SwissFEL: The Big Picture

Athos upgrades:

ESASE: λ_{seed} = 267/400/800 nm

EEHG: λ_{seed} = 267 nm

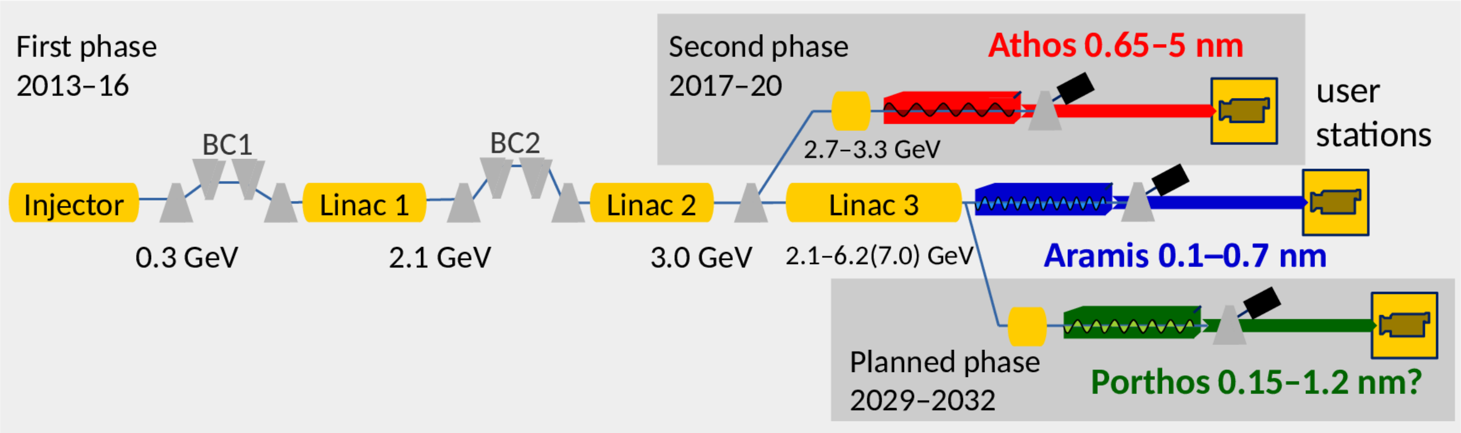
Commissioning 2022/23

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 = 0.15–1.2 nm?

Variable-polarization undulators (technology to be decided)

Start of construction: 2029

Thomas Schietinger (PSI)

PAUL SCHERRER INSTITUT PSI

Science Case: SCNAT/SSPS Roadmap

Swiss Academies Reports, Vol. 16, No. 5, 2021

Content

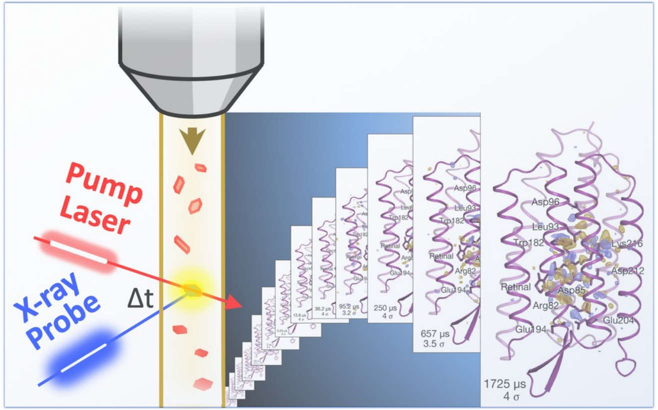
Chapters on:

- Synchrotrons
- Free-Electron lasers
- Institution based laser platforms

PAUL SCHERRER INSTITUT

Porthos Science Case:
Time-resolved structural biology

- Goal: Resolve dynamics responsible for molecular functions (“dynamics-are-function”)
- Require:
  - **Shorter photon pulses** (few fs or less) at still high pulse energy to:
    - enable “diffraction-before-destruction”
    - provide high-resolution data from smaller crystals (even single molecules?)
  - ~~**Higher photon energies** (up to 20–25 keV) to:~~
    - ~~give access to absorption edges of heavier elements~~



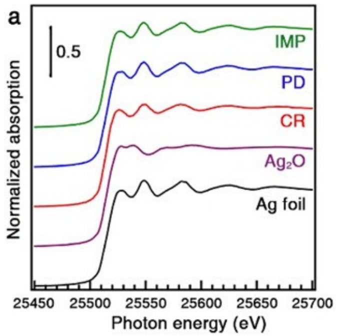
J. Spence, BioXFEL consortium

- Examples:
  - Identify position and orientation of small molecule ligands in a structure-based drug-design task.
  - Mapping of metal clusters acting as catalytic sites in enzymes.
  - Nanochemical synthesis of polyoxometalate clusters in dedicated storage proteins.

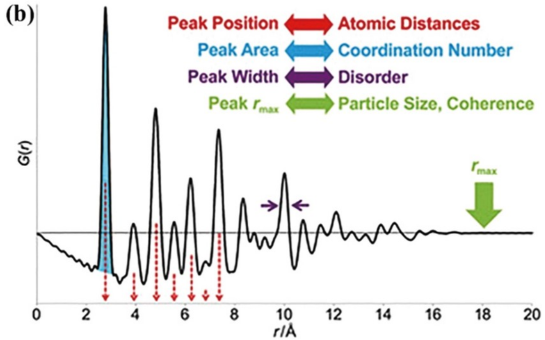
Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

Porthos Science Case: Ultrafast chemistry

R. Shi, G. I.N. Waterhouse, T. Zhang, Sol. RRL 1 (2017) 1700126



- Goal: Study chemical processes with spectroscopy and scattering experiments
- Require:
  - ~~**Higher photon energies** (12–35 keV) for:~~
    - ~~Access to absorption edges of heavier elements (in particular 4d transition metals in spectroscopy)~~
    - ~~Higher spatial resolution in scattering experiments~~
    - ~~Higher penetration depths → more opportunities for in-situ and operando experiments~~
  - **Shorter photon pulses** (5 fs) to:
    - Improve temporal resolution



W. Xuelong et al., Chinese Physics B 29 (2020) 028802

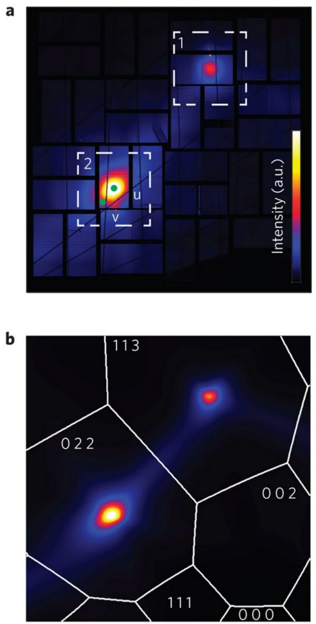
- Examples:
  - Pair Distribution Function scattering to resolve atoms in disordered or nanocrystalline materials
  - Gas-phase X-ray scattering to measure electronic dynamics.
  - Ultrafast hard X-ray scattering to study nanoplasma after laser interaction.

Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

PAUL SCHERRER INSTITUT

Porthos Science Case: Quantum materials

- Goal: study strongly correlated electronic systems
- Require:
  - ~~**Higher photon energies** (20–25 keV) to:~~
    - ~~Enable transmission experiments with thicker samples in forward-scattering geometry.~~
    - ~~Enable diffuse scattering experiments on solids with good q-resolution~~
  - **Bandwidth and polarization control** ~~(up to 14.4 keV)~~ to:
    - enable single-shot, pump-probe X-ray magnetic circular dichroism studies
    - time-resolved resonant diffraction studies
  - **Short pulses (sub-fs)** for low-temperature experiments
- Also interested in:
  - **Timed sequences of X-ray pulses with widely different energies** to:
    - Perform transient grating spectroscopy to measure, e.g., electron-phonon coupling strength or q-dependence of ultrafast demagnetization.
  - **Phase-locked pulse trains** (with self-seeding) to:
    - Perform linear and non-linear spectroscopy of quantum materials

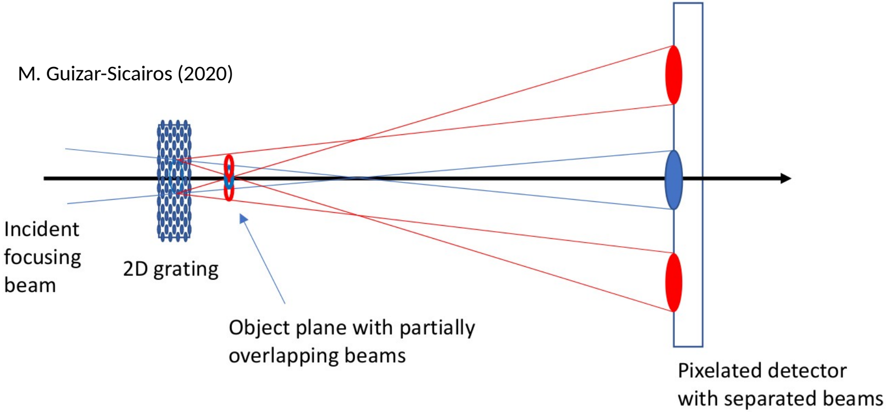


Trigo et al., Nat. Phys. 9,790–794 (2013)

Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

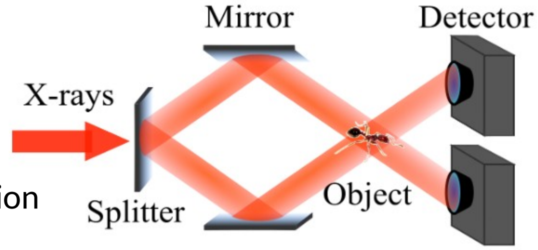
Porthos Science Case:
Single-shot ptychography and 3D imaging

- Goal: ultrafast imaging using single-shot ptychography or X-ray multiprojection imaging (XMPI) (splitting the incoming beam with a grating)
- Require:
  - **High photon pulse energy**
    - Use as many photons as possible
  - ~~**Higher photon energies** (12–30 keV) to:~~
    - ~~Penetrate thicker samples – *operando* studies~~
    - ~~(improve spatial resolution)~~
  - **Shorter photon pulses** (5 fs) to:
    - Improve temporal resolution



M. Guizar-Sicairos (2020)

- Examples:
  - Image ultrafast non-repeatable phenomena with high resolution in complex environments
  - Pump-probe studies of 3D dynamics with enhanced temporal resolution
  - Split-and-delay experiments to study ultrafast phenomena



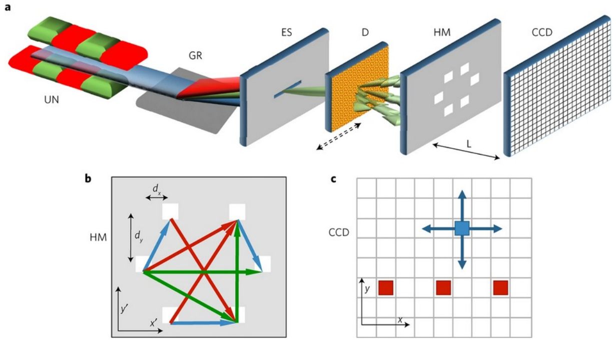
P. Villanueva-Perez,
Optica 5, 1521-1524 (2018)

Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

Porthos Science Case: Novel opportunities at the ultrafast and high-intensity frontier

PAUL SCHERRER INSTITUT PSI

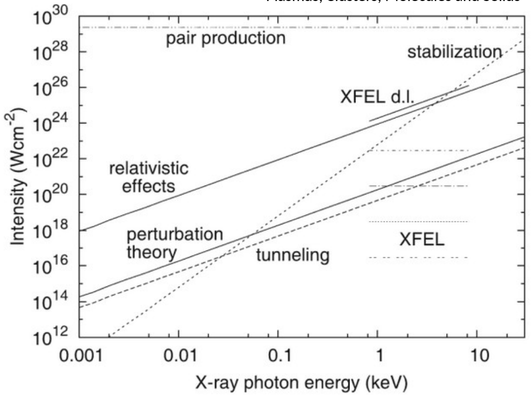
R. Schneider et al., Nat. Phys. 14 (2018) 126



Many novel opportunities are waiting:

- **Quantum chemical imaging:**
  - Exploit quantum characteristics of light to map chemical properties with high spatial and temporal resolution.
  - Requires **intense, short pulses.**
- **Novel nonlinear spectroscopy approaches:**
  - Nonlinear X-ray photon-in photon-out spectroscopy: compensate low nonlinear cross sections with **higher intensity** and increased interaction lengths ~~from **high photon energies.**~~
  - Exploitation of temporal coherence and defined phase relations.
  - Spectroscopy with entangled photons from nonlinear parametric down-conversion of X-ray photons (XPDC).
- **Strong-field interaction phenomena:**
  - Exploration of the **sub-fs** regime of X-ray non-linear interaction effects.
  - Photon-electron coincidence spectroscopy.
  - Fundamental physics questions: **high fields (= high power)**

Stefan P. Hau-Riege: High-Intensity X-rays - Interaction with Matter: Processes in Plasmas, Clusters, Molecules and Solids



Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

User requirements

All subfields require:

- **100 Hz operation**
- ~~**High photon energies** (min. 20–25 keV)~~
- **Short pulses** (≤ 5 fs, ideally sub-fs)

A few critical subfields require:

- **High power** (i.e. strong fields)
- **Polarization and bandwidth control**

Additional desires:

- Two color modes
- Phase locked pulse trains
- …

Porthos implementation

User requirements

Porthos implementation

All subfields require:

- **100 Hz operation** → **Three-bunch distribution system**
- ~~**High photon energies** (min. 20–25 keV)~~ → **Increased electron energy** and/or **reduced emittance**
- **Short pulses** (≤ 5 fs, ideally sub-fs) → **Inter-undulator delaying chicanes (CHIC)**

A few critical subfields require:

- **High power** (i.e. strong fields) → **High-K undulators: cryogenic** or **superconducting**
- **Polarization and bandwidth control** → **Apple-X undulators** or **phase retarder**

Additional desires:

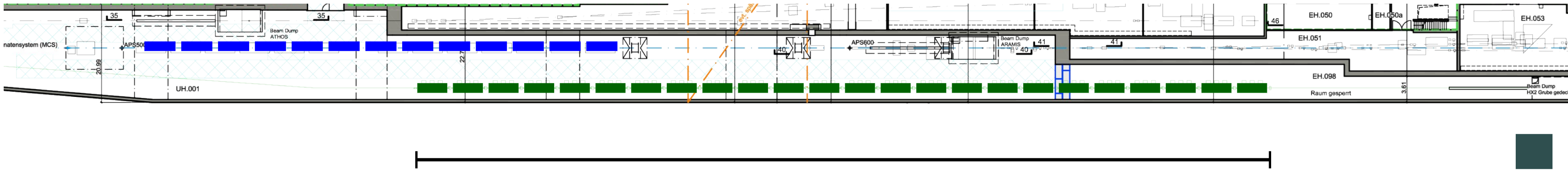
- Two color modes
- Phase locked pulse trains
- …

Red: *Porthos baseline*

Violet: *Pursue as alternative options*

Porthos undulator line: original provision

Aramis line (in operation)



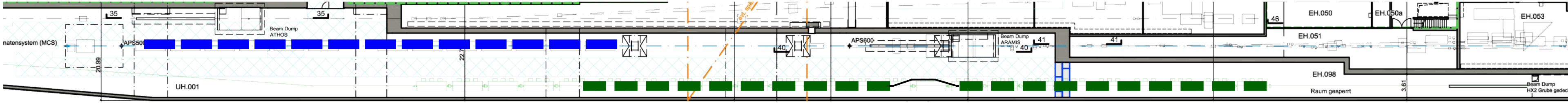
Original provision: 24 × 4.75 m = 114 m undulator line

Beam dump (certified to 7 GeV)

PSI drawing
No. 2R-393601 (2019)

Porthos undulator line: possible configuration

Aramis line (in operation)



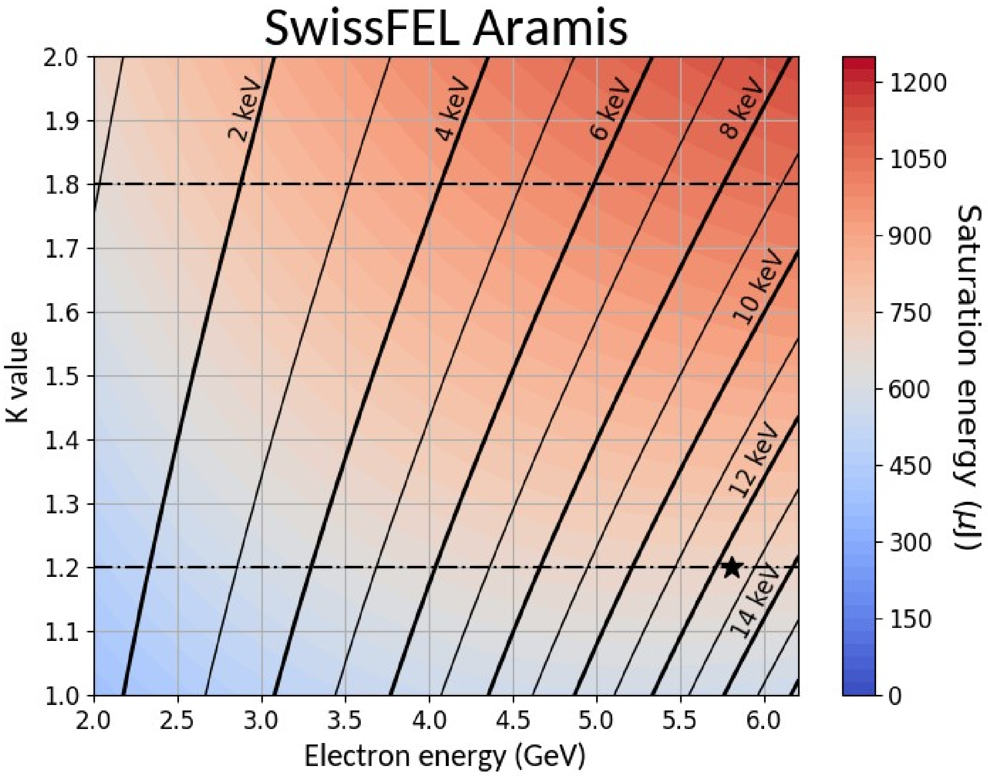
Space for RF and
beam manipulation devices
(active and/or passive)

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

Beam dump
(certified to
7 GeV)

PSI drawing
No. 2R-393601 (2019)

Aramis now



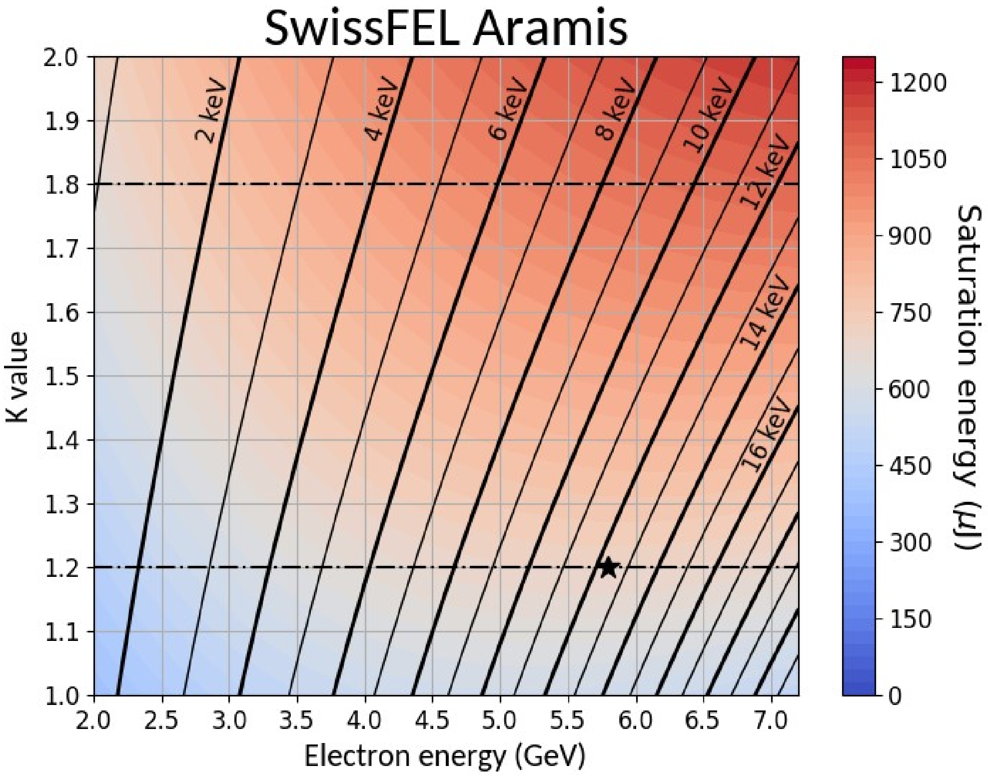
Model:

Ming Xie, PAC 1995, p. 183-185

Assumptions:

peak current: 2.2 kA
emittance: 200 nm
energy spread: 1.0 MeV
beta function: 10.0 m
pulse duration (rms): 40 fs

Aramis with 7 GeV



Model:

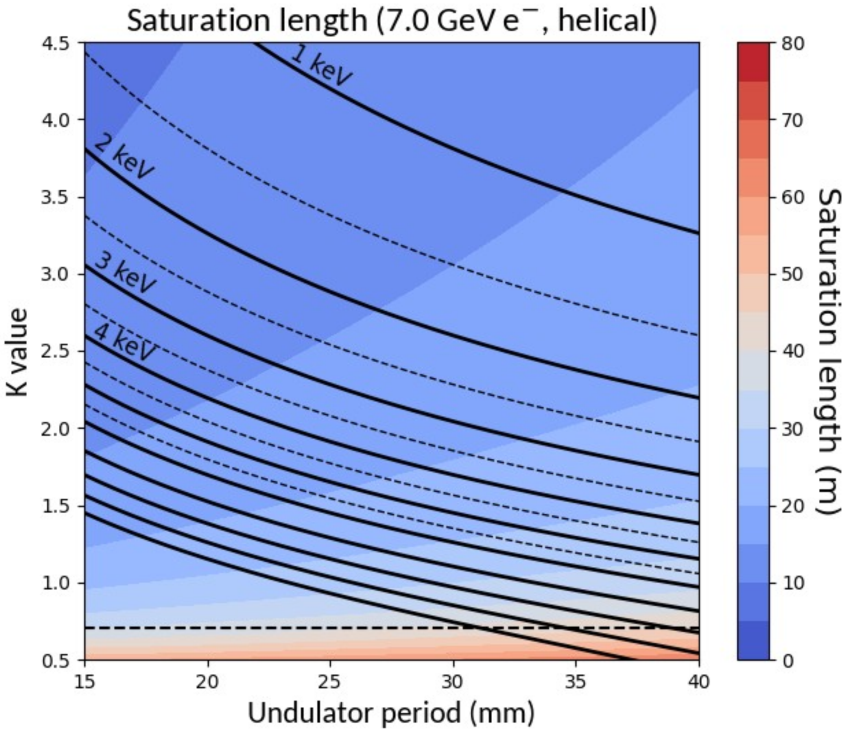
Ming Xie, PAC 1995, p. 183-185

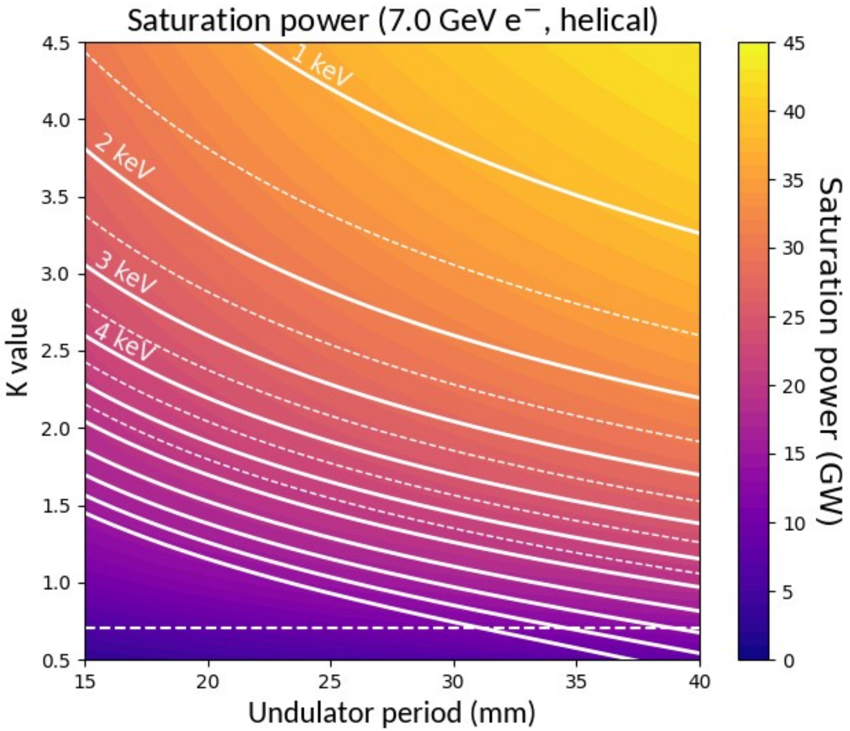
Assumptions:

peak current: 2.2 kA
emittance: 200 nm
energy spread: 1.0 MeV
beta function: 10.0 m
pulse duration (rms): 40 fs

Which undulator period for Porthos? (7 GeV)

(Model assumptions as for previous slide)

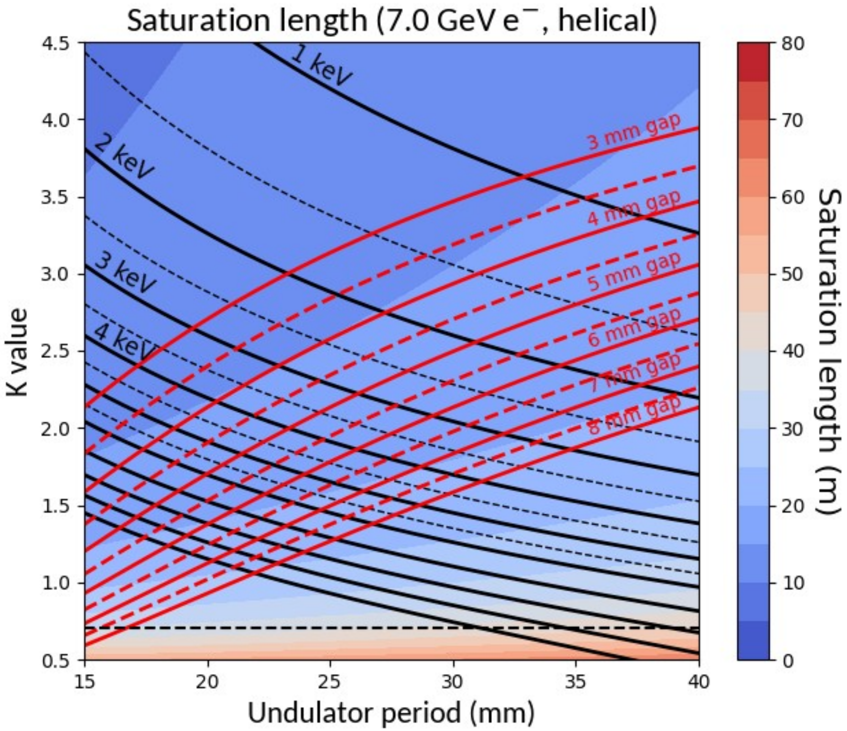


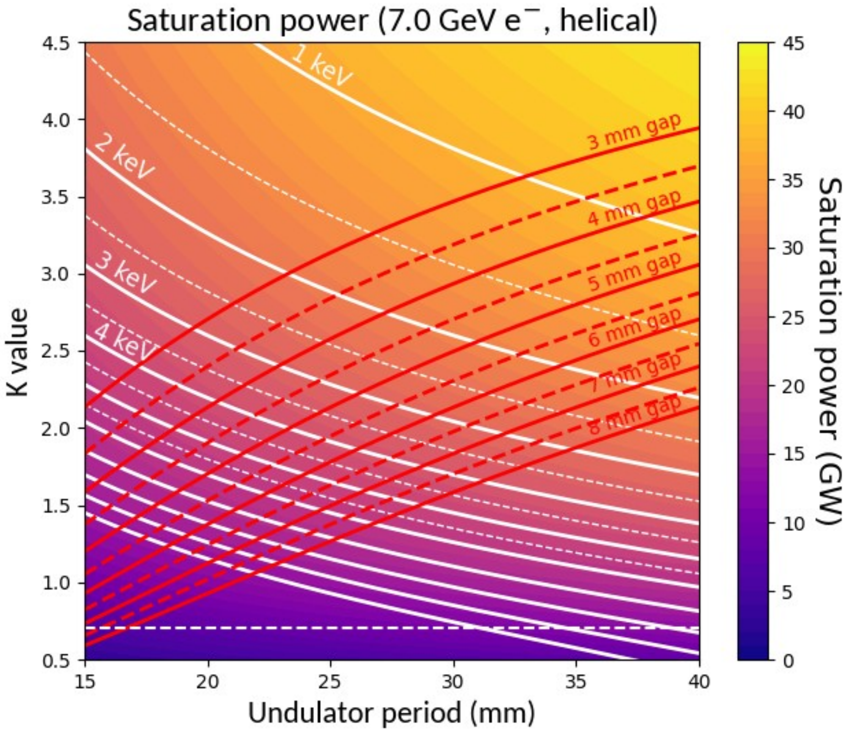


Cryogenic permanent magnet (7 GeV)

Undulator K (period, gap): **cryogenic in-vacuum APPLE-X** (simulation data, M. Calvi, private communication).

(Model assumptions as for previous slide)

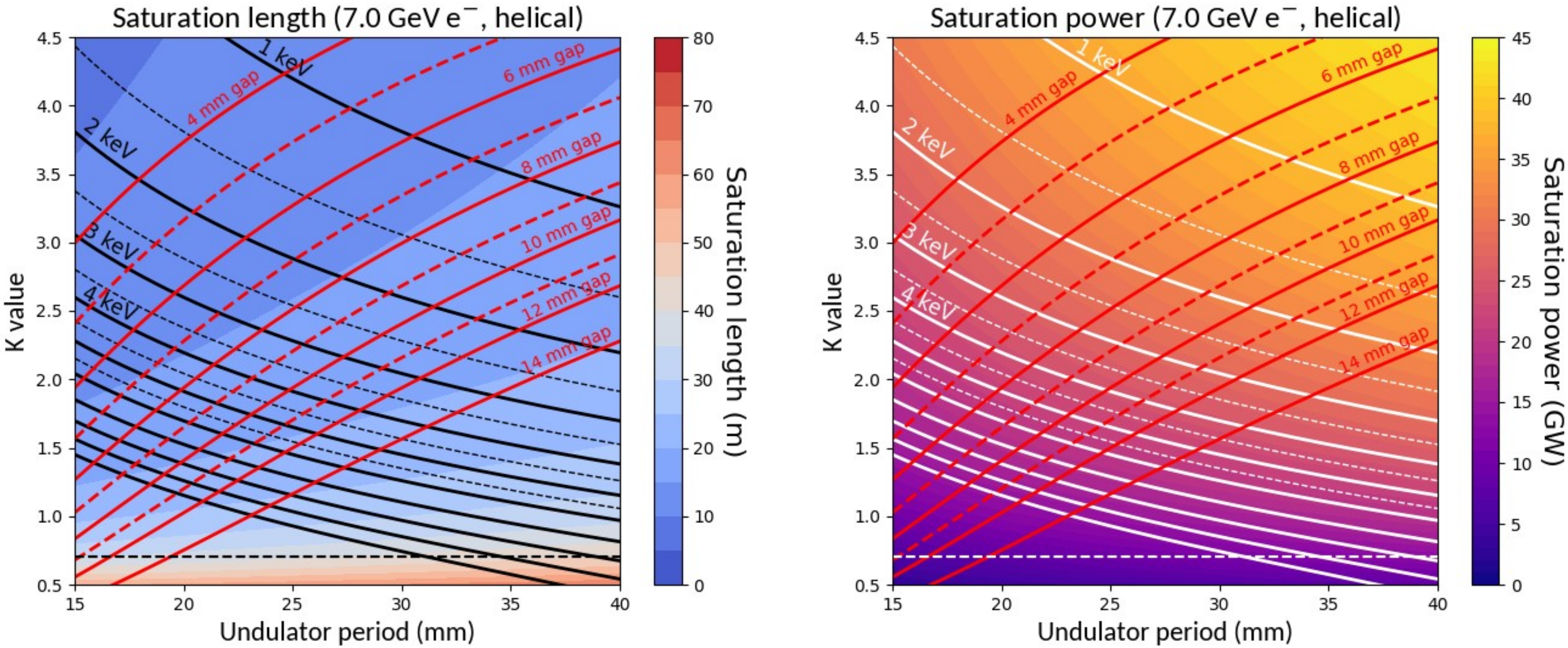




Superconducting magnet (7 GeV)

Undulator K(period, gap): **superconducting undulator** (simulation data, M. Calvi, private communication)

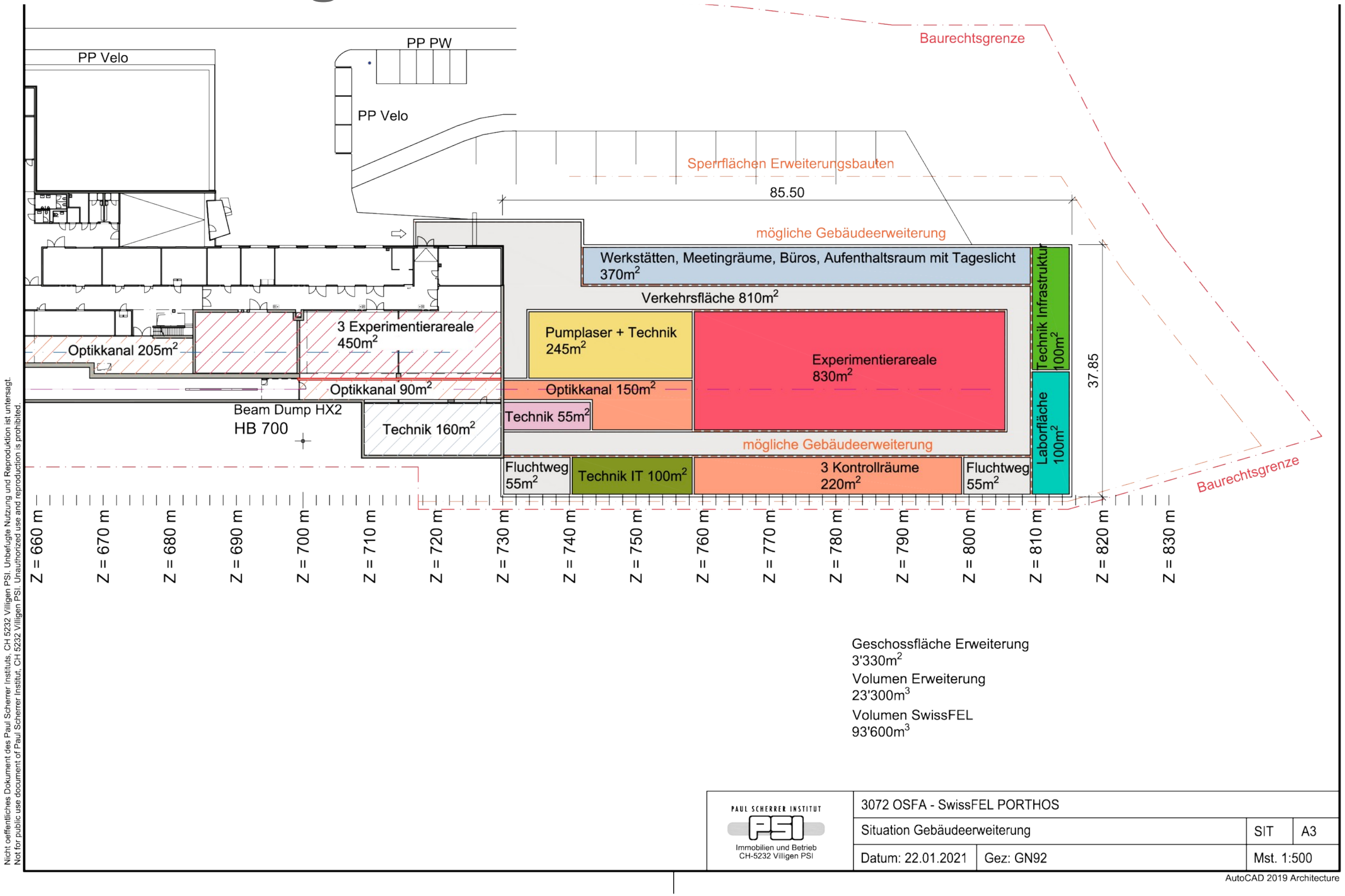
(Model assumptions as for previous slide)



OSFA building extension

Ivo Widmer & A. Gottstein

- First estimate making maximum use of space reserve.
- Additional building volume of 23’300 m^3 (about 35% of existing OSFA!)
- First cost estimate is **35–40 MCHF.**
- About two years construction time.
- Careful: building costs cannot be changed later!

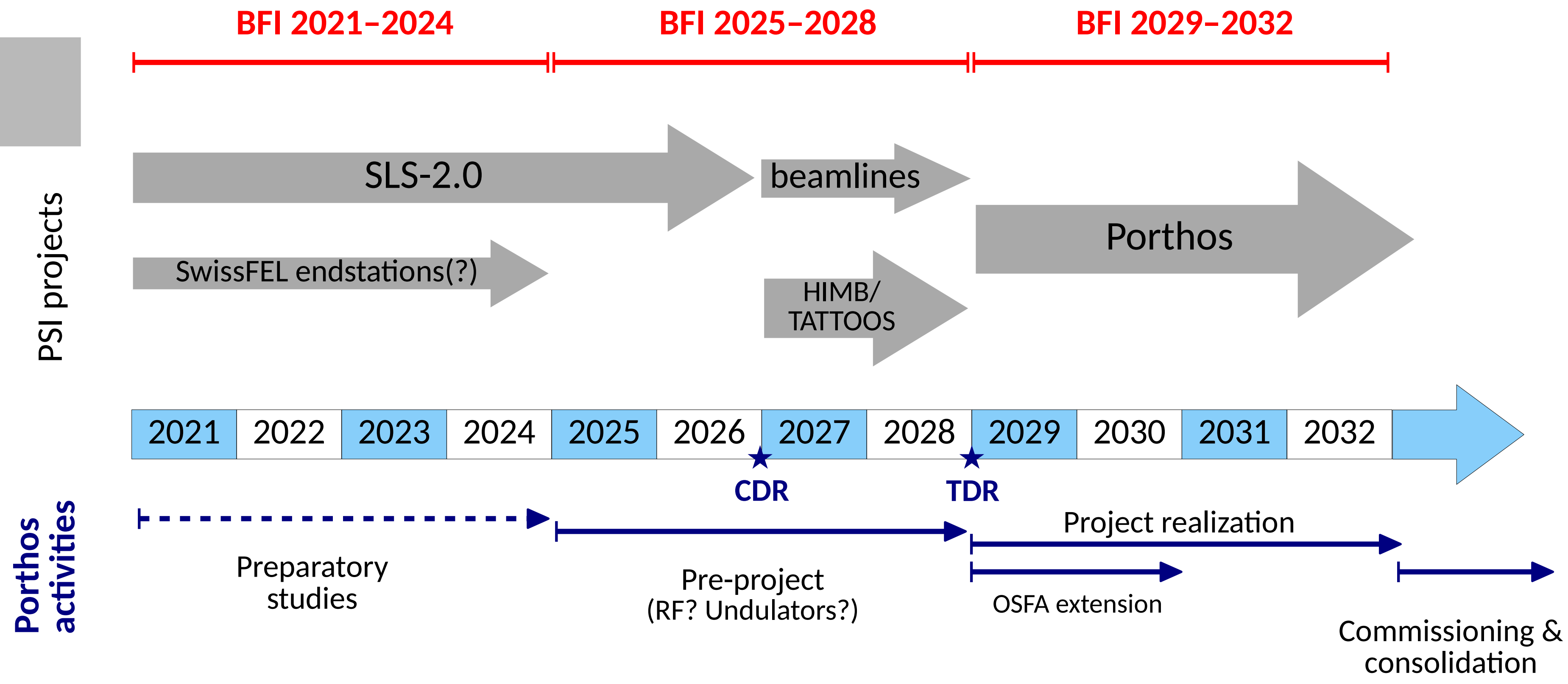


First, rough budget estimate (all items ±20%)

- Machine:
  - **Undulators:** 20 3-m Apple-X modules à 1 MCHF, add 100 kCHF each for cryogenics and interundulator stuff: 20 × 1.2 MCHF = **24 MCHF**
  - **Cryogenic plant** for undulators: **2 MCHF**
  - New **gun laser lab** (incl. building extension): **6 MCHF**
  - **Kicker** upgrade and new kicker hardware: **2 MCHF**
  - **Diagnostics upgrades** for dealing with 21 ns bunch spacing: **2 MCHF**
  - **RF upgrade** (X-band & C-band stations, injector upgrades as a preproject?): **25 MCHF**
  - **Electron beamline components** (vacuum, diagnostics etc.): **4 MCHF**
  - **Machine total: 65 MCHF**
- **Front end and photon beam transport** (optics, monochromators, diagnostics etc.): **10 MCHF(?)**
- **End stations:** 10–15 MCHF per station – start with 1–2 stations? → **20 MCHF**
- **IT & controls** (general system upgrades and extensions): **5 MCHF**
- **Building extension:** 35–40 MCHF first estimate → **40 MCHF**

→ Porthos total: 140 MCHF (±30 MCHF)

New Porthos timeline



The case for high K

S. Reiche

To reach high photon energy at a given (maximum) electron energy, you have to aim for low K values. Nevertheless, it makes sense to aim for large K values:

1) At a given wavelength and undulator period, the FEL power increases significantly with higher K value.
   - But this means the electron energy has to increase accordingly!
   - If the electron energy is limited, can only profit at longer wavelengths.
2) If both K and E are higher, the relative energy spread σ_E/E is smaller, the beam can be compressed more (higher peak current), giving even more power.
3) High K values provide a large tuning range for two-color operation!