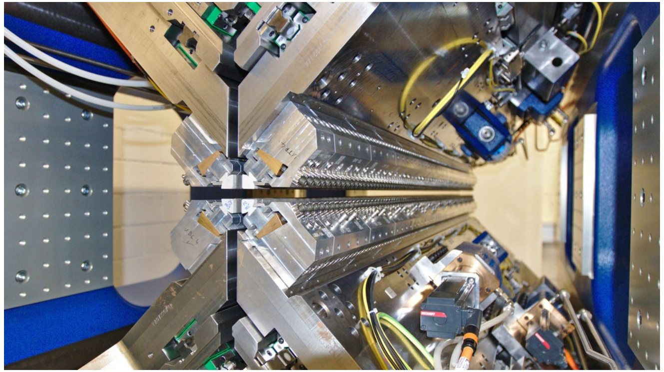
(Victorinox Swiss Champ XXL,
CHF 349.-)

Athos: variable polarization

Generation: Athos APPLE-X undulators

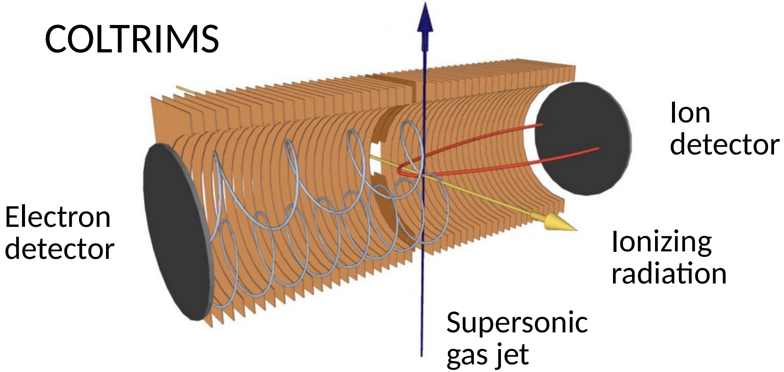


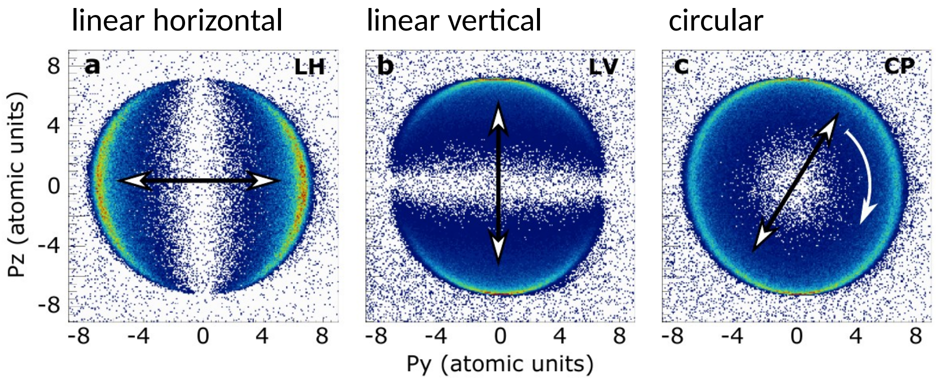




Carolin Schmitz-Antoniak,
Rep. Prog. Phys. 78 (2015) 062501

Measurement: cold target recoil ion spectroscopy at Maloja experiment (Athos)





H. Schmidt-Böcking et al.
Ann. Phys. (Berlin) 533 (2021) 2100134

Athos: short pulses with tilted beams

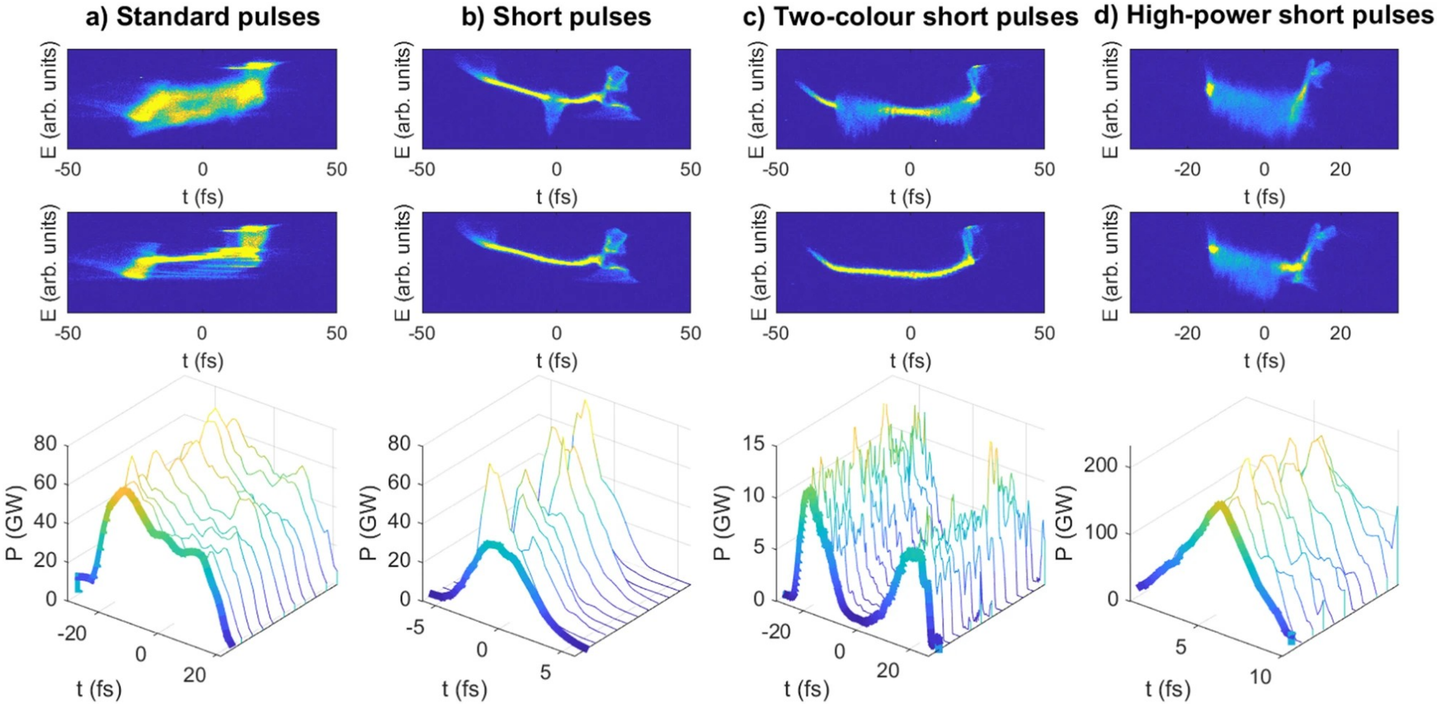
900 eV | 900 eV | 500/760 eV | 650 eV

electron phase space:

Lasing on

Lasing off

FEL power profiles
(single shots, average in bold)



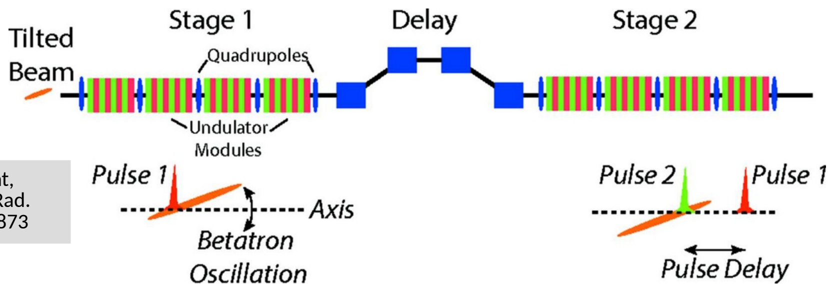
Standard pulse duration ~16 fs (rms), peak power about 60 GW

Down to 1.4 fs, peak power up to 60 GW

About 5 fs each pulse, 10 GW power

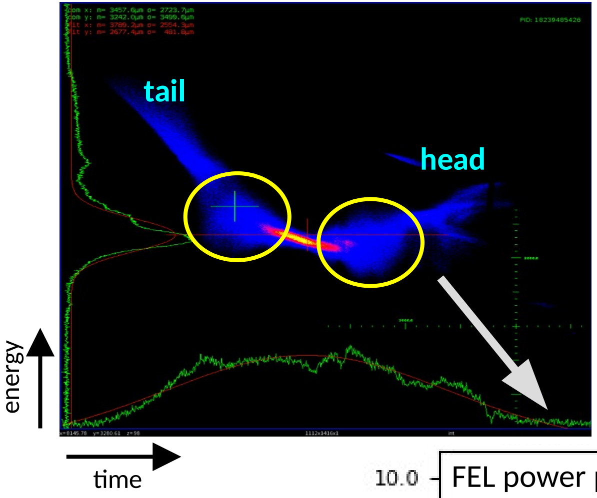
2 fs pulse duration, ~200 GW power

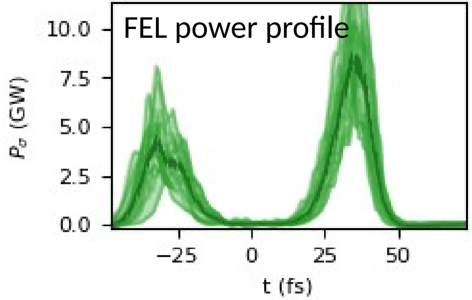
Athos: two-color fresh slice technique



S. Reiche, E. Prat,
J. Synchrotron Rad.
23 (2016) 869–873

Example (Maloja, May 2023):
- Color 1: 531 eV (O), ~110 uJ
- Color 2: 405 eV (N), ~170 µJ

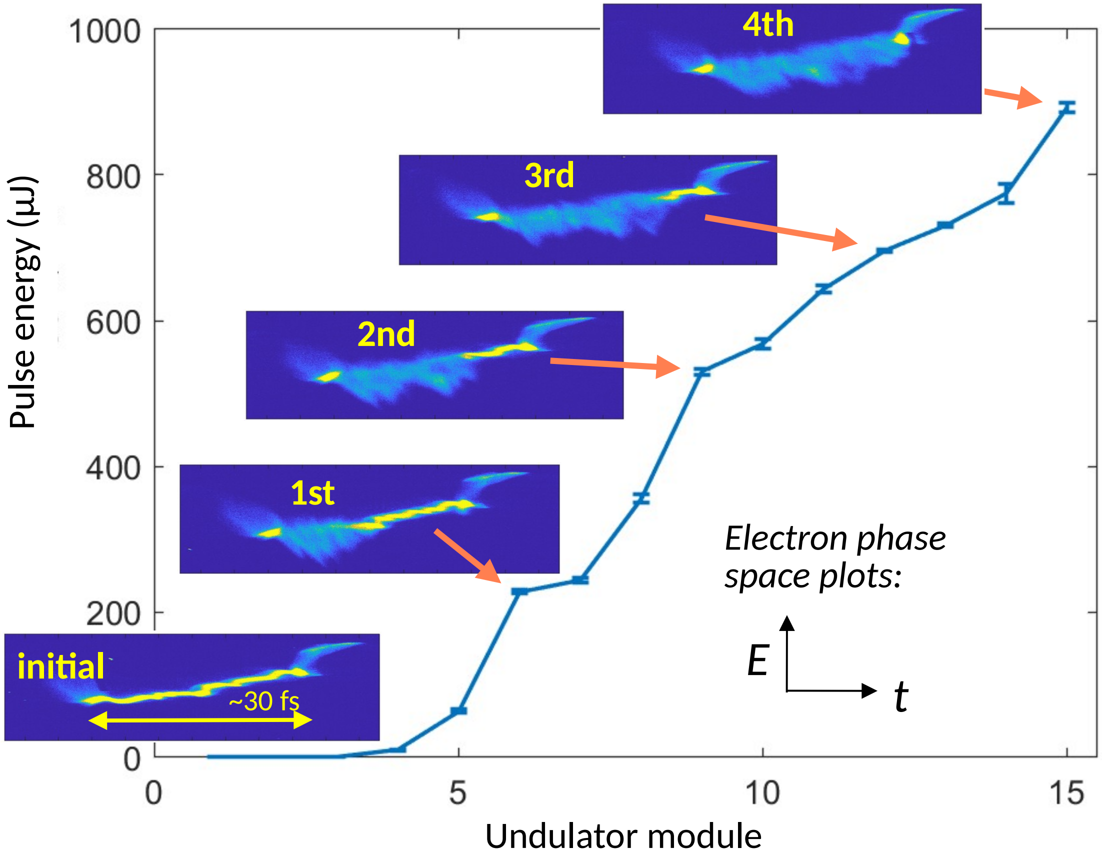


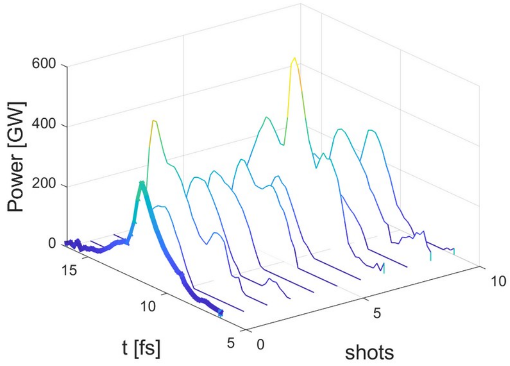


- Generate two colors in two undulator segments with two (fresh) slices of the electron beam (with beam tilt)
- Wide tunability both in color and time separation.
- Separate polarizations for the two colors are possible.
- First demonstration in 2021.
- Now routinely used by experiments.

E. Prat et al.,
Phys. Rev. Res. 4 (2022) L022025

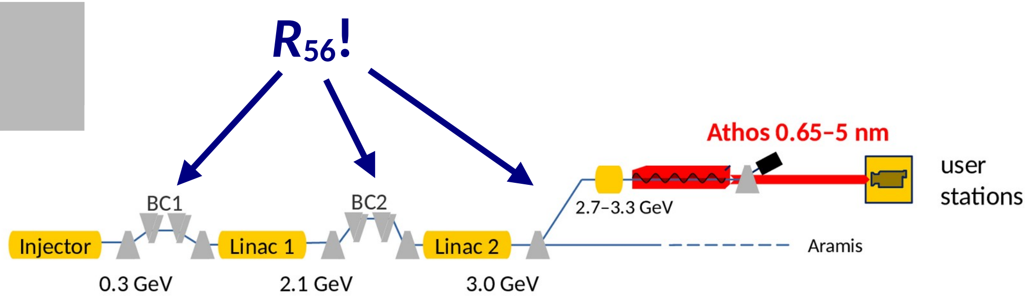
Multistage amplification (superradiance)



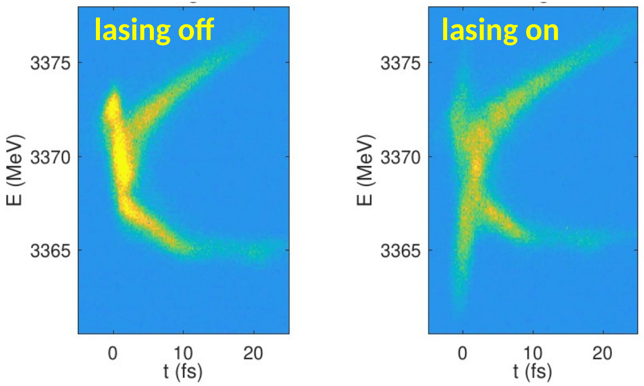


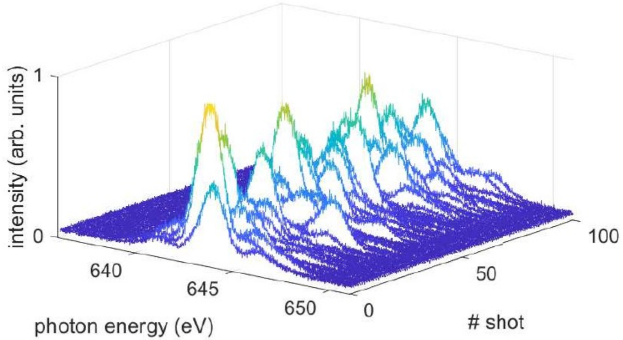
- Photon energy 520 eV
- Four amplification stages (6+3+3+3 undulator modules)
- ~920 μJ in ~1.3 fs (rms) (>300 GW)
- FEL energy gain consistent with $z^{3/2}$ tendency expected from FEL superradiance regime.
- More details in Guanglei Wang's contributed talk **(TH2A3)**

Athos: sub-fs pulses (nonlinear compression)



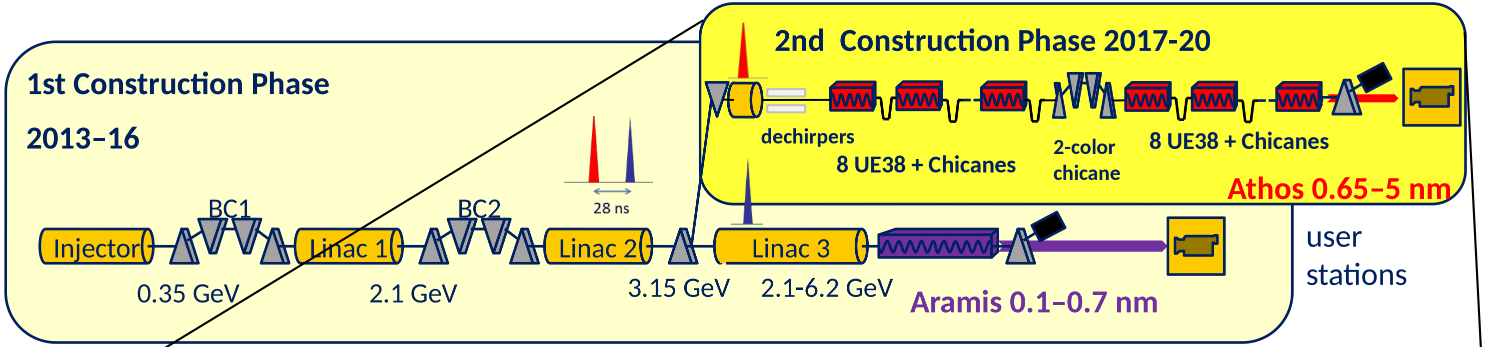
electron phase space after nonlinear compression:





- Three-stage nonlinear compression of low-charge electron bunch (10 pC). Switchyard dogleg as third stage.
- Method similar to Aramis (energy collimator as third stage).
- Strong experimental interest to study coherent electron motion.
- A large fraction of the pulses (≥70%) are single spike.
- Paper submitted to Appl. Phys. Lett. Photonics

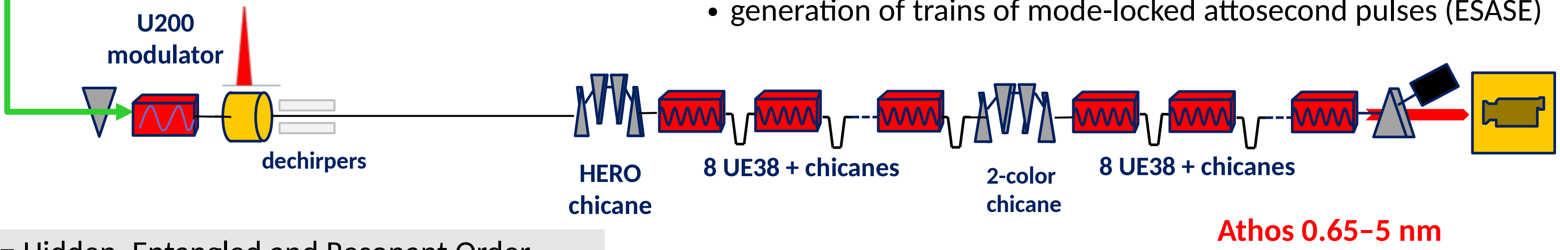
SwissFEL Athos upgrades: HERO & EEHG



HERO Project 2020–22 (Phase 1)

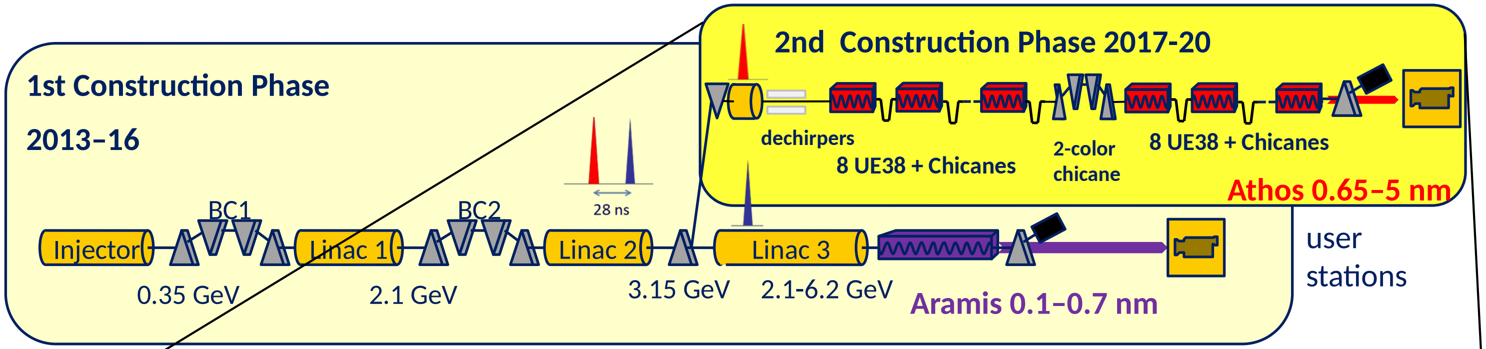
- increase longitudinal coherence
- generation of trains of mode-locked attosecond pulses (ESASE)

1st seed laser



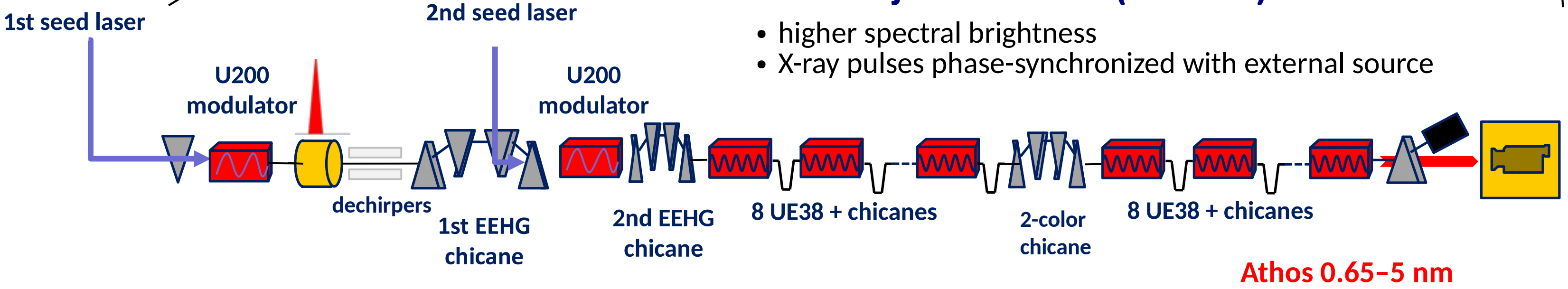
HERO = Hidden, Entangled and Resonant Order
(Title of European Research Grant paying for all this stuff…)

SwissFEL Athos upgrades: HERO & EEHG



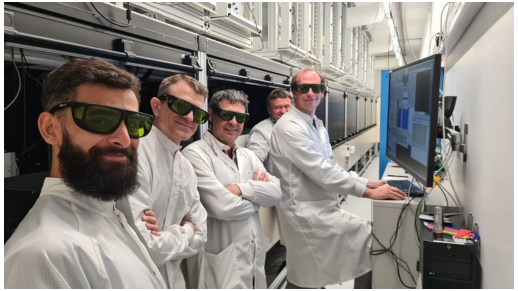
EEHG Project 2021–23 (Phase 2)

- higher spectral brightness
- X-ray pulses phase-synchronized with external source

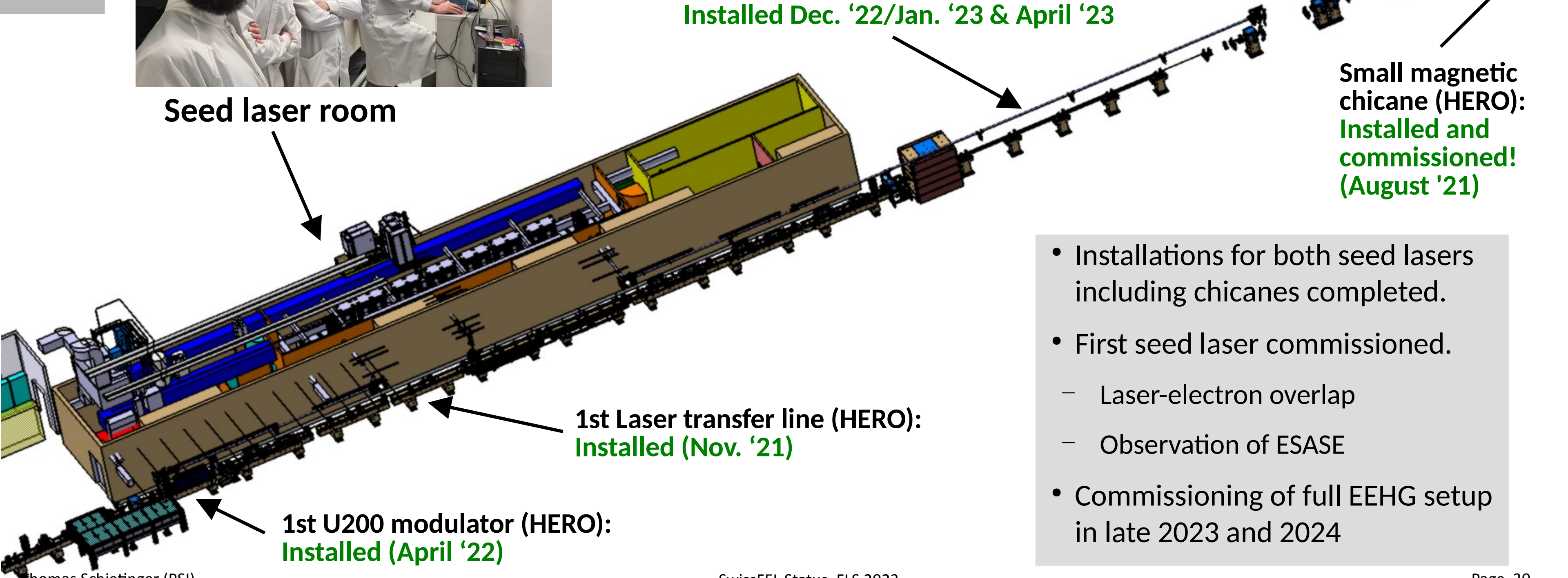


EEHG = Echo-Enabled Harmonic Generation

EEHG installations



Seed laser room



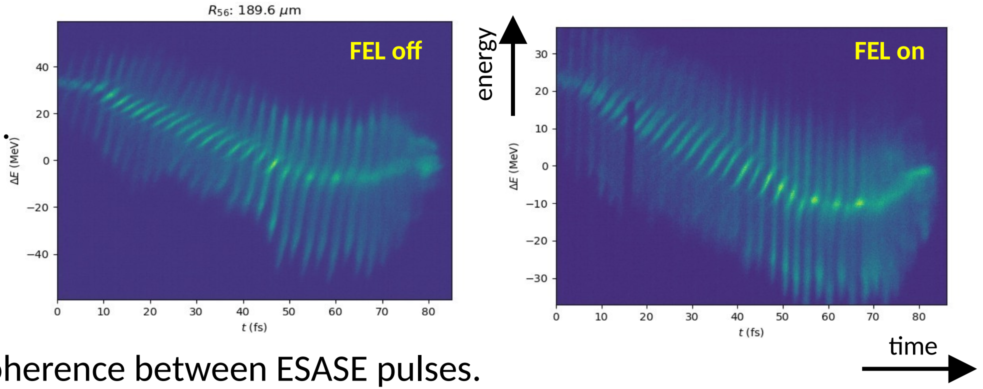
- Installations for both seed lasers including chicanes completed.
- First seed laser commissioned.
  - Laser-electron overlap
  - Observation of ESASE
- Commissioning of full EEHG setup in late 2023 and 2024

Seeded modes (Athos)

Longitudinal phase space measurement with post-undulator X-band deflector

Enhanced SASE (ESASE)

- FEL seeding at 800 nm and 400 nm wavelength.
- Successful generation of attosecond FEL pulse train



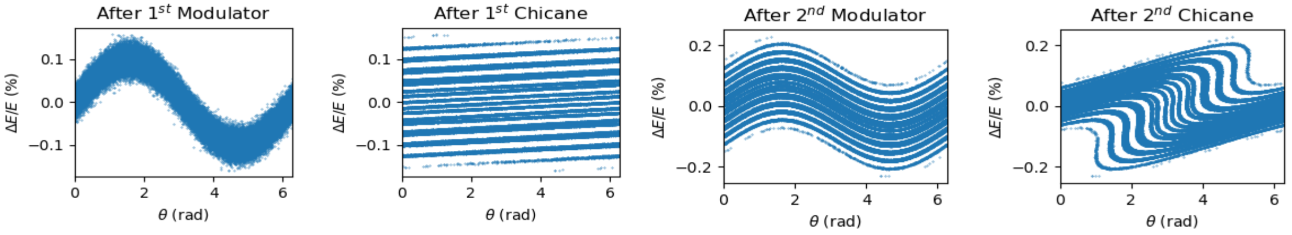
Mode-locked lasing (MLL)

- Use intraundulator chicanes to propagate coherence between ESASE pulses.
- Was attempted (and may have been successful) but clean experimental verification of coherence not yet possible.

Echo-enabled harmonic generation (EEHG)

EEHG simulation (S. Reiche)

- The ultimate goal of the Athos seeding upgrade!
- Hardware ready for commissioning (2023/24)
- Seeding at 267 nm wave-length.



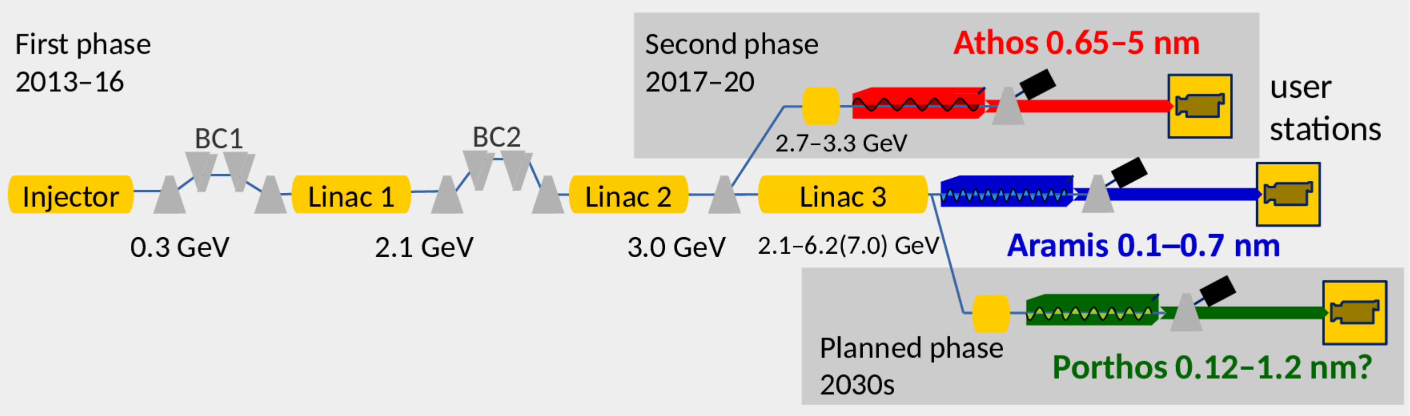
Porthos upgrade

Athos:

Soft X-ray FEL, λ = 0.65–5.0 nm

Variable polarization, APPLE-X undulators

First users 2021



Linac:

Pulse duration : 1–20 fs

Electron energy : up to 6.2 GeV (7 GeV after upgrade)

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz, 2 bunches (3 bunches after upgrade)

Aramis:

Hard X-ray FEL, λ = 0.1–0.7 nm

Linear polarization, in-vacuum, variable-gap undulators

First users 2018

Porthos:

Hard X-ray FEL, λ = 0.12–1.2 nm?

Variable-polarization undulators (technology to be decided)

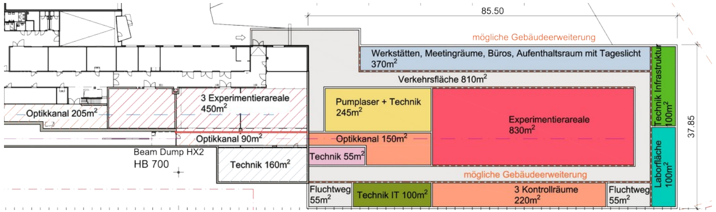
Construction: 2030s

Porthos upgrade

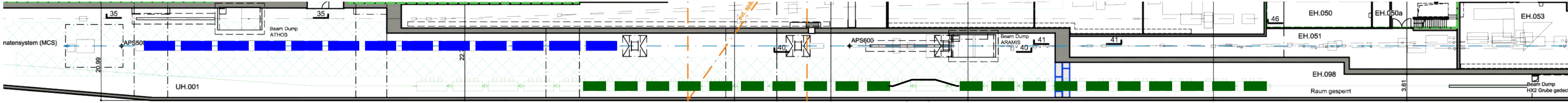
Porthos

- Preliminary plans for a third undulator line, dubbed “Porthos.”
- Firmly anchored in the Swiss *Photon Science Roadmap* (published 2021)
- Science case still in preparation (international workshop in November). Likely photon energy range is 1–10 keV.
- Preproject period to develop undulator prototype and implement various accelerator improvements towards Porthos.

New Porthos experimental hall



Aramis line (in operation)



new Porthos line (planned)

Space for RF and beam manipulation devices (active and/or passive)

20 × (3+1) m undulator modules
≈100 m undulator line
(total,with large chicane)

Beam dump
(already installed)

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Thank you!

Special thanks to the whole SwissFEL team and to the expert groups!

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SwissFEL contributions to FLS '23

Contributed Orals:

- Th. G. Lucas: *A High Brightness Travelling-wave C-Band Photogun for a Brightness Upgrade to SwissFEL* **(WE3A6)**
- G. Wang, E. Prat, S. Reiche, K. Schnorr: *Progress on Fresh-slice Multi-stage Amplification at SwissFEL* **(TH2A3)**

Posters:

- G. Wang, E. Prat, S. Reiche, K. Schnorr: *Simulation Studies of Producing Attosecond-terawatt X-ray FEL Pulses Using Irregularly Spaced Current Peaks at SwissFEL* **(TU4P01)**
- Ph. Dijkstal, P. Craievich, E. Prat, A. Malyzhenkov: *Measurements of Dipole and Quadrupole Wakefields From Corrugated Structures at SwissFEL* **(TU4P02)**