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Thomas Schietinger :: Paul Scherrer Institute

for the SwissFEL team

SwissFEL Status, Lessons from Athos

SwissFEL Porthos Science Workshop, 28 November 2023

Contents

- SwissFEL in a nutshell
  - Key systems
  - Experimental stations
  - Timeline
- Operation and performance in 2022/23
- FEL special modes
- Athos seed laser upgrade (EEHG)
- Lessons learned from Athos

  ...what it means for Porthos
- Outlook:
  - Some mid-term improvements
  - Long-term upgrade: Porthos

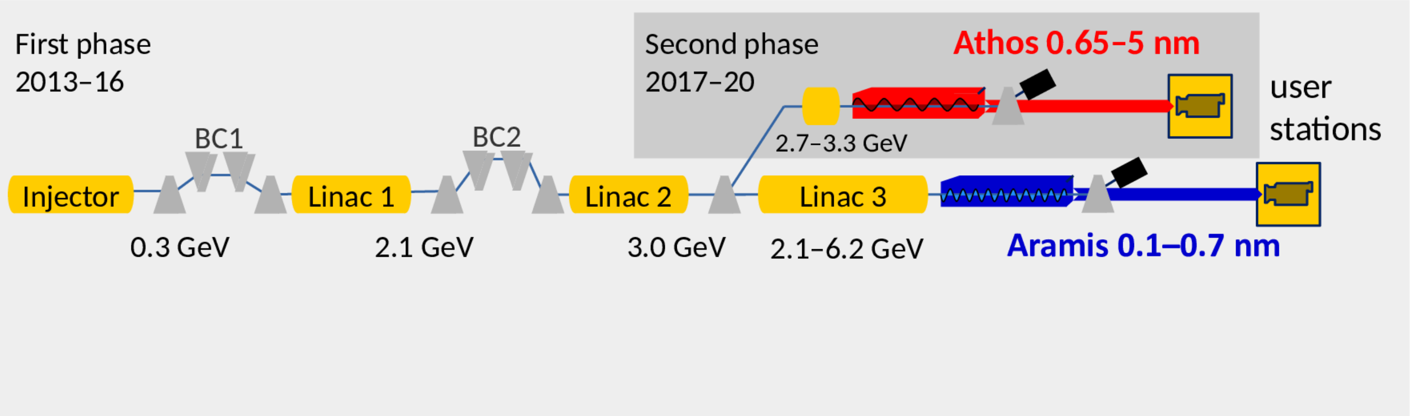
SwissFEL:
The Big Picture

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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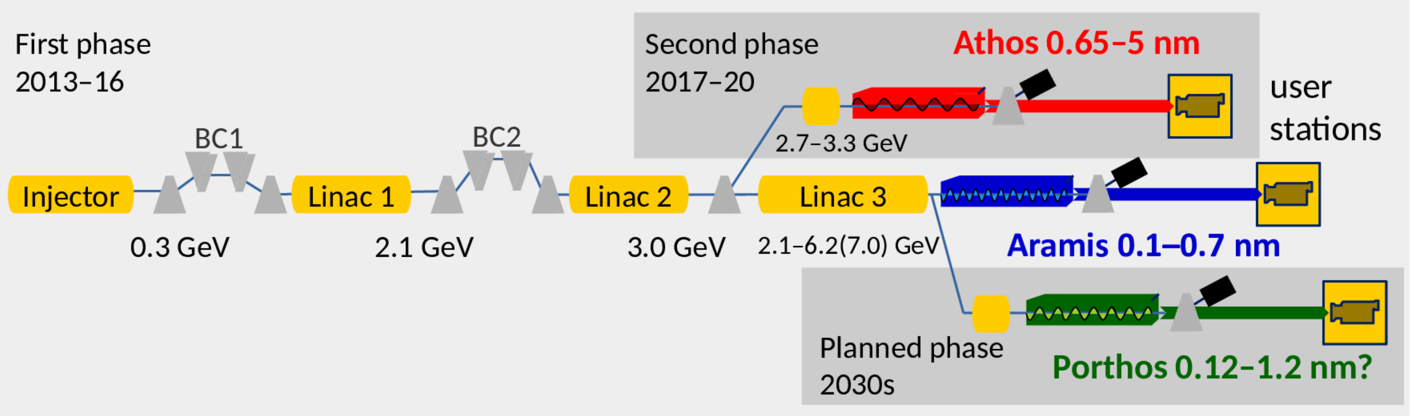
Athos:

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?

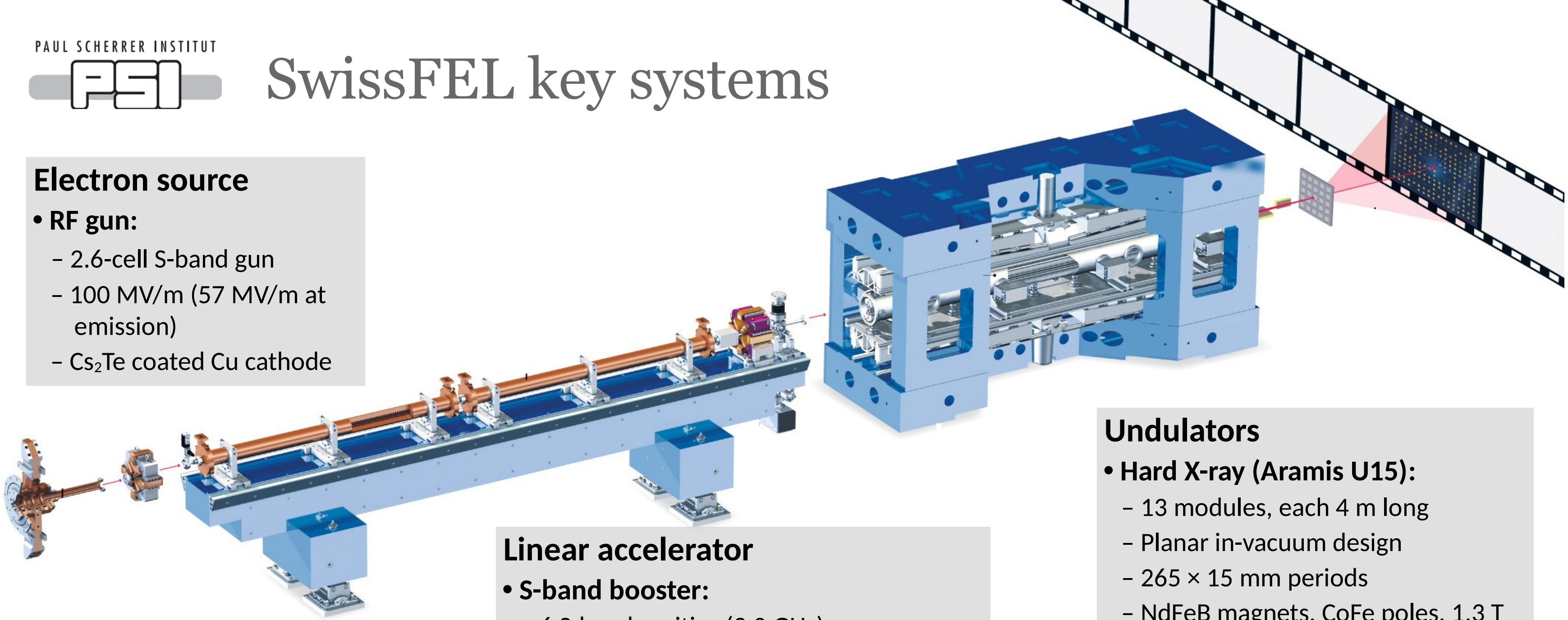
Variable-polarization undulators (technology to be decided)

Construction: 2030s

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

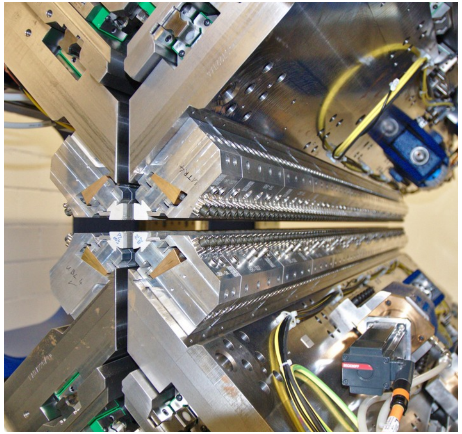
- **Hard X-ray (Aramis U15):**
  - 13 modules, each 4 m long
  - Planar in-vacuum design
  - 265 × 15 mm periods
  - NdFeB magnets, CoFe poles, 1.3 T

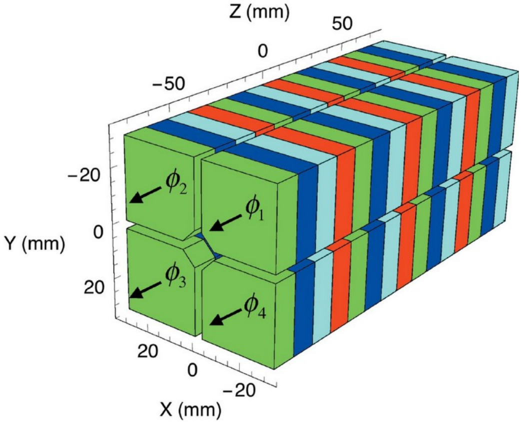
- **Soft X-ray (Athos U38):**
  - 16 modules, each 2 m long
  - Apple-X design
  - 52 × 38 mm periods
  - SmCo magnets, 1.1 T
  - Magnetic chicanes between modules (“CHIC”)

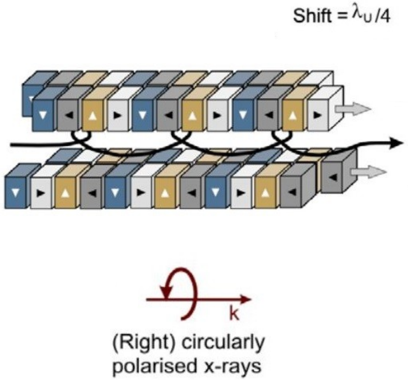
SwissFEL Athos layout

Athos U38 undulator:

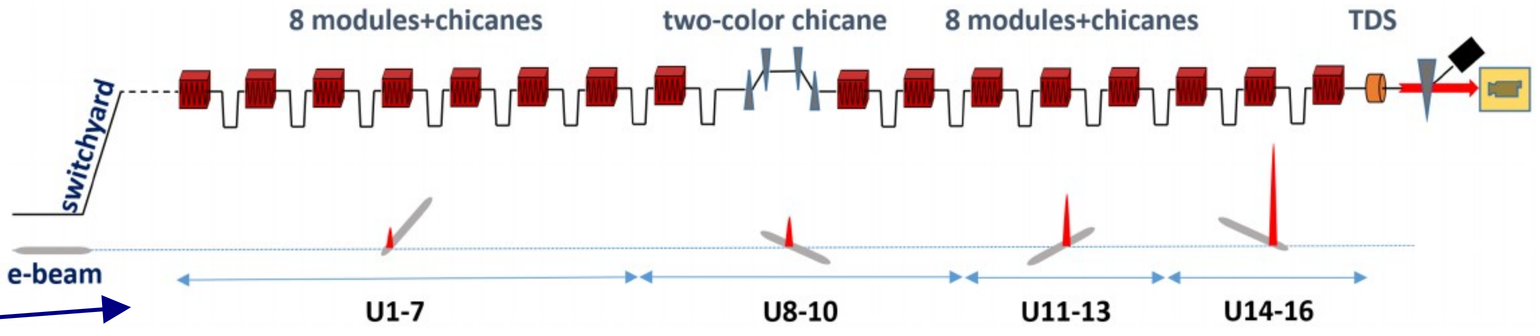
- Apple-X design → individual radial and longitudinal movements of the four magnet arrays for arbitrary linear and elliptical/circular polarization control
- 52 × 38 mm periods
- SmCo magnets, 1.1 T







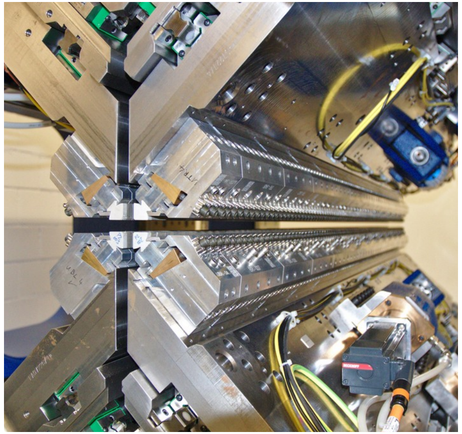
SwissFEL Athos layout

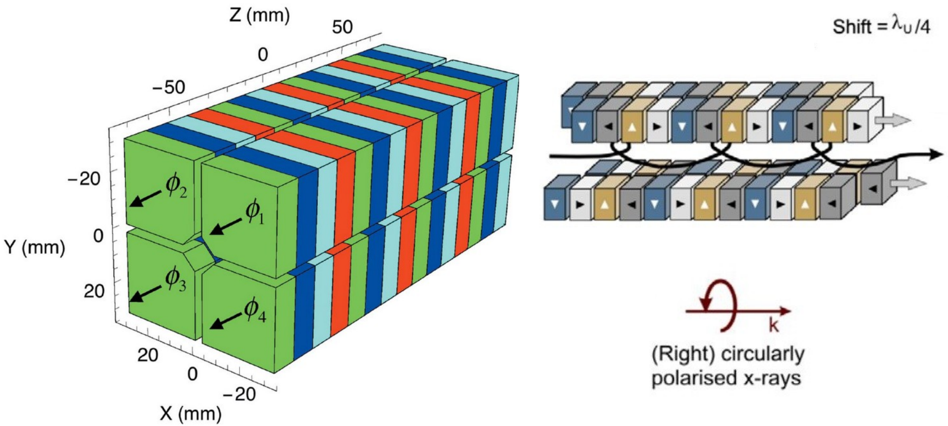


Example use:
"Short-Pulse High-Power"
mode

Athos U38 undulator:

- Apple-X design → individual radial and longitudinal movements of the four magnet arrays for arbitrary linear and elliptical/circular polarization control
- 52 × 38 mm periods
- SmCo magnets, 1.1 T

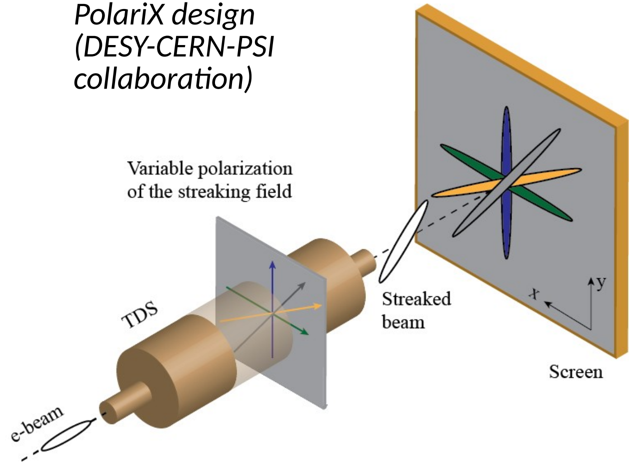




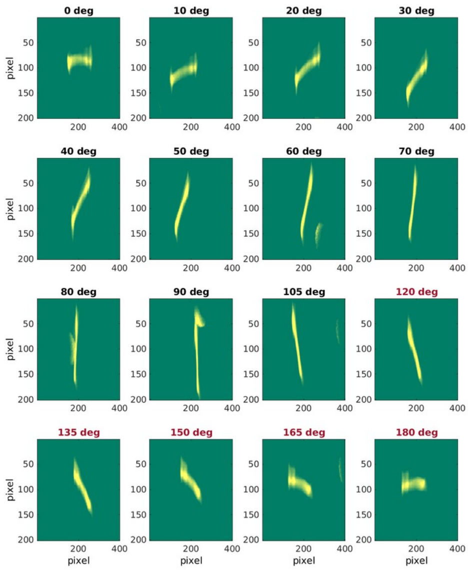
Transverse deflecting cavities for Athos

- 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!

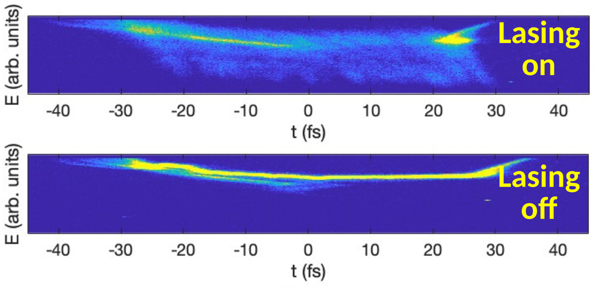
PolariX design (DESY-CERN-PSI collaboration)

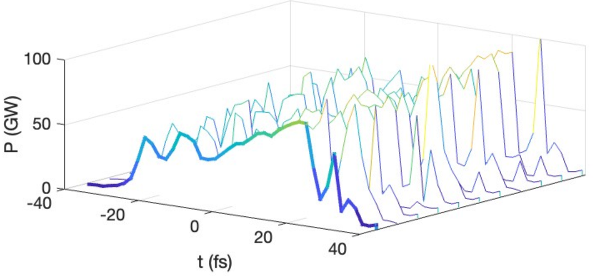


Streaking at arbitrary angles

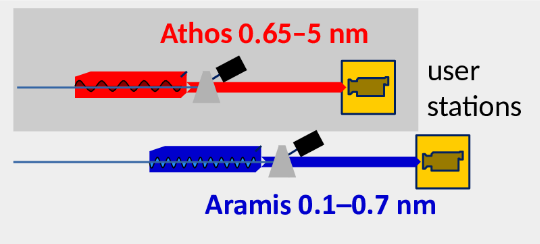


Horizontally streaked beam in vertically dispersive beam dump section:
FEL power profile reconstruction!

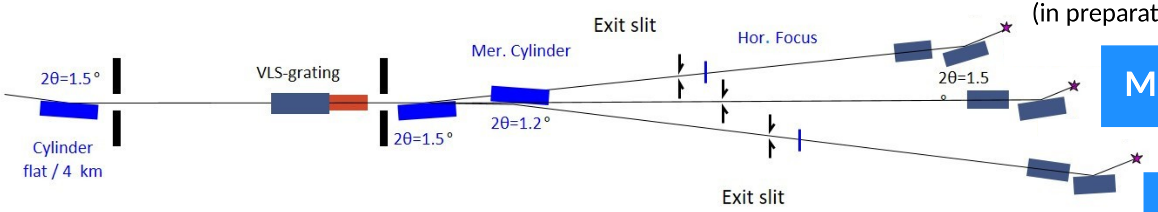




SwissFEL experimental stations



Athos



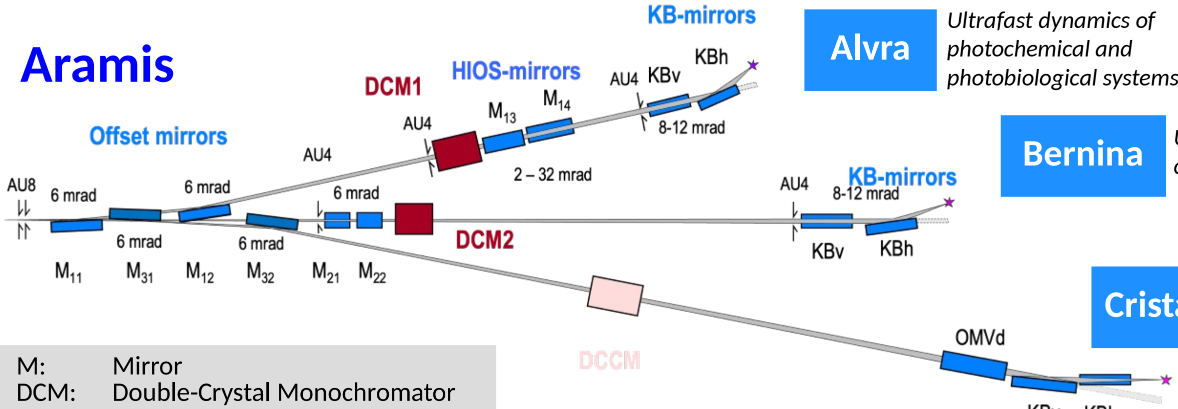
Diavolezza (in preparation) — *Attosecond and nonlinear X-ray science*

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

Furka — *Ultrafast dynamics in quantum matter*

Experimental stations are named after Swiss passes

Aramis



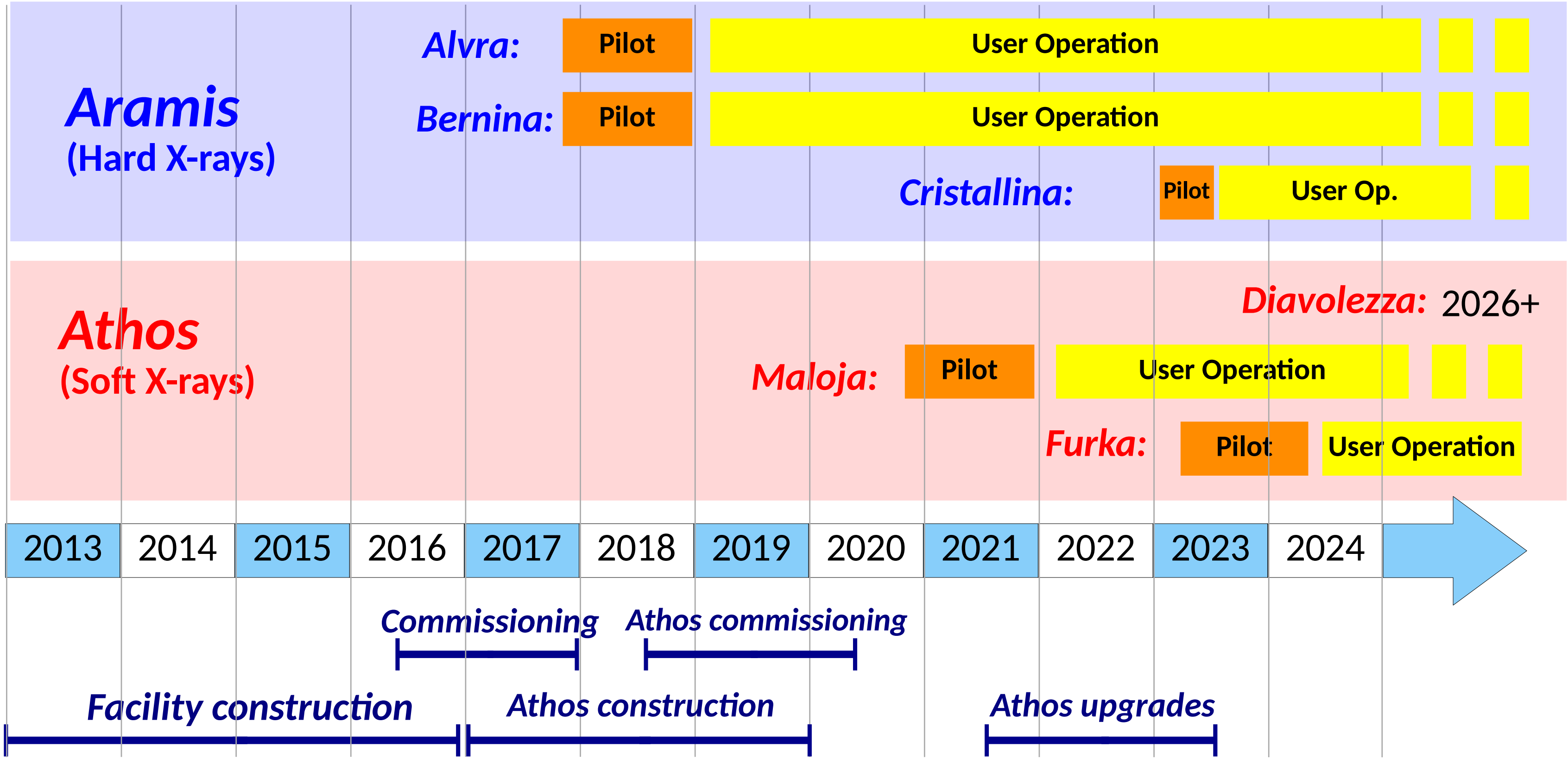
Alvra — *Ultrafast dynamics of photochemical and photobiological systems*

Bernina — *Ultrafast phenomena in condensed matter systems*

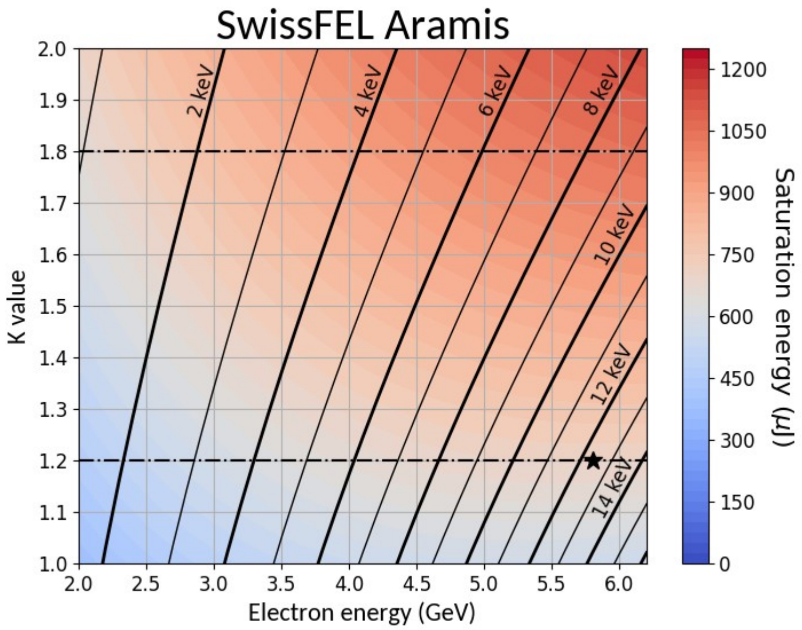
Cristallina — *Quantum science and structural biology*

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

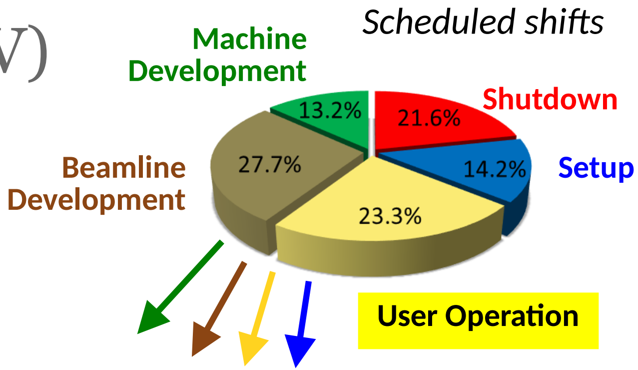
SwissFEL timeline

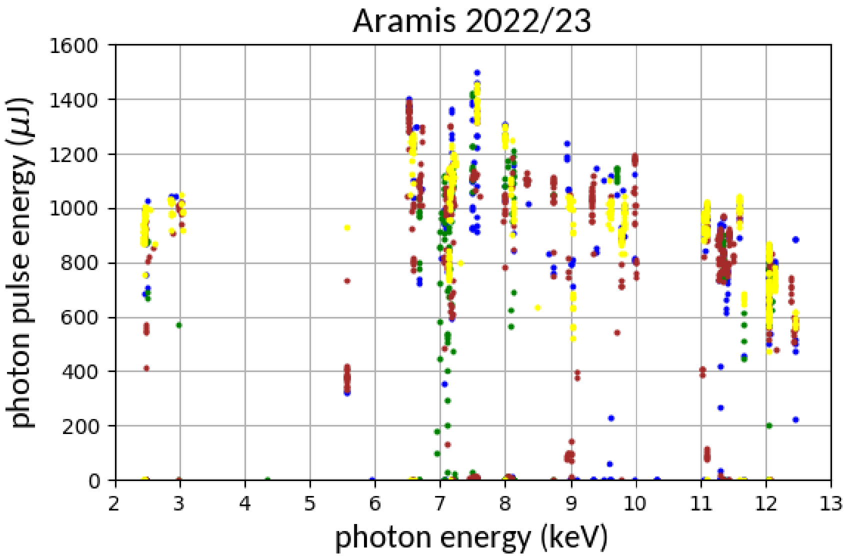


Aramis operation (2–12.4 keV)

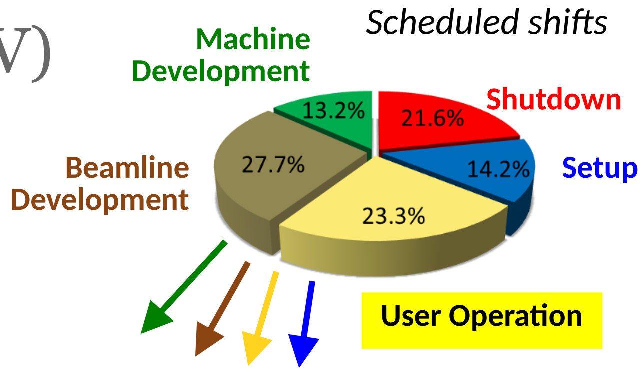


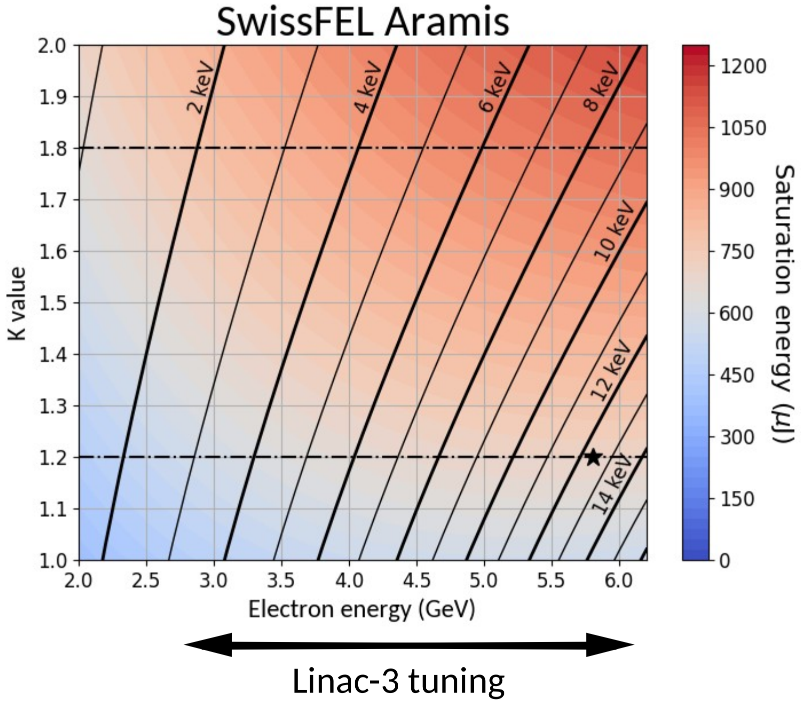
Linac-3 tuning

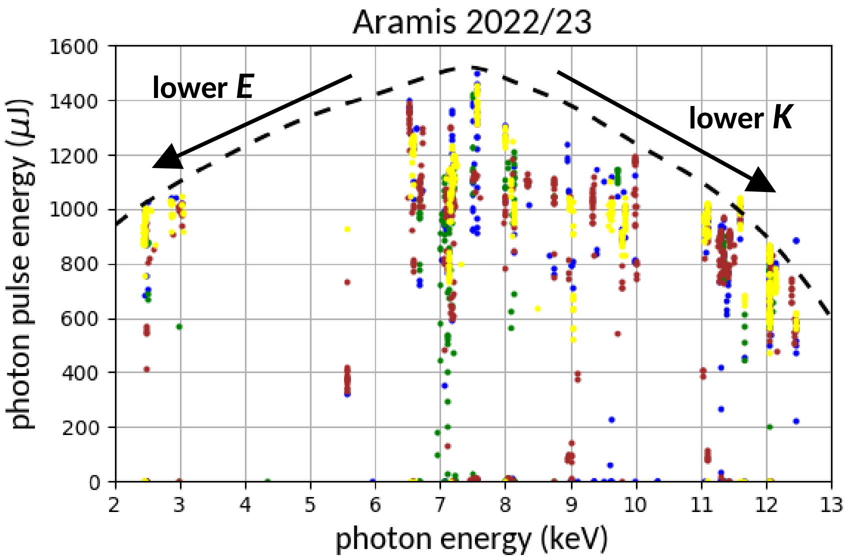




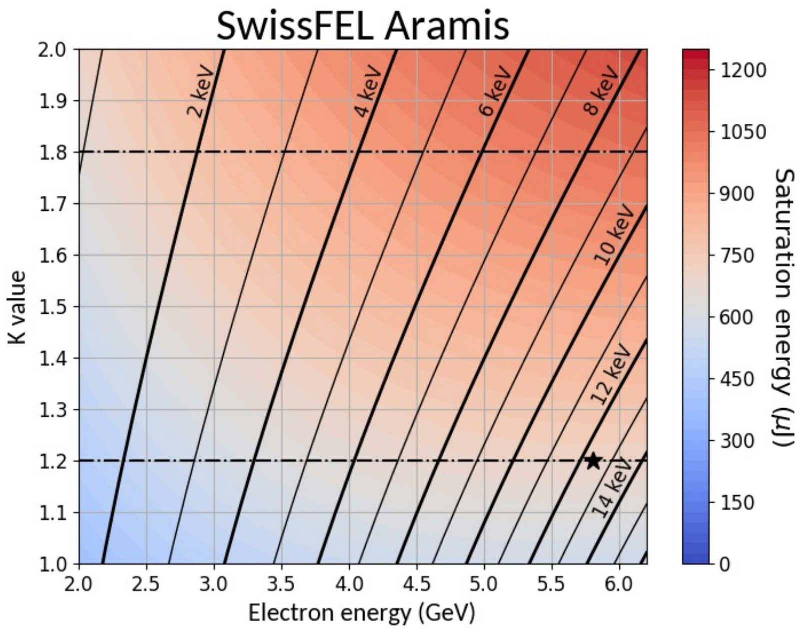
Aramis operation (2–12.4 keV)



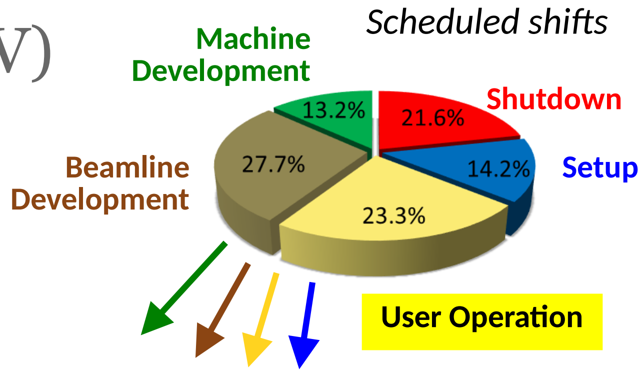


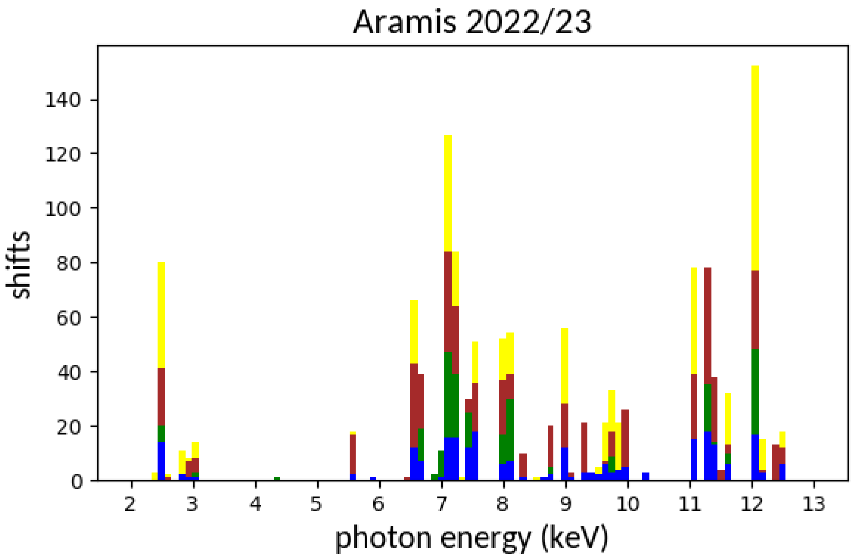


Aramis operation (2–12.4 keV)

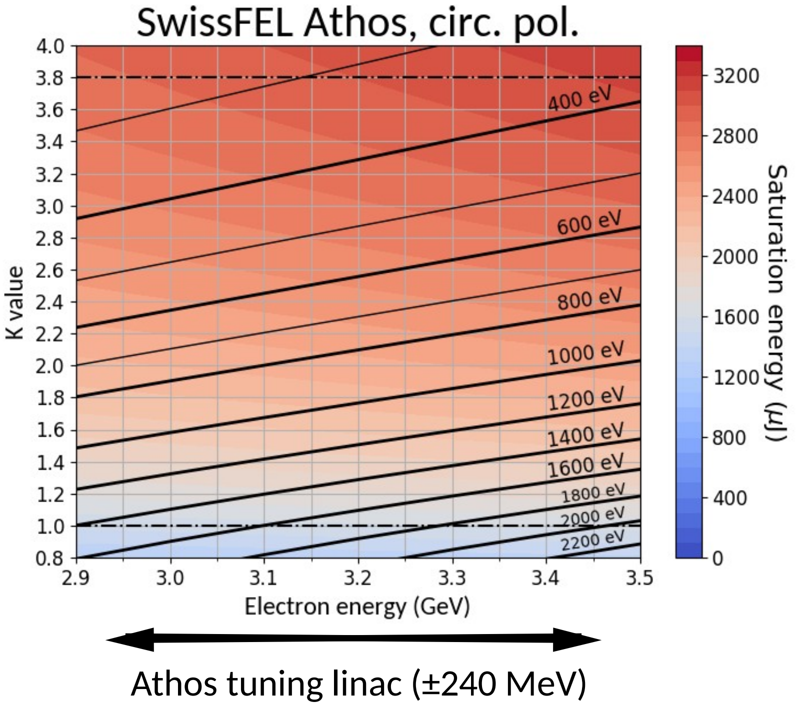


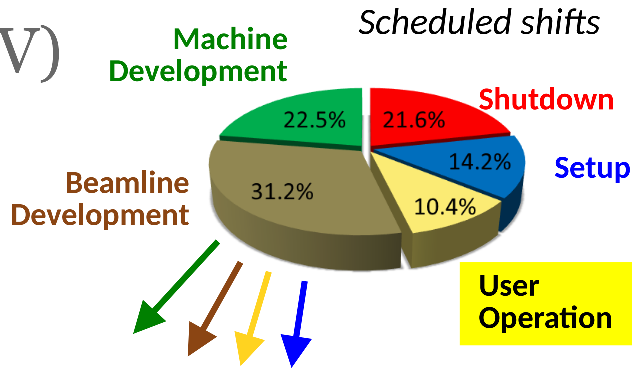
Linac-3 tuning

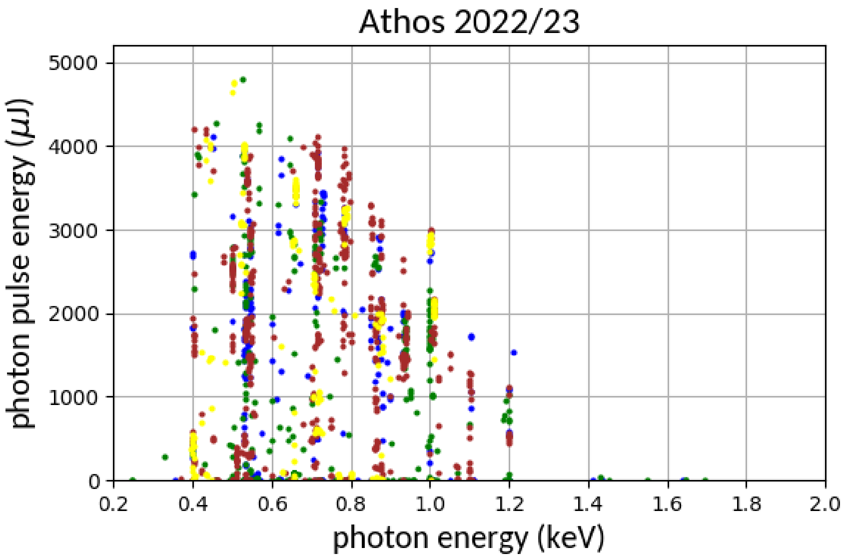




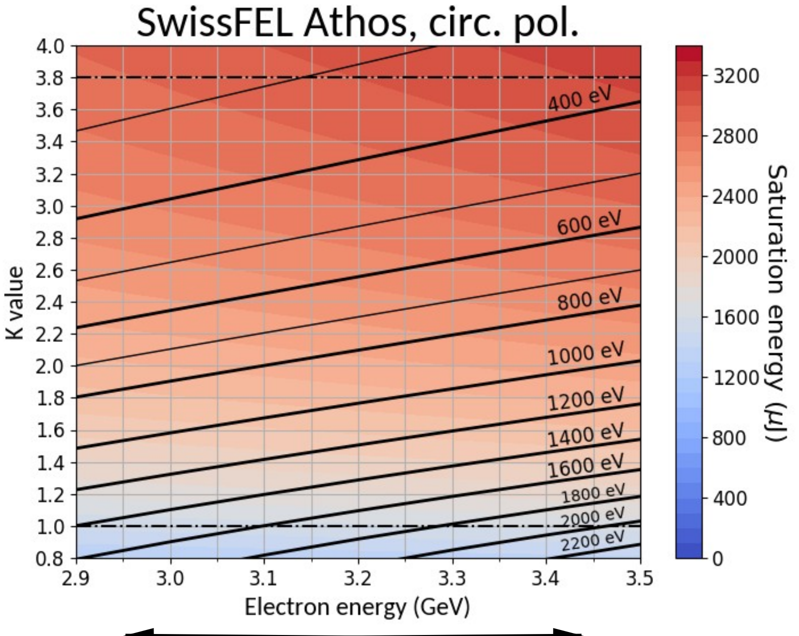
Athos operation (0.25–1.8 keV)



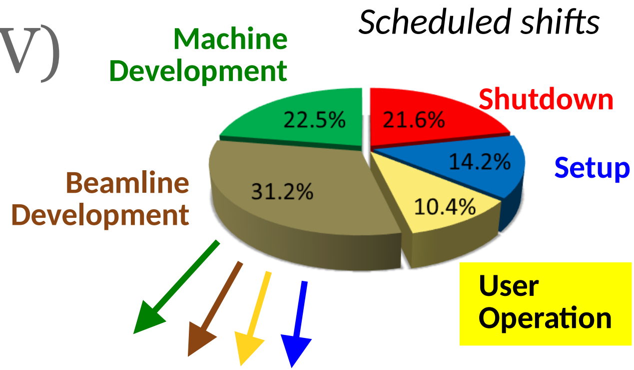


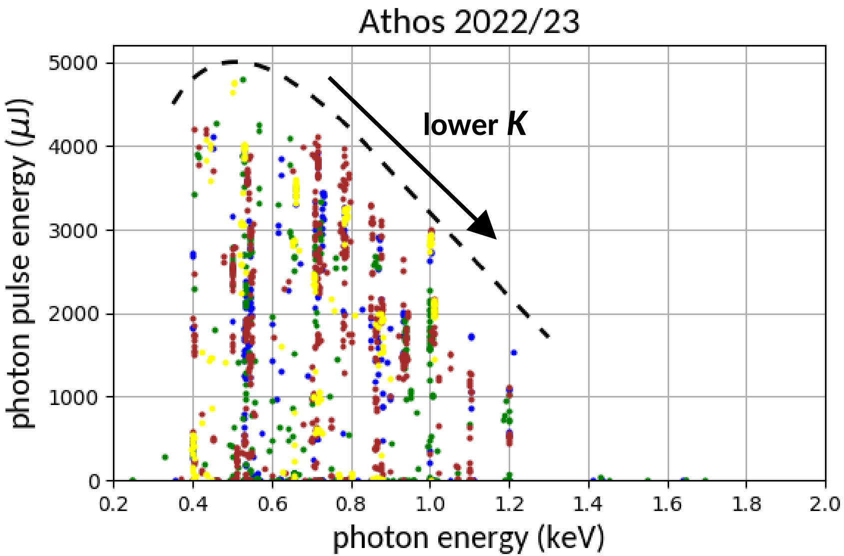


Athos operation (0.25–1.8 keV)

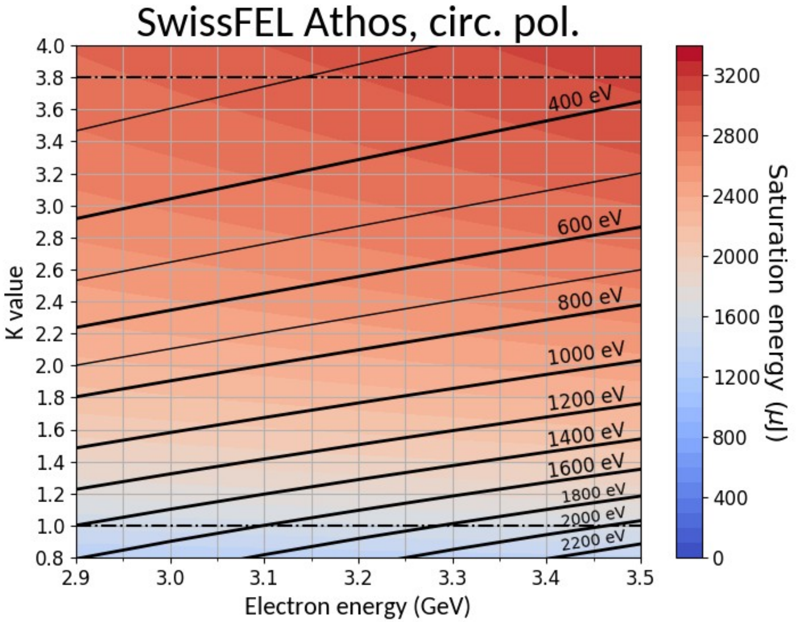


Athos tuning linac (±240 MeV)





Athos operation (0.25–1.8 keV)



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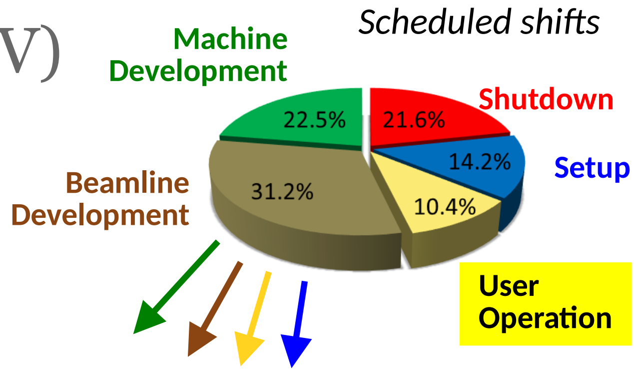

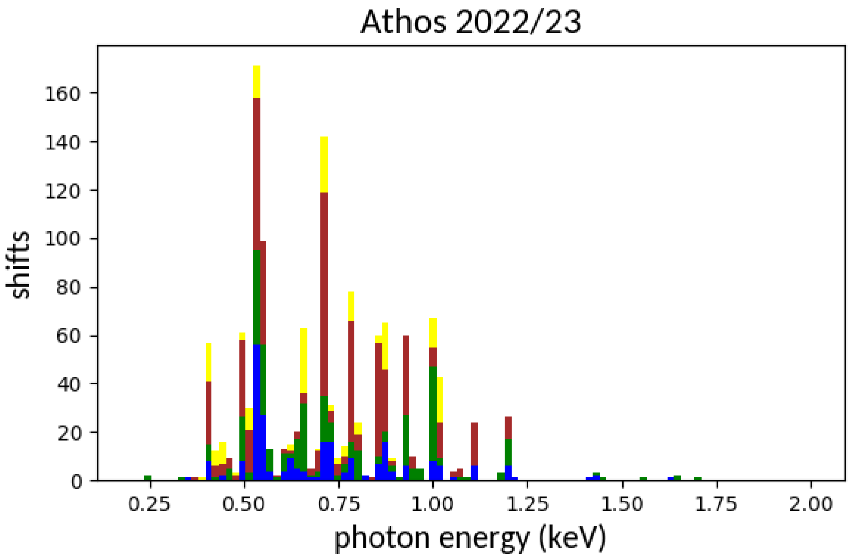

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Aramis special modes – overview

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!

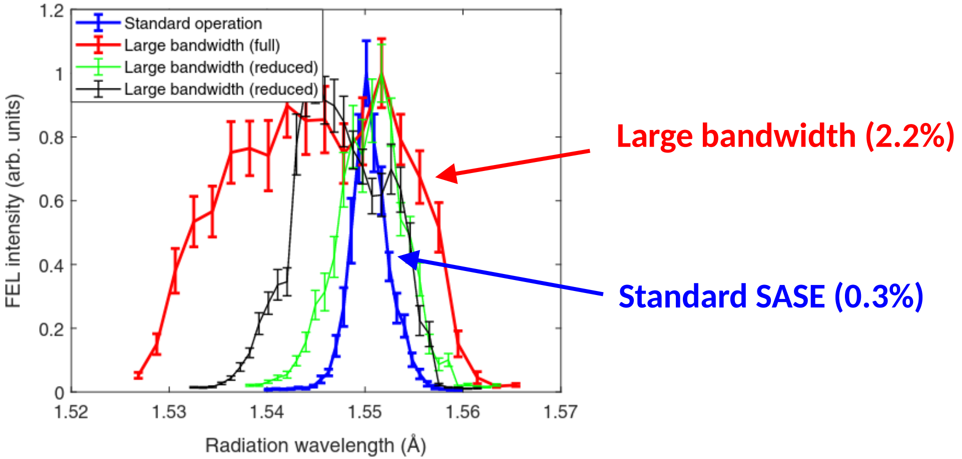
https://www.victorinox.com/ch/en/Products/Swiss-Army-Knives/Small-Pocket-Knives/Classic-SD-Classic-Colors/p/0.6223.G

Aramis: large-bandwidth mode

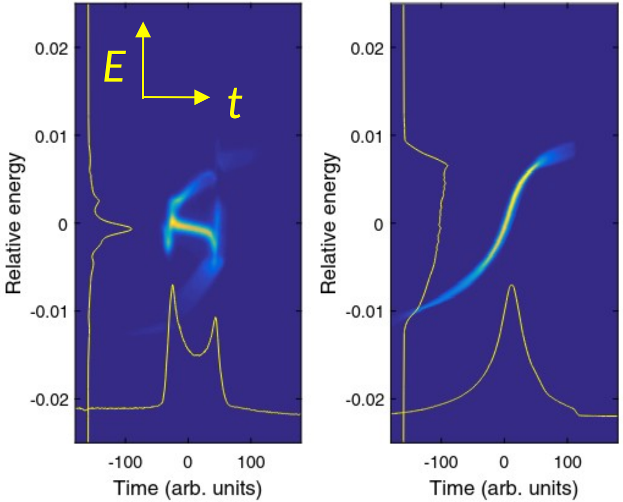
E. Prat et al.,
Phys. Rev. Lett. 124 (2020) 074801

S. Reiche et al.,
Phys. Rev. Res. 5 (2022) 022009

- Overcompression to invert sign of electron beam energy chirp
- Then use linac wakefields (strong in the SwissFEL case since we use C-band with small aperture) to *enhance* this chirp further!
- The large energy chirp translates to a large bandwidth in the photon beam (factor > 7 larger than with SASE)
- Can be combined with a correlated spatial chirp by leaking out disperson into the undulator line.



Electron phase space



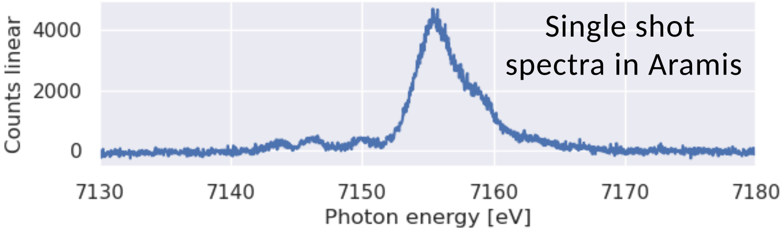
Standard SASE mode *Large-bandwidth mode*

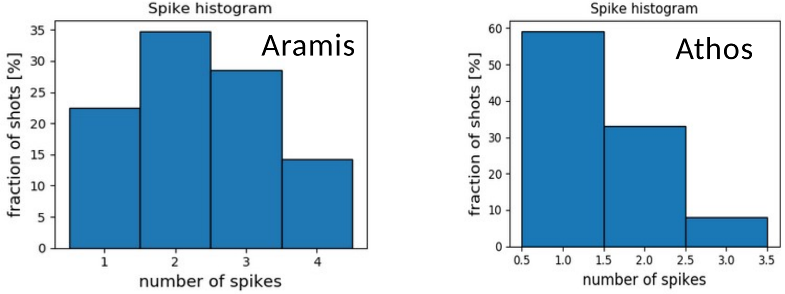
Attosecond pulses in both Aramis and Athos

- Method: non-linear compression of low charge (10 pC) beam in both lines, using three stages for compression:
  - Aramis: BC1, BC2, and energy collimator chicane before undulator
  - Athos: BC1, BC2, and dogleg
- Photon spectra with few spikes: >20% single spikes in Aramis (~10 µJ), >50% in Athos (~20 µJ). FWHM pulse durations deduced from spike width: ~350 as in Aramis, ~1 fs in Athos.
- Post-undulator streaking of electron beam useful for setup (passive in Aramis, X-band RF in Athos), but not enough resolution for a direct reconstruction of attosecond pulses.

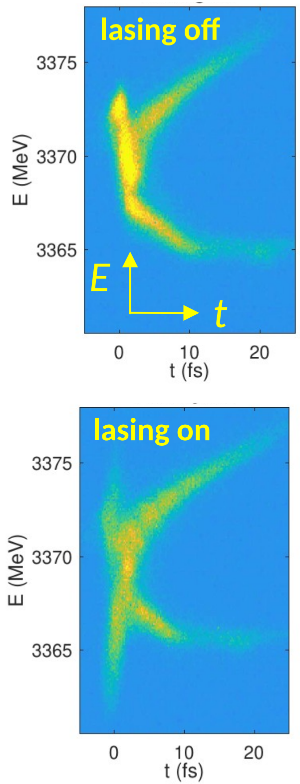
A. Malyzhenkov et al.
Phys. Rev. Research 2, 042018(R)

E. Prat et al.,
APL Photonics 8 (2023) 111302





electron phase space after nonlinear compression:



Athos special modes – overview

not yet attempted or possible
in commissioning
✔ ready for experiments!

(Optical klystron) ✔

Short pulses ✔
(beam tilt)

Variable polarization ✔

Large bandwidth
(energy chirp)

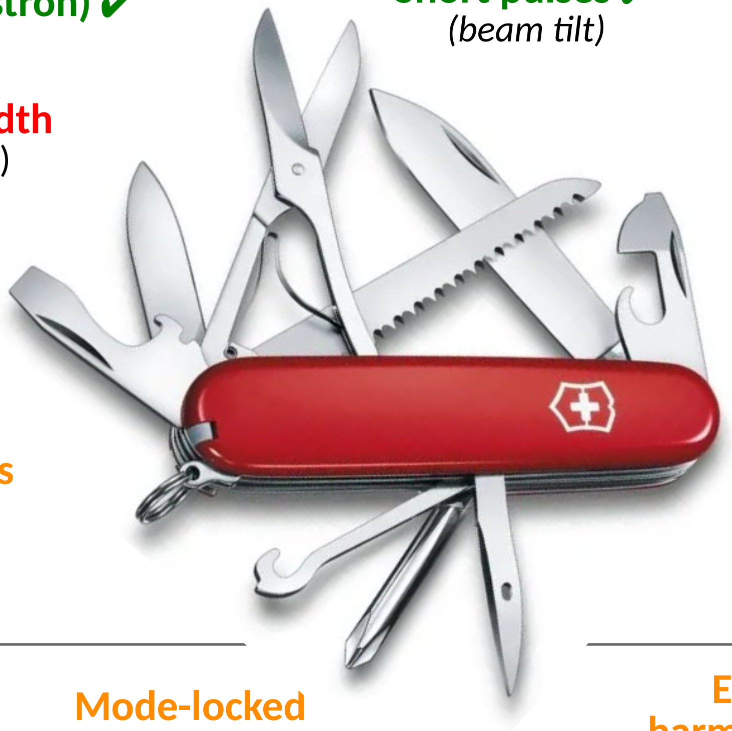
Attosecond pulses ✔
(three-stage compression)

Ultralarge bandwidth
(TGU)

Two-color with fresh slices ✔

High-brightness SASE

Short-pulse high-power ✔
(superradiance)



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

Laser seeded modes:

Enhanced SASE ✔

Mode-locked lasing

Echo-enabled harmonic generation (EEHG)

Porthos user wish list after this workshop?

(Victorinox Swiss Champ XXL,
CHF 349.-)

Athos: variable polarization

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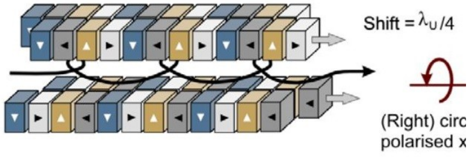
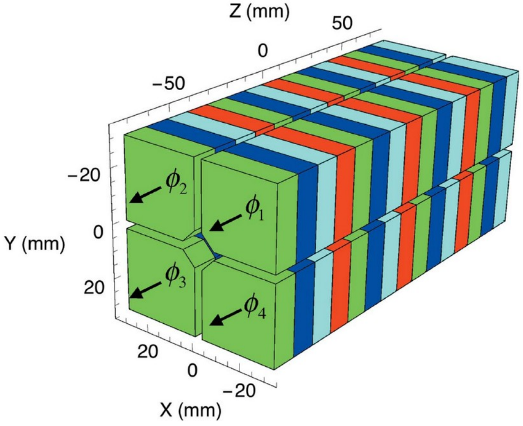
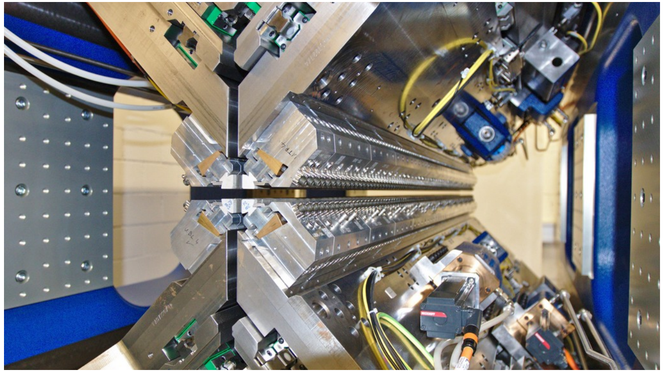
Generation: Athos APPLE-X undulators

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

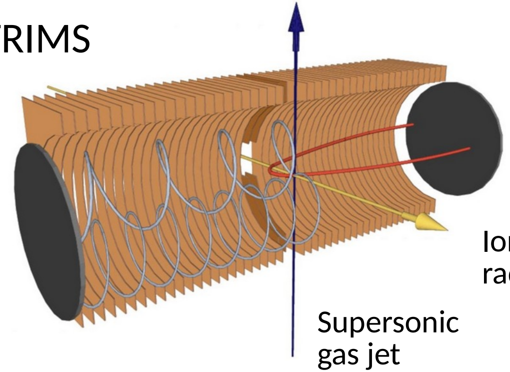




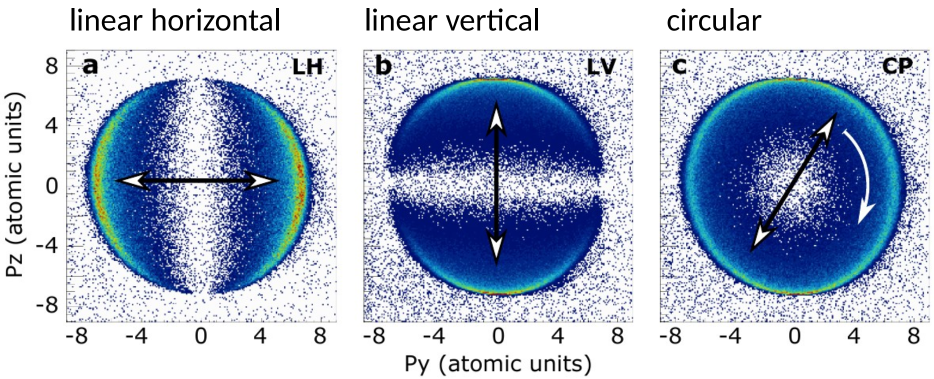


Measurement: cold target recoil ion spectroscopy at Maloja experiment (Athos)

COLTRIMS



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



Athos: short pulses with tilted beams

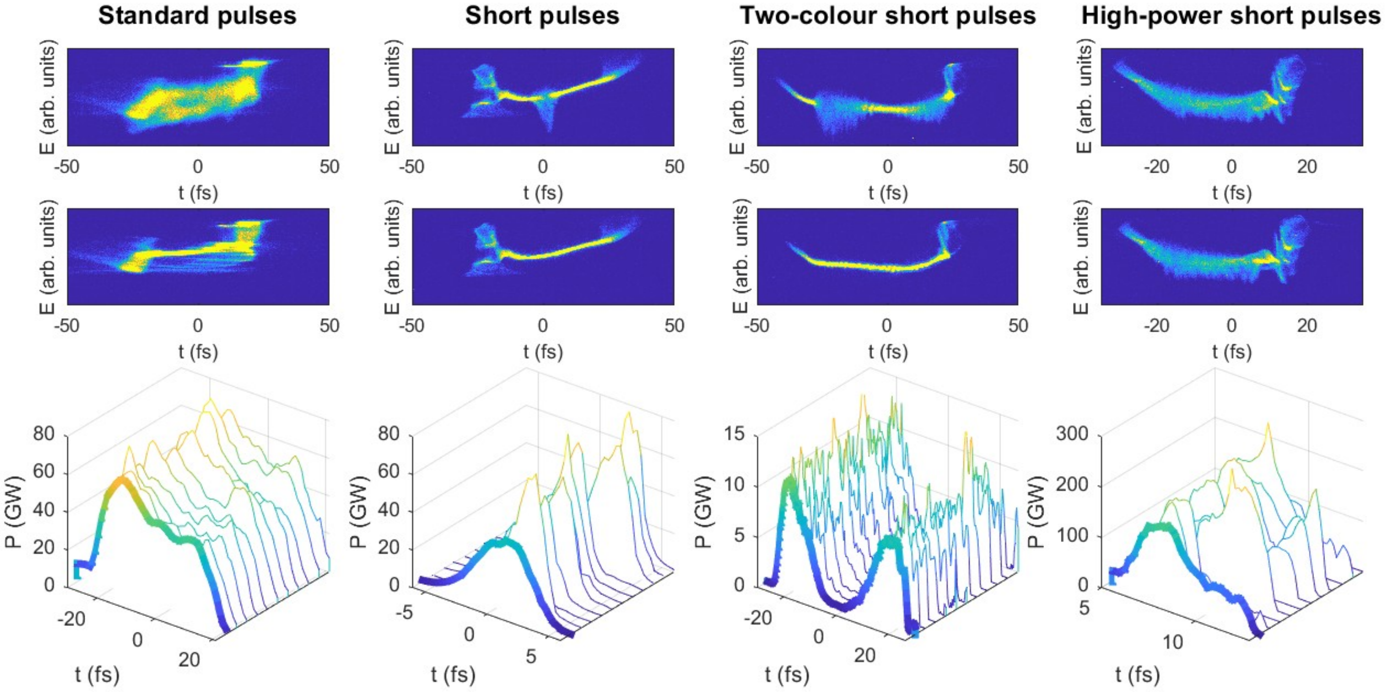
900 eV | 900 eV | 500/760 eV | 620 eV

electron phase space:

Lasing on

Lasing off

FEL power profiles
(single shots, average in bold)



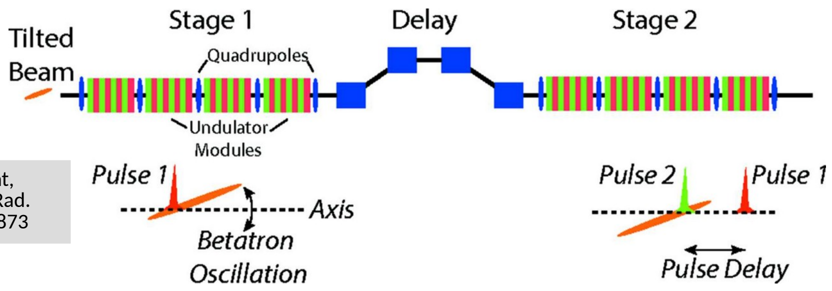
Standard pulse duration ~25 fs (rms), peak power about 50 GW

Down to 1.5 fs, peak power up to 50 GW

About 5 fs each pulse, 10 GW power

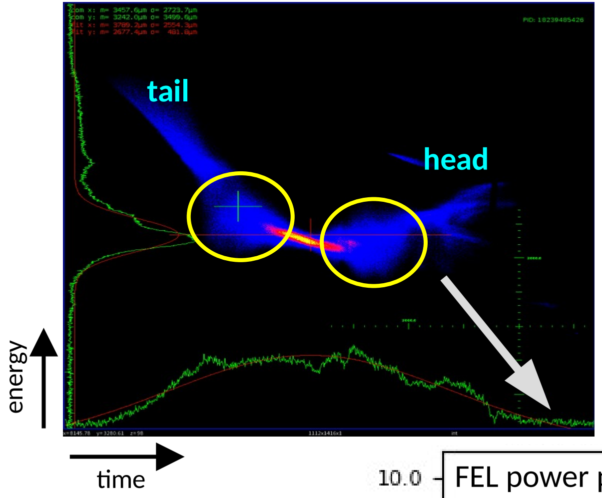
1.5 fs pulse duration, >200 GW power

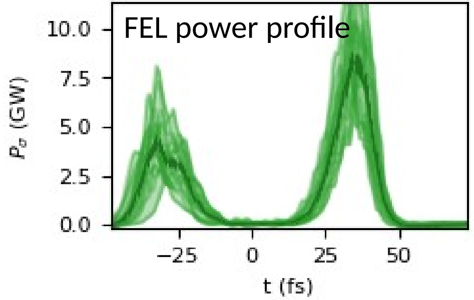
Athos: two-color fresh slice technique



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

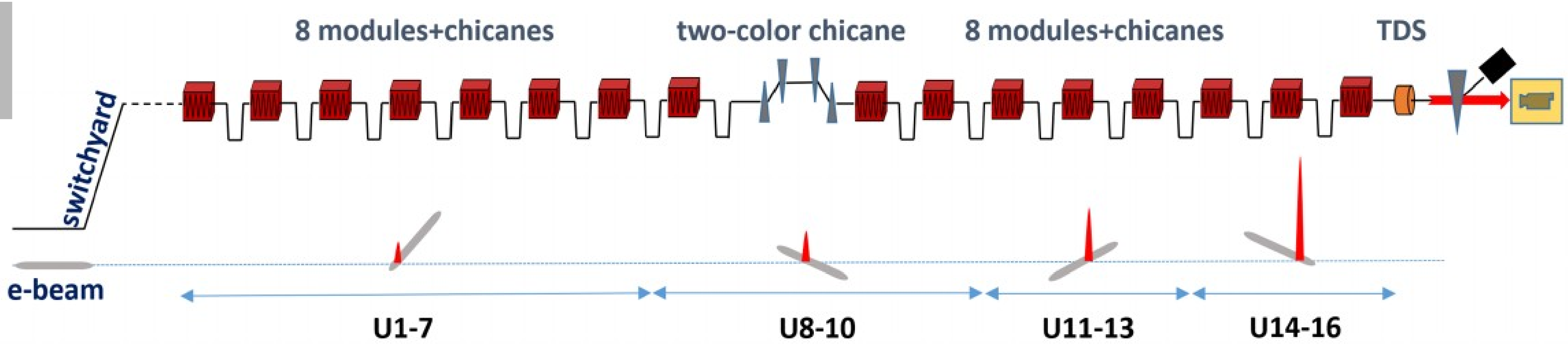




- Generate two colors in two undulator segments with two (fresh) slices of the electron beam (with beam tilt)
- Wide tunability both in color and time separation.
- Separate polarizations for the two colors are possible.
- First demonstration in 2021.
- Now routinely used by experiments.

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

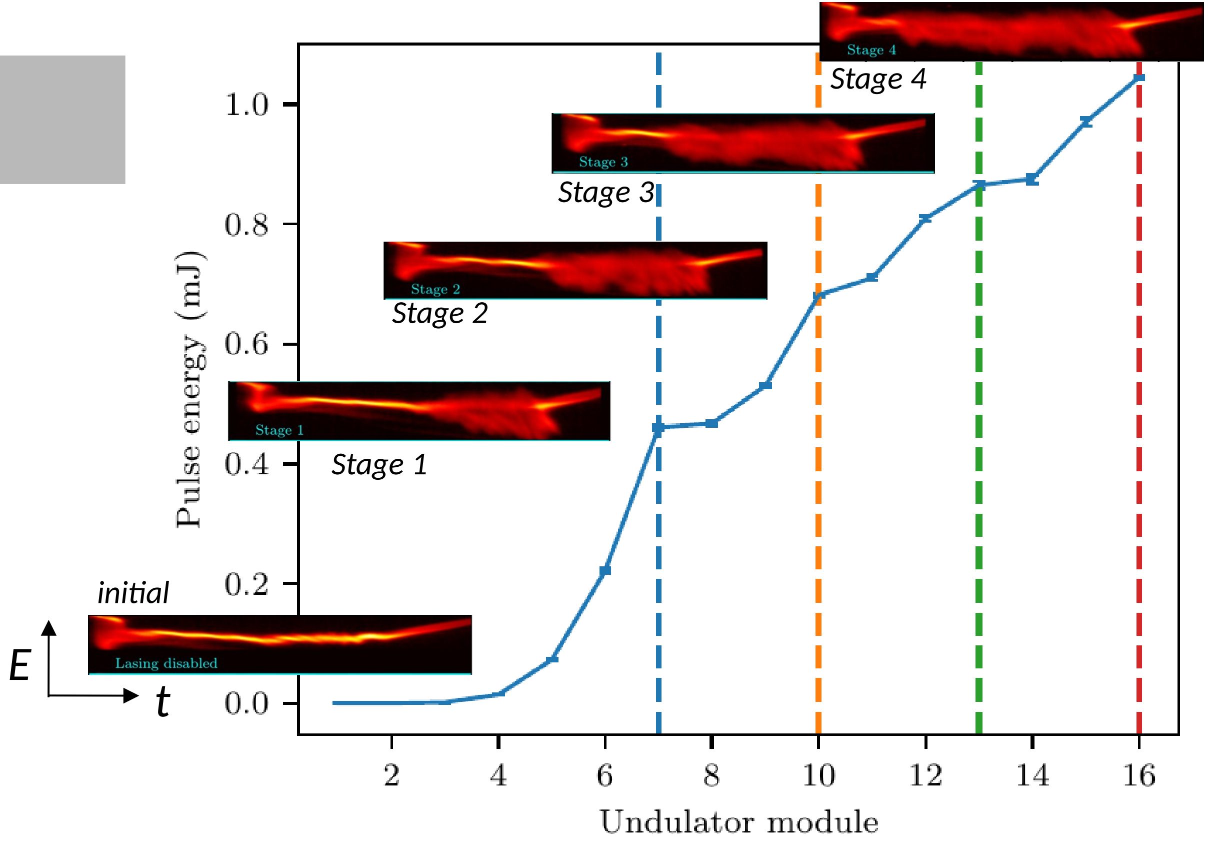
Multistage amplification (superradiance)

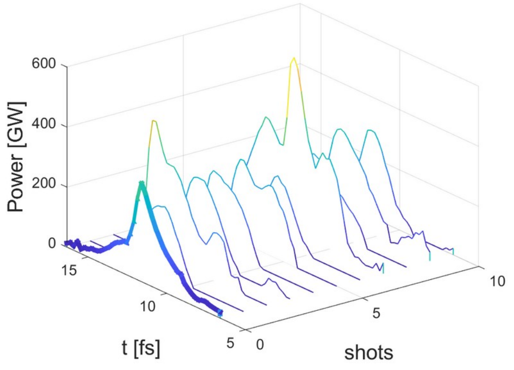


- Tilted beam to limit lasing to a short section of the bunch
- Start with the tail slice of the bunch lasing
- Use the delaying chicanes to move the lasing to a “fresh” electron bunch slice, while further amplifying the existing radiation pulse (→ superradiance!)
- Use orbit corrector magnets to make sure the correct slice overlaps with the photon beam

E. Prat, F. Löhl, S. Reiche,
Phys. Rev. Accel. Beams 18 (2015) 100701

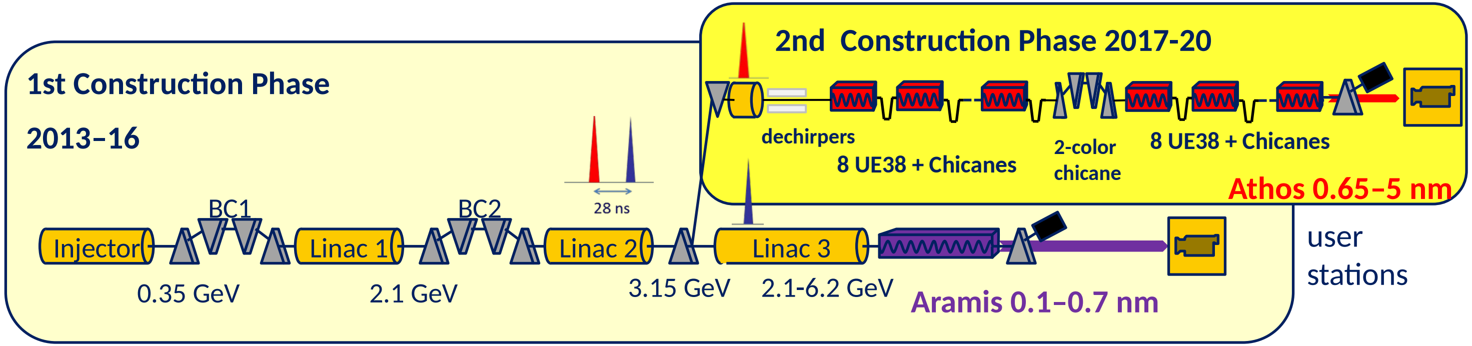
Multistage amplification (superradiance)





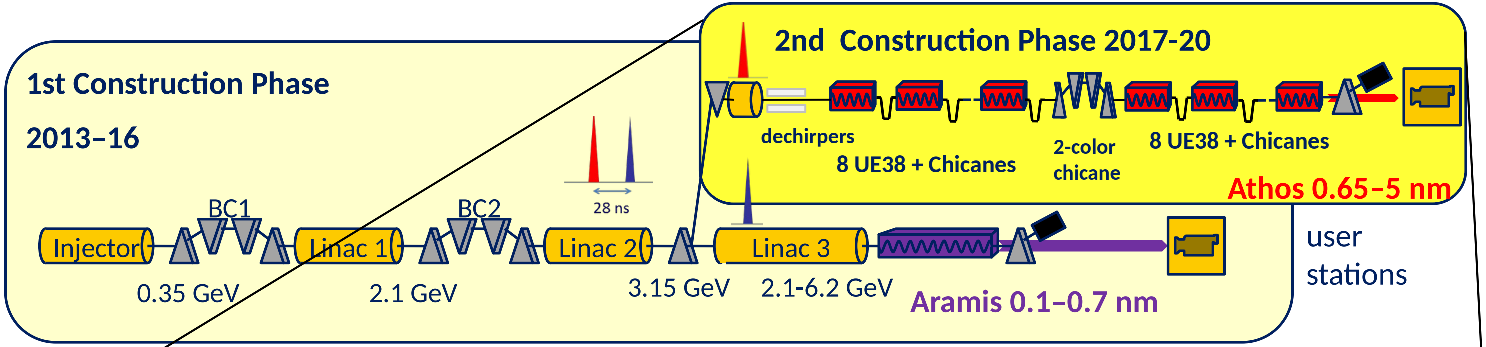
- Photon energy 520 eV
- Four amplification stages (6+3+3+3 undulator modules)
- **~1.05 mJ** in **~1.9 fs** (rms) **(>250 GW)**
- FEL energy gain consistent with $z^{3/2}$ tendency expected from FEL superradiance regime.
- Publication submitted to Phys. Rev.

SwissFEL Athos upgrades: HERO & EEHG



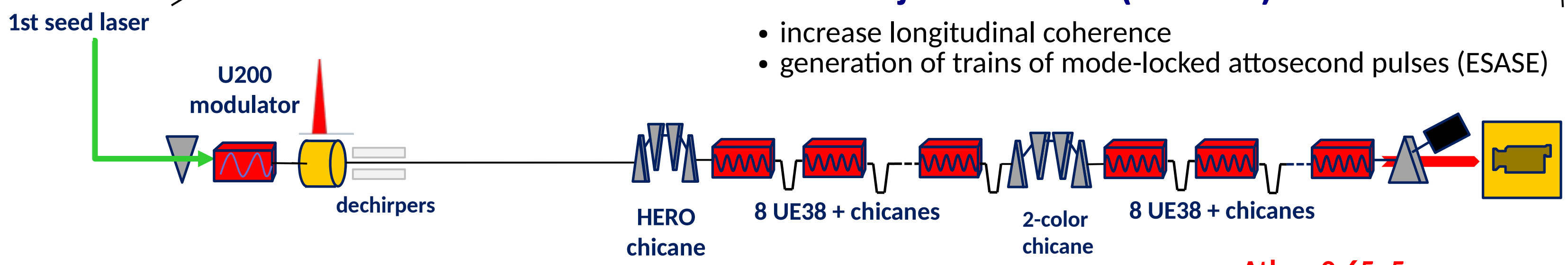
courtesy R. Ganter

SwissFEL mid-term upgrades: HERO & EEHG



HERO Project 2020–22 (Phase 1)

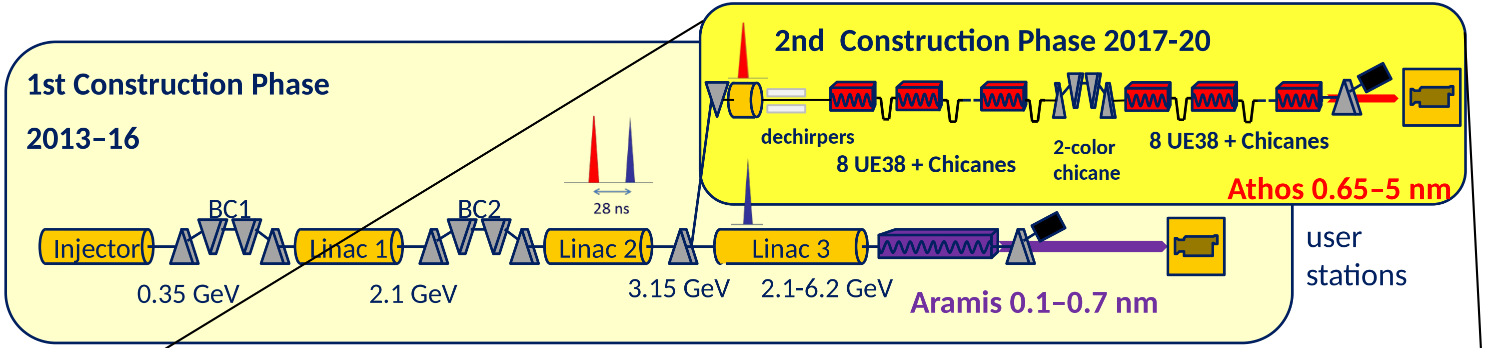
- increase longitudinal coherence
- generation of trains of mode-locked attosecond pulses (ESASE)



courtesy R. Ganter

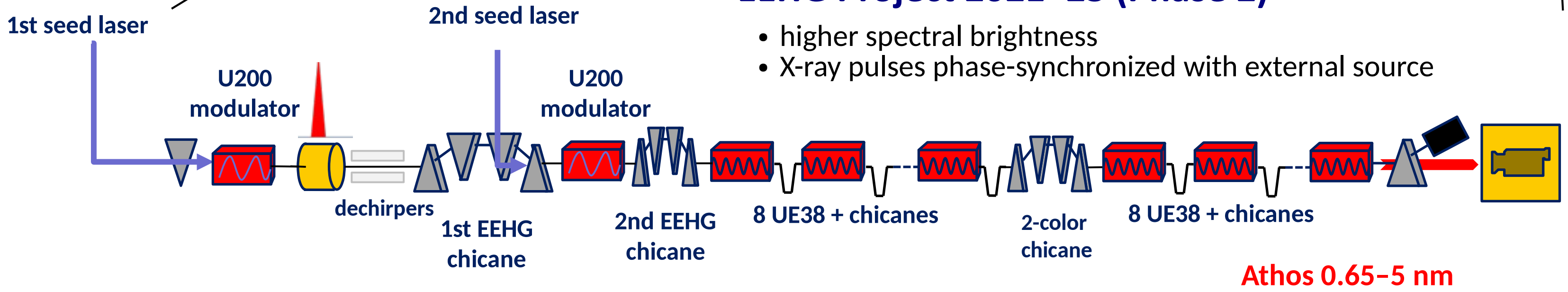
HERO = Hidden, Entangled and Resonant Order
(Title of European Research Grant paying for all this stuff...)

SwissFEL mid-term upgrades: HERO & EEHG



EEHG Project 2021–23 (Phase 2)

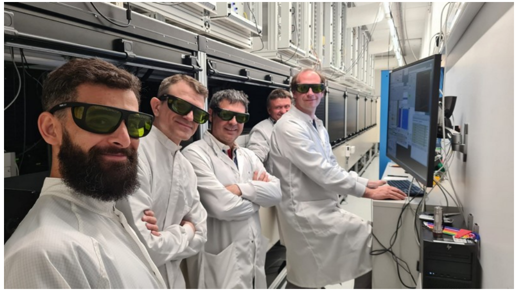
- higher spectral brightness
- X-ray pulses phase-synchronized with external source



courtesy R. Ganter

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

Modes based on external ("seed") laser (Athos)

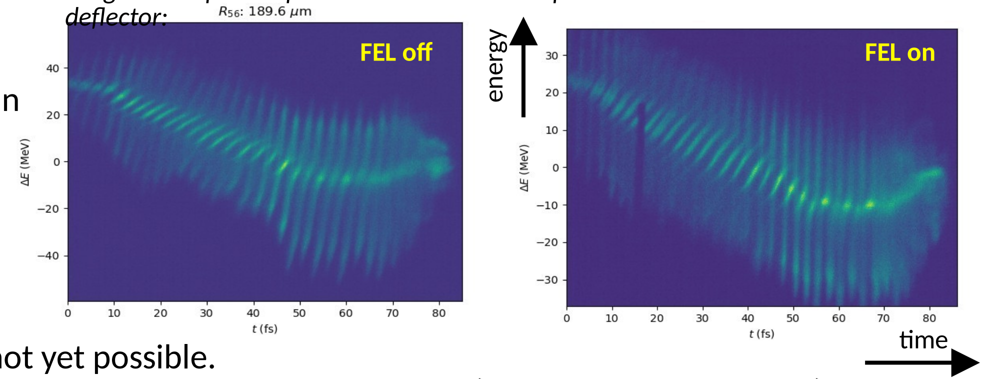
Enhanced SASE (ESASE) ✔

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

Mode-locked lasing (MLL) (✔)

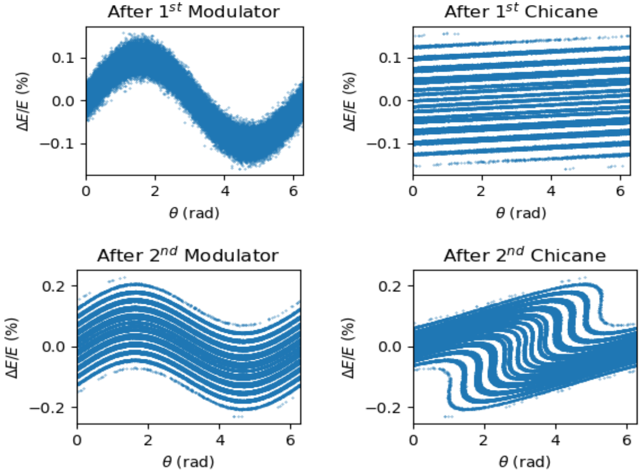
- Use intraundulator chicanes to propagate coherence between ESASE pulses.
- Was attempted (and may have been successful) but clean experimental verification of coherence not yet possible.

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



Echo-enabled harmonic generation (EEHG) ✘

- Hardware ready and commissioned since August 2023.
- Seeding at 266 nm wavelength.
- Achievements so far:
  - Demonstrated use of laser heater to suppress microbunching instability
  - Electron beam preparation (reduced "horns", flat energy profile)
  - Overlap found in both seed stages.
- Current bottleneck: reduced efficiency in coupling of 266 nm laser and electron beam – currently under investigation



EEHG simulation (S. Reiche)

Lessons learned from Athos… (1)

What it means for Porthos:

- **Undulator design:**
  - Overall concept for producing arbitrary polarization works well.
  - Complex mechanical setup leads to frequent motion issues (magnet arrays getting stuck).
  - Orbit kicks from undulator depend on *K* value and polarization setting – renders correction difficult! Problem for beam-based alignment!
  - Aperture (5 mm inner-diameter vacuum pipe) very tight for operation modes based on tilted beam.
- **Inter-undulator chicanes** have proven to be very effective (optical klystron, high-power short-pulse mode)

→ viable concept for Porthos

→ improved mechanical design?

→ consider during undulator design

→ find optimum trade-off between magnet strength and aperture

→ include also in Porthos design

Lessons learned from Athos… (2)

What it means for Porthos:

- **Injector design:**
  - Current density peaks at head and tail of electron bunch ("horns") lead to coherent synchrotron radiation effects in the switchyard, distorting the longitudinal phase space. (Okay for SASE, but limiting factor for EEHG…)

    → implement "horn cutting" (first compression stage), or find clever compression setup to avoid "horns"
  - Intrinsic energy spread too large in SwissFEL (requires revision of injector design)

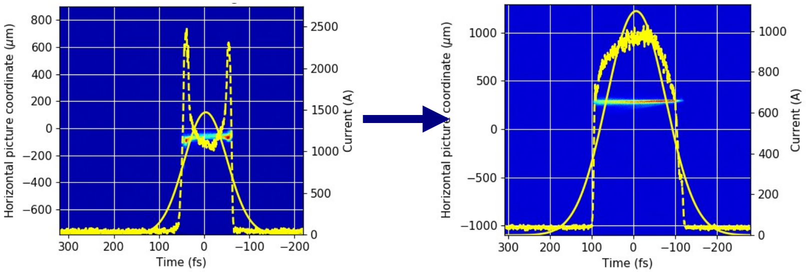
    → include injector upgrade in Porthos project
- **Switchyard design:** coupling of beam transverse optics and R56 (compression) is a problem

  → improved switchyard design ready
- **Beam phase space manipulation:** options for generating or removing (higher-order) energy chirps are too limited for some modes (e.g. high-brightness SASE).

  → no straight-forward solution, needs R&D!
- **Diagnostics:** post-undulator transverse deflecting cavity is a must! It should be capable of the full repetition rate of the machine for correlation studies.

  → include also in Porthos design

SwissFEL outlook



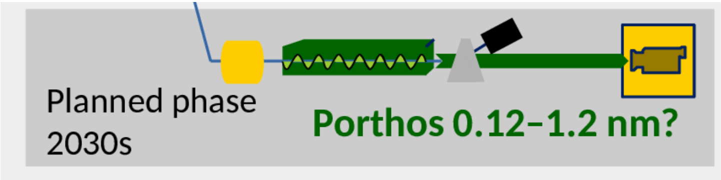
Midterm improvements

- Beam profile cleaning in BC1 (“horn cutting”)
  - Copper collimator: ready to be used, but generates too much radiation.
  - Radiation shielding: first version installed, *requires further iterations.*
- Stabilization of EEHG mode (Athos)
  - Current hardware installation good enough for first demonstration.
  - Exploitation as a user mode will require investments in stabilization of seed laser systems and electron-laser overlap
  - Electro-optical monitor for electron-laser overlap (concept phase).

BC1 shielding

Longterm upgrade

- “Porthos”: a third undulator beamline for SwissFEL (1–10 keV)
- In principle building layout can support up to four beamlines.
- New experiment hall required to house end stations.



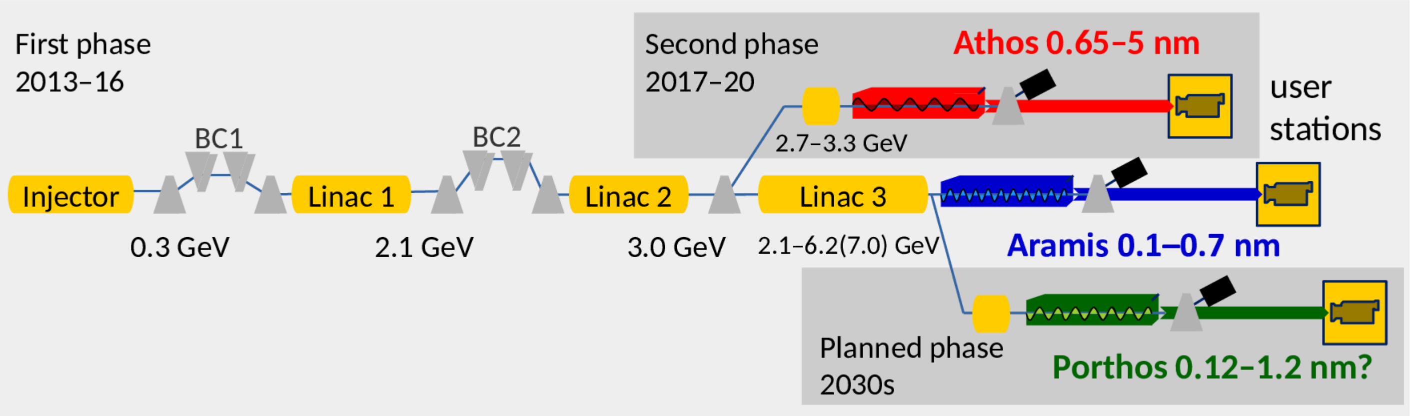
Porthos upgrade

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

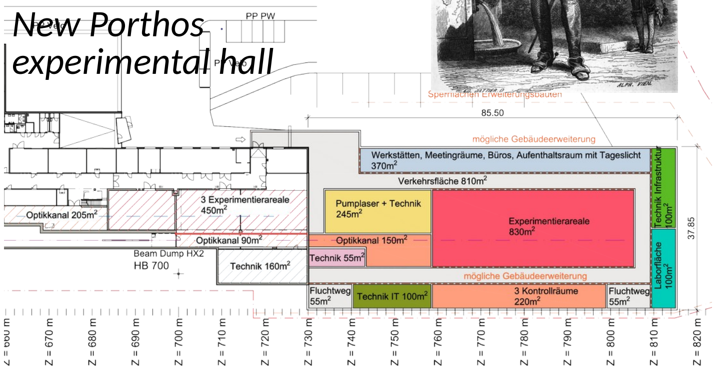
PAUL SCHERRER INSTITUT PSI

Porthos upgrade

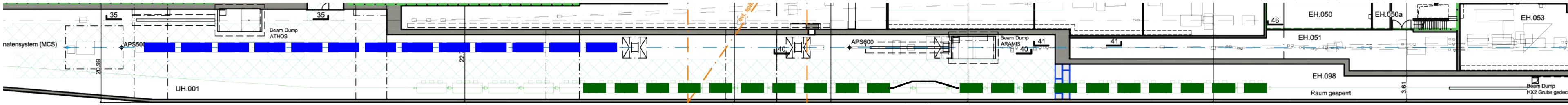
Porthos

- Preliminary plans for a third undulator line, dubbed "Porthos."
- Firmly anchored in the Swiss *Photon Science Roadmap* (published 2021)
- Science case still in preparation – that's why we have this workshop!!
- Preproject period to develop undulator prototype and implement various accelerator improvements towards Porthos.

New Porthos experimental hall



Aramis line (in operation)



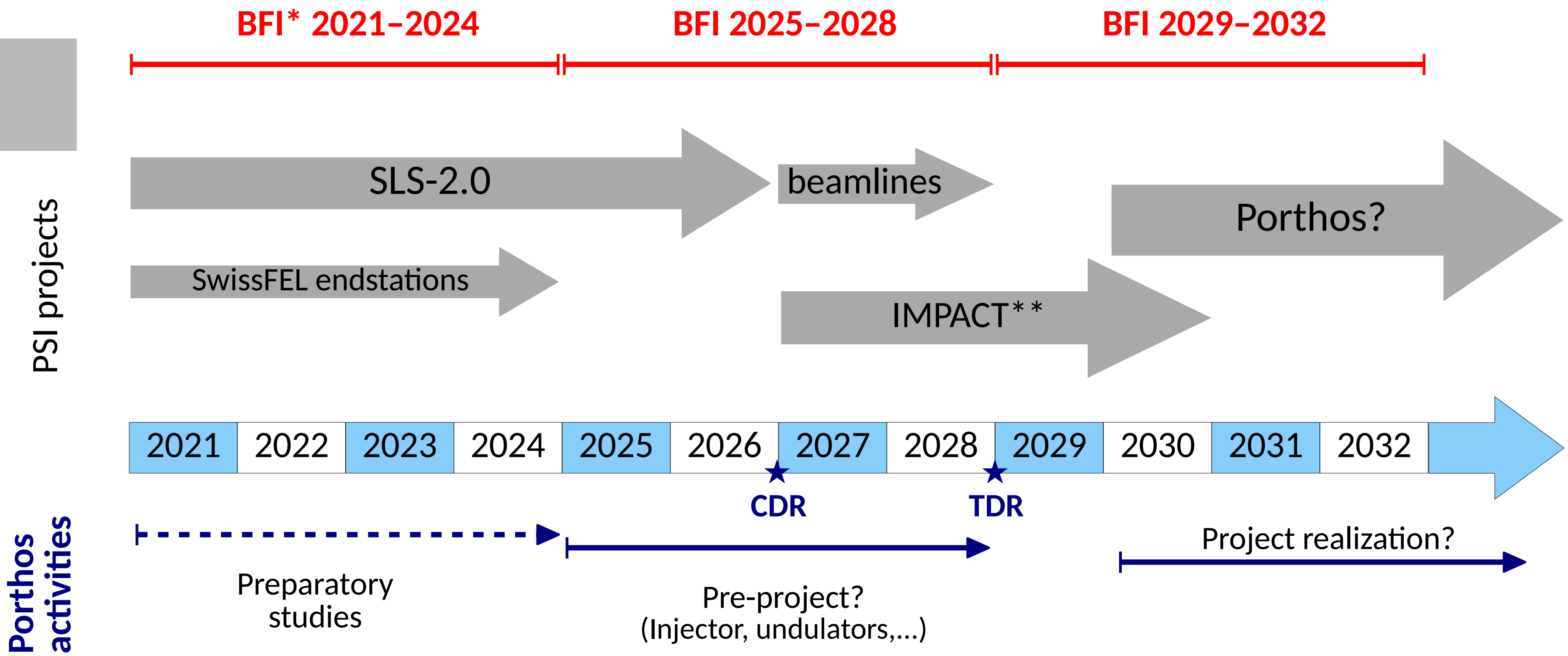
new Porthos line (planned)

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

≈100 m space available for undulator line
(about 80 m of pure undulators taking into
account focusing and diagnostics elements…)

Beam dump
(already
installed)

SwissFEL upgrades in the PSI context



* BFI = Swiss Government funding periods (four years)
** IMPACT = Upgrade of the PSI proton facility

Thank you for being here!