
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Thomas Schietinger, Marco Stampanoni :: Paul Scherrer Institut

on behalf of the Porthos Machine Working Group: S. Bettoni, M. Calvi, P. Craievich, E. Ferrari, Z. Geng, R. Ischebeck, F. Löhl, M. Paraliev, E. Prat, S. Reiche, A. Trisorio, I. Widmer, C. Zoller

Porthos: A second hard X-ray beamline for SwissFEL

PSAC, 1 December 2021

Contents

Porthos

> *“Porthos, honest and slightly gullible,*
> *is the extrovert of the group,*
> *enjoying wine, women and song.”*

Wikipedia, “Porthos”

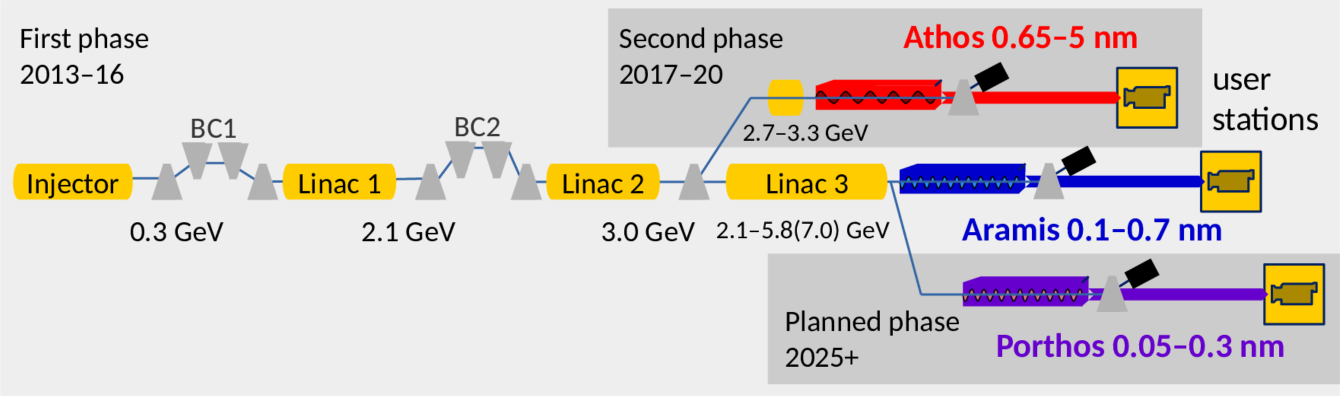
Porthos within SwissFEL

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 5.8 GeV
(7–8 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: (possible configuration)

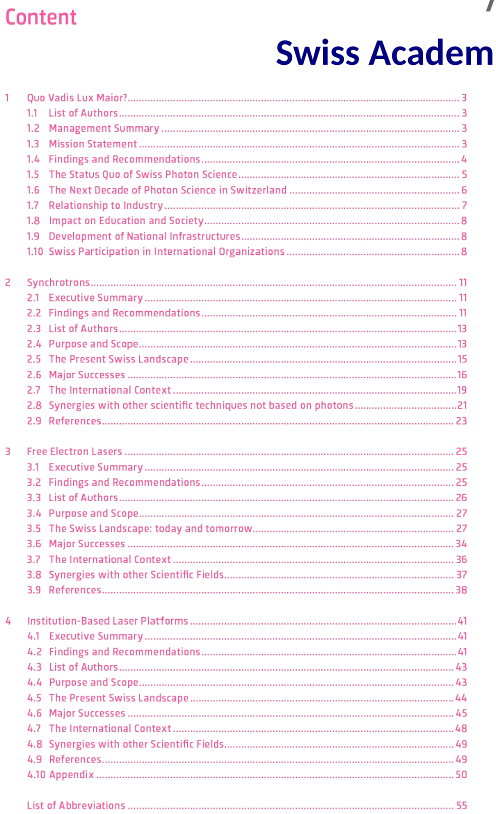
Hard X-ray FEL, λ=0.05–0.3 nm
Variable polarization, in-vacuum, cryogenic APPLE-X undulators

Start of construction: 2025+

S. Reiche

Science Case: SCNAT/SSPS Roadmap

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



Content

Chapters on:

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

Vol. 16, No. 5, 2021

scnat
swiss academy of sciences

swiss academies reports

swiss-academies.ch

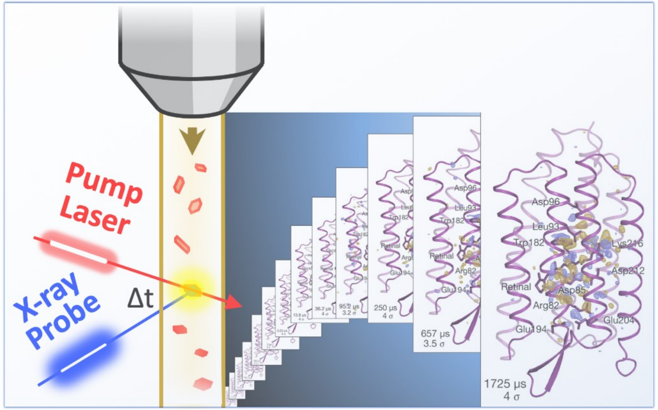
Photon Science Roadmap

for Research Infrastructures 2025–2028
by the Swiss Photon Community

Swiss Society for Photon Science

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

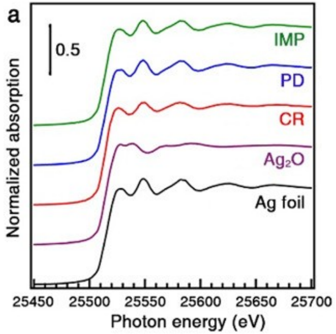
- Examples:
  - Identify position and orientation of small molecule ligands in a structure-based drug-design task.
  - Mapping of metal clusters acting as catalytic sites in enzymes.
  - Nanochemical synthesis of polyoxometalate clusters in dedicated storage proteins.

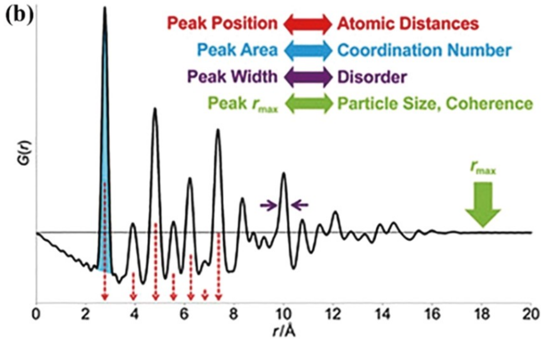
Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

Porthos Science Case: Ultrafast chemistry

- 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
- 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.

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



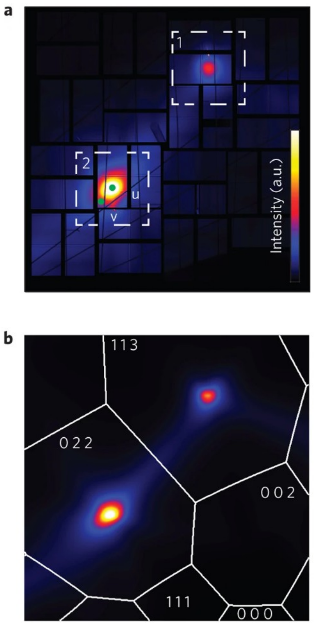


W. Xuelong et al., Chinese Physics B 29 (2020) 028802

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

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

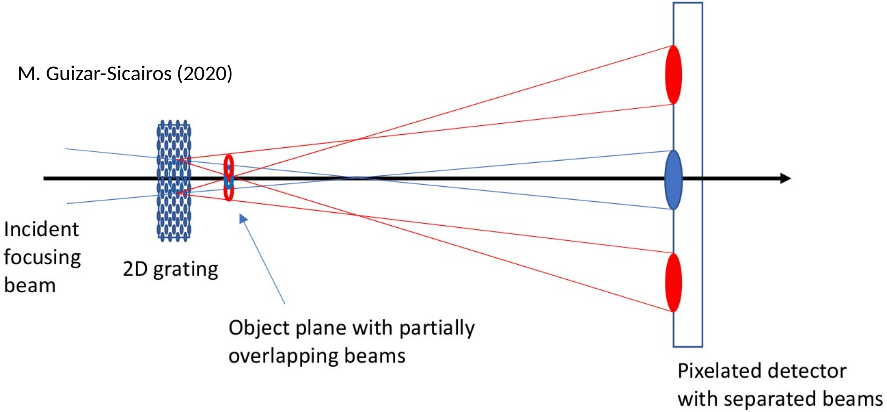


Trigo et al., Nat. Phys. 9,790–794 (2013)

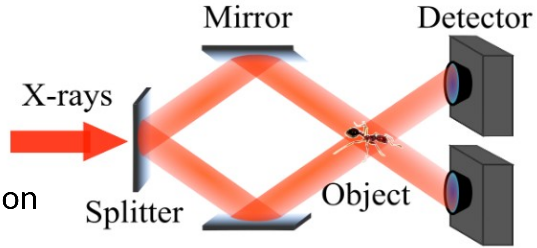
Source: Photon Roadmap for Research Infrastructures 2025–2028 by the Swiss Photon Community

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

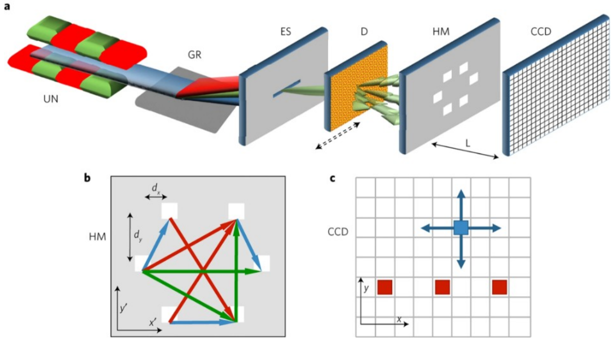


P. Villanueva-Perez, Optica 5, 1521-1524 (2018)

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

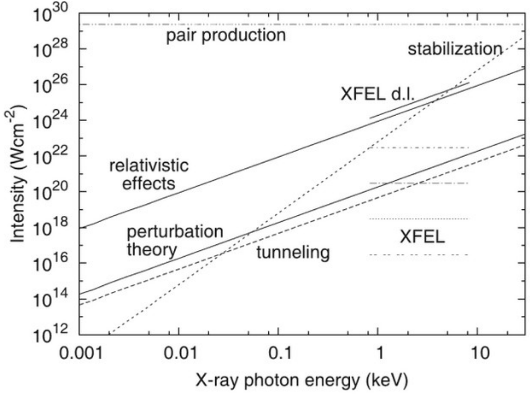
R. Schneider et al.,
Nat. Phys. 14 (2018) 126



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

swiss academies
reports

swiss-academies.ch

Photon Science Roadmap

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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

scnat

swiss academies
reports

Photon Science Roadmap

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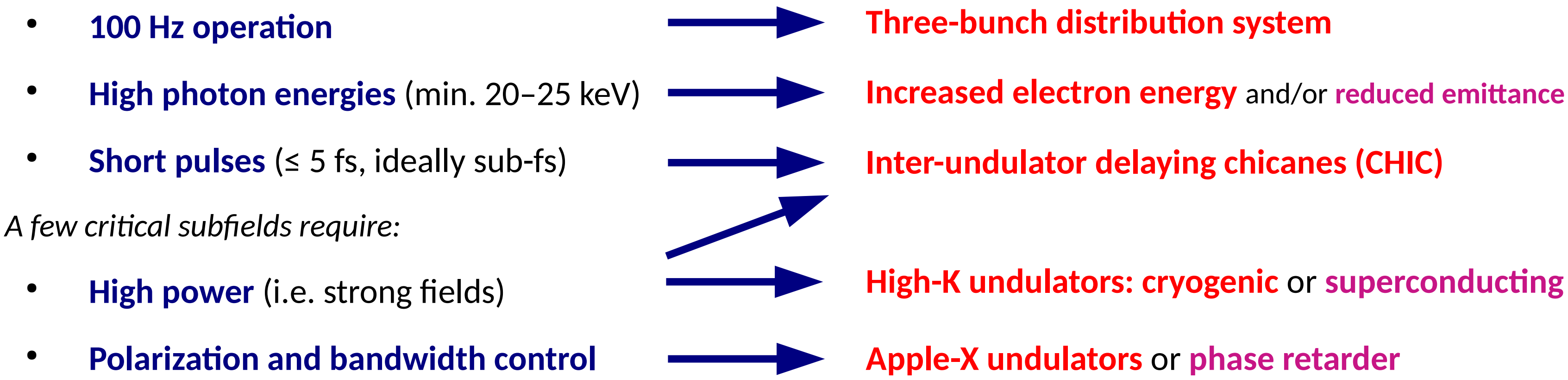
Porthos implementation



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- **Polarization and bandwidth control**

Three-bunch distribution system

Increased electron energy and/or **reduced emittance**

Inter-undulator delaying chicanes (CHIC)

High-K undulators: cryogenic or **superconducting**

Apple-X undulators or **phase retarder**

Additional desires:

- Two color modes
- Phase locked pulse trains
- …

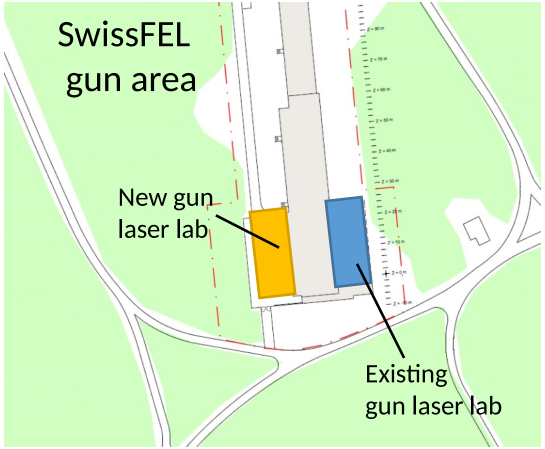
Red: *Porthos baseline*

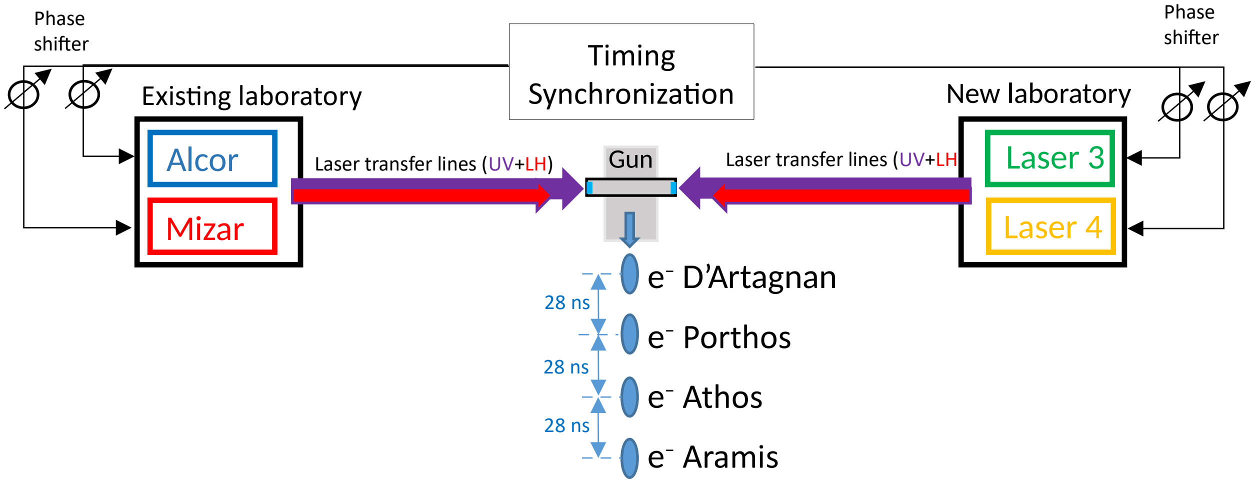
Violet: *Pursue as alternative options*

Bunch generation: gun laser

A. Trisorio

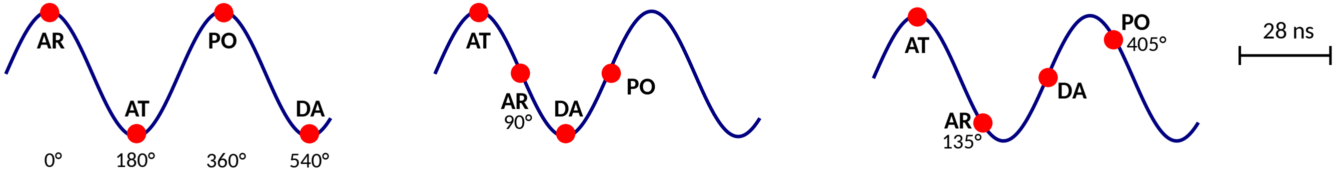
- 100 Hz operation and pulse flexibility mandate a separate gun laser for Porthos.
- No more room in existing gun laser lab → additional gun laser lab opposite the existing one (additional building cost!).
- Plan infrastructure already for a fourth gun laser (second soft-X-ray FEL D’Artagnan).





Kicker options without RK upgrade: difficult!

- Assume that the first kicker remains the same, delivering a sine curve with 56 ns period.
- There are different ways to place the bunches along this sine curve, leading to different bunch spacings:



28 ns **14 ns** **21 ns**

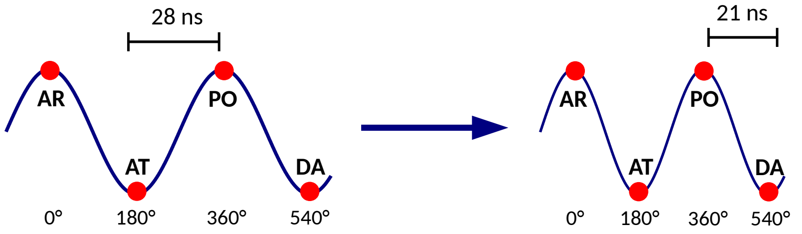
- Bunches placed on the zero crossing of the kicker voltage will suffer from voltage jitter.
- Swapping the bunches we can select which bunches profit from the highest stability (on-crest kicker voltage) – but this leads to weird septum designs and the need to remerge beams.
- In view of the difficulties these options are not further pursued…

Resonant kicker upgrade options

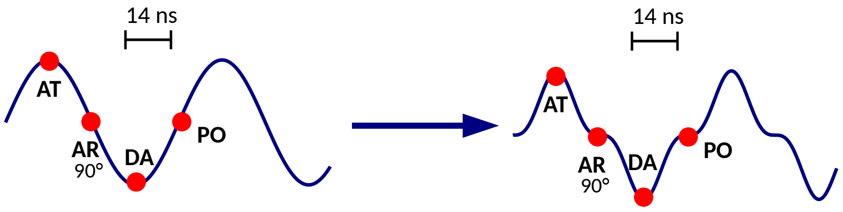
M. Paraliev

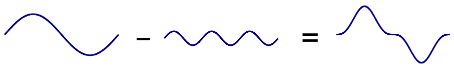
Two possibilities to upgrade the kicker to avoid or mitigate the problems associated with shorter bunch separations:

- **Faster oscillation**
  - The emergence of GaN transistors means that higher voltages are now possible than 10 years ago (our current system is based on Si MOSFET and pushed that technology to the limit).
  - A faster kicker with the same active length will be challenging but should be possible.

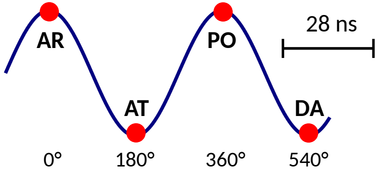
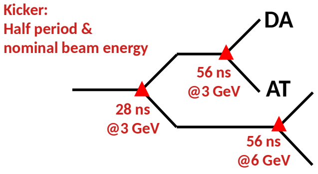
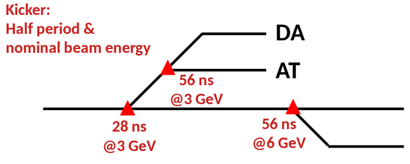
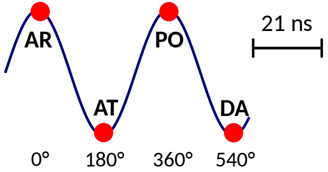
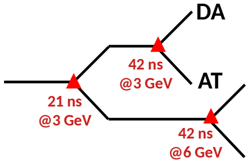
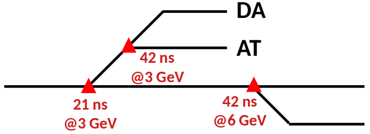
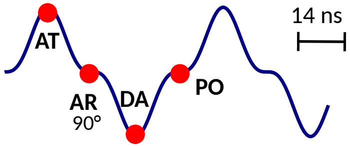
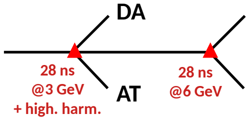
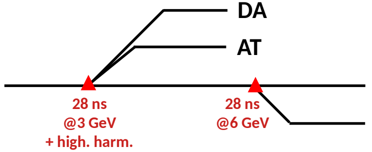


- **Addition of higher-harmonic oscillation**
  - Can we create a two-resonance system with coupled resonators?



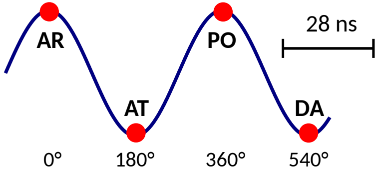
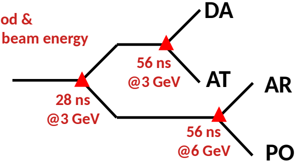
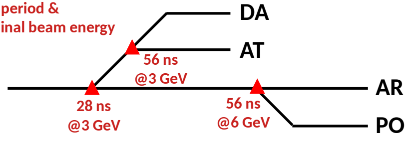
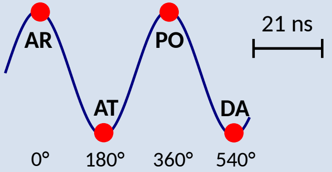
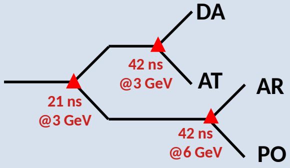
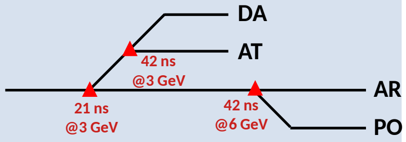
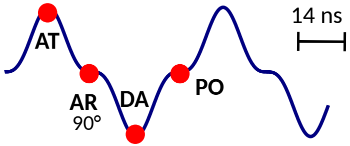
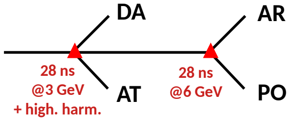
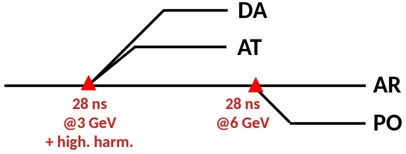


Resonant kicker upgrade options

Bunch spacing / allocation	Bunch placement at first kicker	Topology	Actual layout (schematic)
28 ns Status quo with four bunches, all on-crest			
21 ns, fast kicker Status quo with four bunches, but **faster** kicker			
14 ns, inflection Using inflection points at zero crossings to go straight.			

Resonant kicker upgrade options

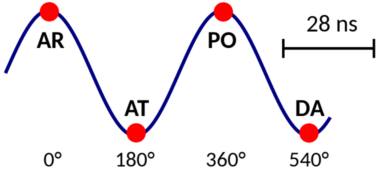
Porthos baseline

Bunch spacing / allocation	Bunch placement at first kicker	Topology	Actual layout (schematic)
28 ns Status quo with four bunches, all on-crest		Kicker: Half period & nominal beam energy 	Kicker: Half period & nominal beam energy 
21 ns, fast kicker Status quo with four bunches, but **faster** kicker			
14 ns, inflection Using inflection points at zero crossings to go straight.			

Resonant kicker upgrade options

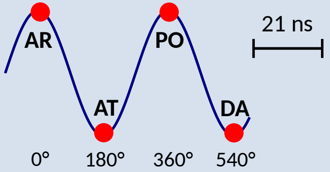
Porthos baseline

<table>
<tr><th>Bunch spacing / allocation</th><th>Bunch placement at first kicker</th><th>Evaluation (pulsed magnets, RF, other)</th></tr>
<tr><td>28 ns

Status quo with four bunches, all on-crest</td><td>
</td><td>

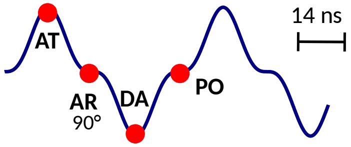
- Maximum stability for all bunches.
- 6 GeV kicker doable (twice stronger but twice lower frequency).
- New kicker and electronics need to be designed.
- Other diagnostics and (LLRF) control systems will not suffer.
- **Unacceptable loss of RF power at 84 ns separation.**
- Maximum RF tunability, minimum wakefield effects.

</td></tr>
<tr><td>21 ns, fast kicker

Status quo with four bunches, but faster kicker</td><td>
</td><td>

- 21 ns is a good compromise for all systems that need upgrading. (Gun laser…).
- Maximum stability for all bunches.
- Normal septa – we can keep the first as it is.
- Acceptable loss of RF power.
- Acceptable RF tunability, wakefield effects (?) …to be evaluated!

</td></tr>
<tr><td>14 ns, inflection

Using inflection points at zero crossings to go straight.</td><td>
</td><td>

- In principle good stability for all bunches.
- Three-way Lambertson may be difficult to realize!
- Separating at 6 GeV will require (most likely) 4 more kickers identical to the existing ones – no new development needed.
- Minimal loss of RF power.
- But: minimum RF tunability, maximum wakefield effects, other systems suffer.

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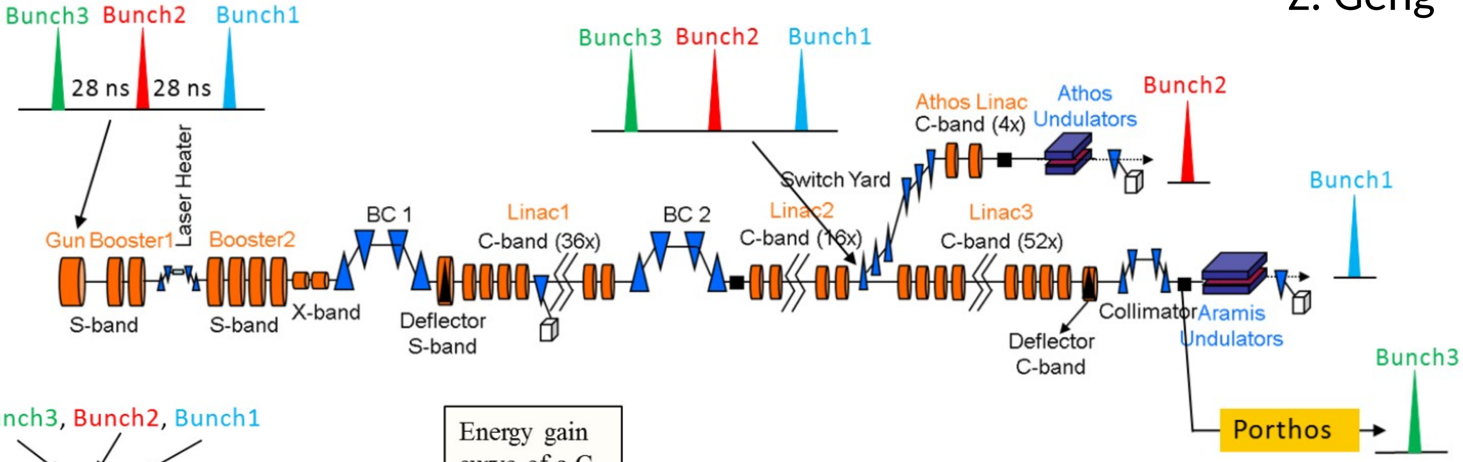
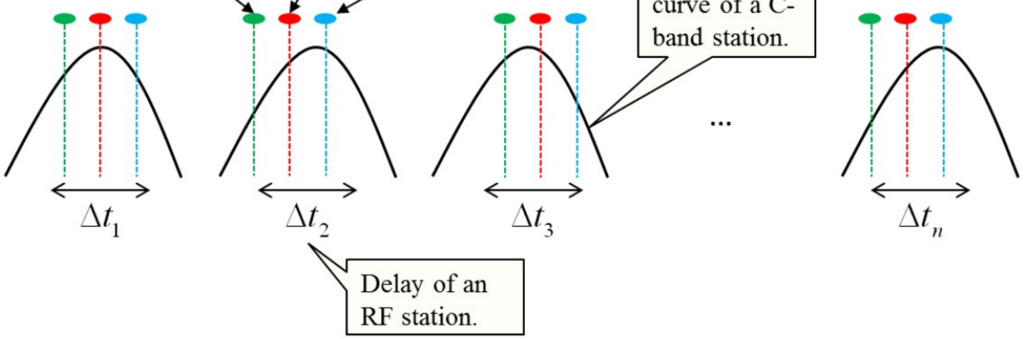
</table>

Low-level RF scheme for three bunches

Z. Geng





Expected energy loss (C-band overall), as a function of bunch spacing:

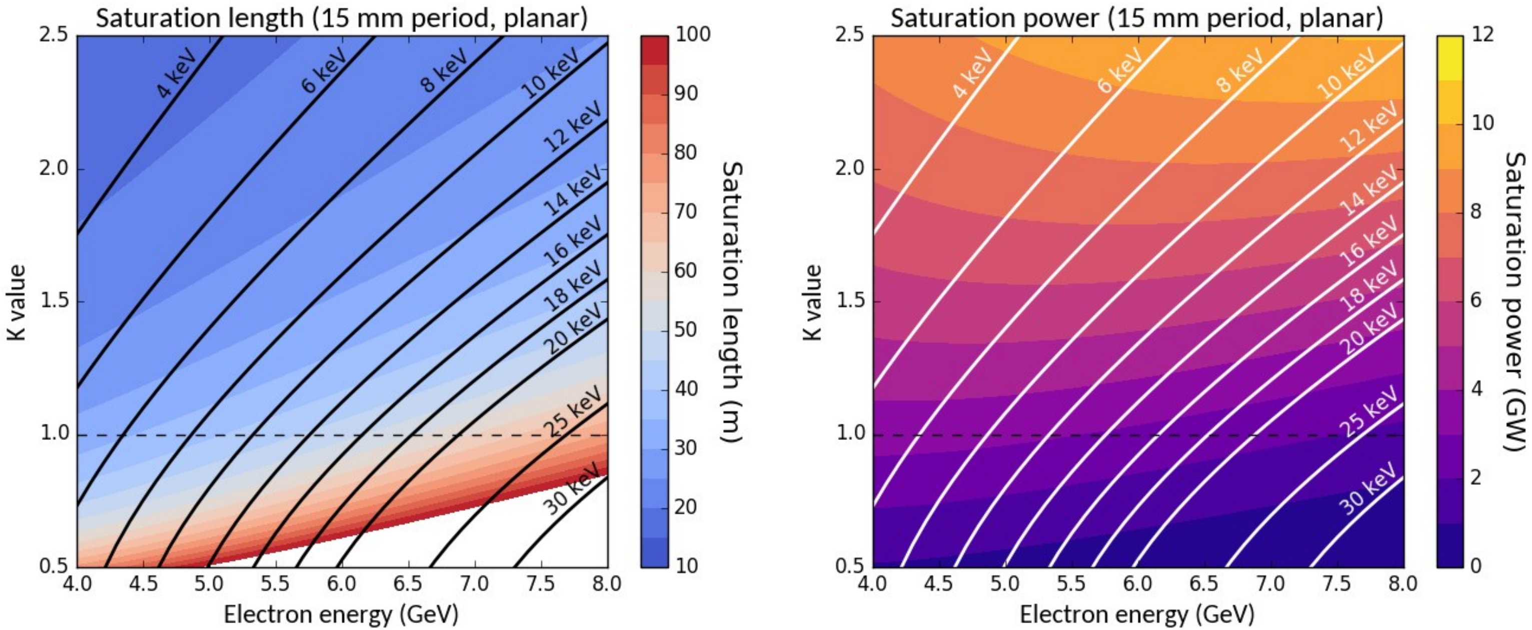
28 ns	21 ns	14 ns
−200 MeV	−129 MeV	−73 MeV

Porthos baseline

The case for high electron energy

- FEL saturation length and power for 15 mm undulator period (example).
- High photon energy requires high electron energy (at the fundamental)!

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



RF upgrades: summary

P. Craievich
M. Pedrozzi

Three upgrades, *that can be implemented independently:*

1) **Injector upgrade (upgraded S-band only or upgraded S-band and C-band)**
   - Option A: +360 MeV* for 2.6 MCHF (preferred by RF)
   - Option B: +480 MeV* for 4.1 MCHF (preferred by beam dynamics)
   - Effects on Athos operation to be evaluated…
   - Realization before and independent of Porthos?

2) **Linac-3 upgrade (X-band)**
   - +720 MeV* for 10 MCHF
   - Benefits Porthos and Aramis!
   - Fits into existing building.
   - Realization before Porthos possible.

3) **Porthos linac (C-band)**
   - +960 MeV for 8.2 MCHF (+2.2 MCHF for building extension)
   - Independent energy tuning for Porthos only.
   - Requires building extension (extension of klystron gallery).

*Energy gains for a single bunch – losses due to multibunch acceleration to be subtracted!

Undulator configurations

Interundulator delaying chicanes (CHIC scheme) are a given for all concepts!

Simultaneous desire for high photon energy *and* polarization control can be satisfied by different concepts (none of which is entirely convincing):

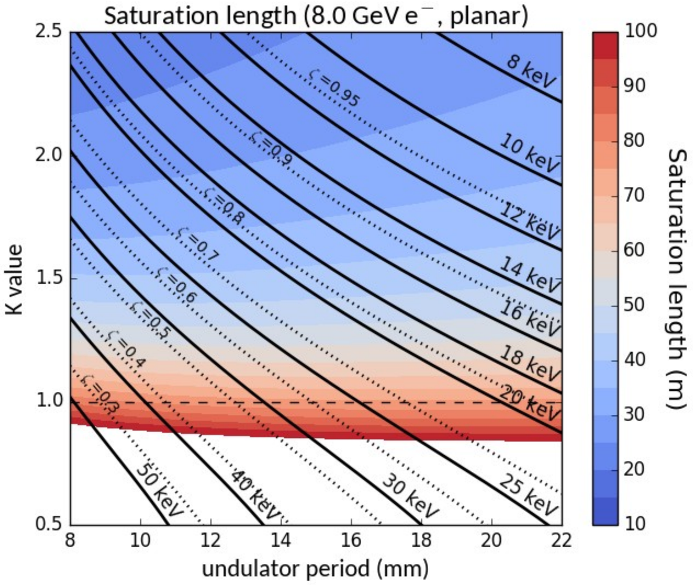
Concept	Pro	Con	
Planar undulator followed by a helical afterburner 	• Simple and cost effective.	• Difficult to tune two undulator segments • Only partial polarization (60–70%) can be achieved, polarization must be measured. • Limited flexibility (special modes).	✗
Apple-X followed by a planar high-energy afterburner 	• Limited, efficient use of Apple-X (cost, mechanics,..). • Afterburner can be optimized for highest photon energies.	• Difficult to tune two undulator segments • Only little gain from subharmonic preamplifier → you end up building two undulator lines capable of full saturation (expensive and inefficient) • No gain from going to smaller period (coherence loss)	✗
Apple-X undulator 	• Polarization control up to highest energies – maximum flexibility (but also a bit of an overkill…) • Single undulator series	• Expensive solution (many Apple-X modules) • Cannot easily reach highest photon energies (with 15 mm period) • Challenging mechanics/controls.	✓
Planar or helical und., polarization with phase retarder 	• Best quality beam for high-energy photon beams while still allowing for some polarization studies. • Polarization is generated close to experiments. • Single undulator series, mechanically straightforward.	• Insufficient flexibility for complex experiments.	✓

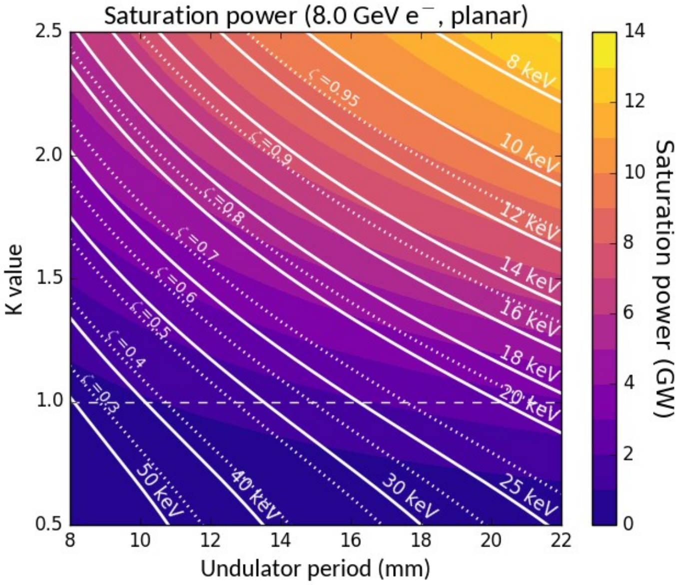
Ming Xie estimates (planar, fixed energy)

- Ming-Xie parameterization for saturation length/power (Proc. PAC’95, p.183–185)
- Photon energy given by FEL resonance condition
- Coherence parameter (Saldin, Schneidmiller, Yurkov, Opt. Commun. 281 (2009) 1179)

$\frac{\epsilon_n}{\gamma} \leq \frac{\lambda}{2\pi} \Rightarrow \hat{\epsilon} \equiv \frac{2\pi\epsilon_n}{\gamma\lambda} \leq 1$ $\quad \zeta \approx \frac{1.1\hat{\epsilon}^{1/4}}{1+0.15\hat{\epsilon}^{9/4}}$ We want ζ ≥ 0.7.

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m





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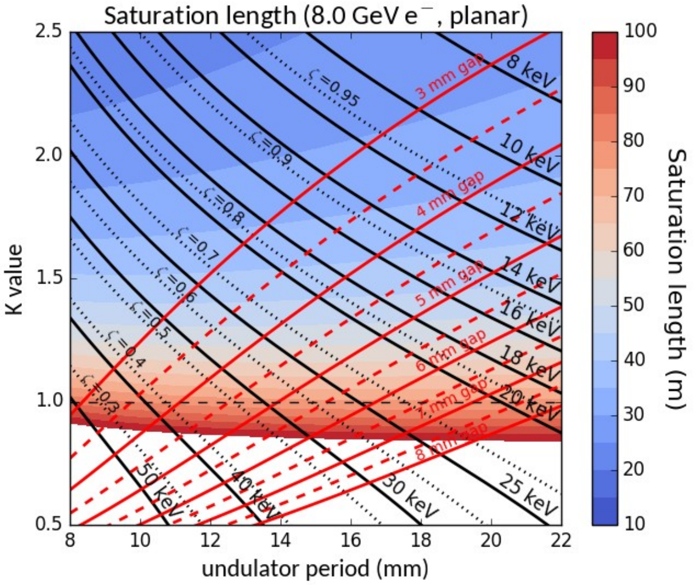
We want $\zeta \geq 0.7$.

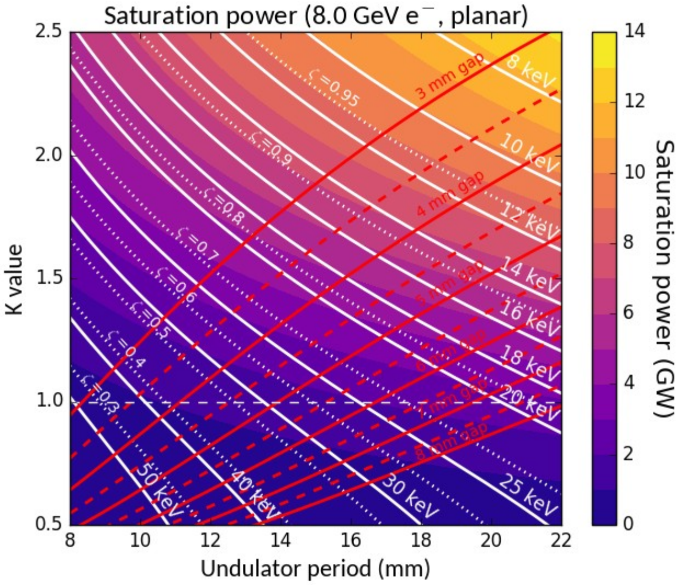
Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

- Undulator K vs. gap: **permanent magnet** (example Aramis U15, M. Calvi et al., J. Synchrotron Rad.(2018) 25, 686-705)

$$K(g) = K_0 \exp\left(-a\frac{g}{\lambda_u} + b\frac{g^2}{\lambda_u^2}\right)$$

To be evaluated the smallest gap we can aim for (losses, wakefields,…)


Saturation length (8.0 GeV e$^-$, planar)


Saturation power (8.0 GeV e$^-$, planar)

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We want ζ ≥ 0.7.

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

- Undulator K vs. gap: **cryogenic permanent magnet** (example SLS cryo U14, M. Calvi et al., J. Phys.: Conf. Series 425 (2013) 032017)

$$K(g) = K_0 \exp\left(-a\frac{g}{\lambda_u} + b\frac{g^2}{\lambda_u^2}\right)$$

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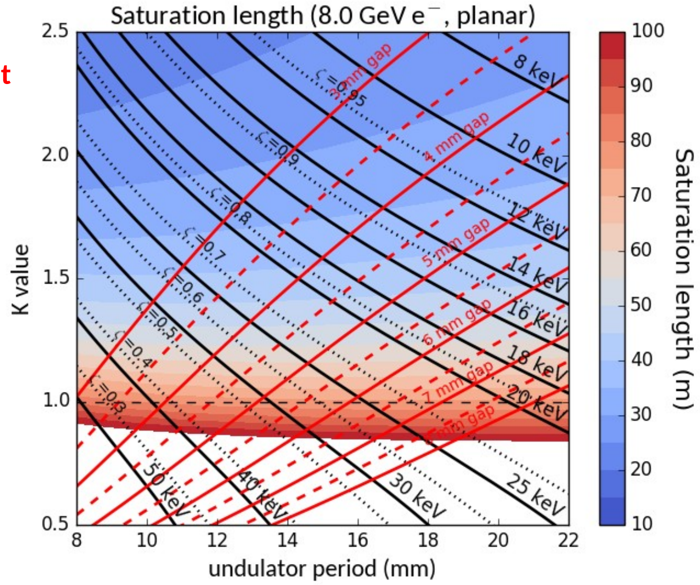

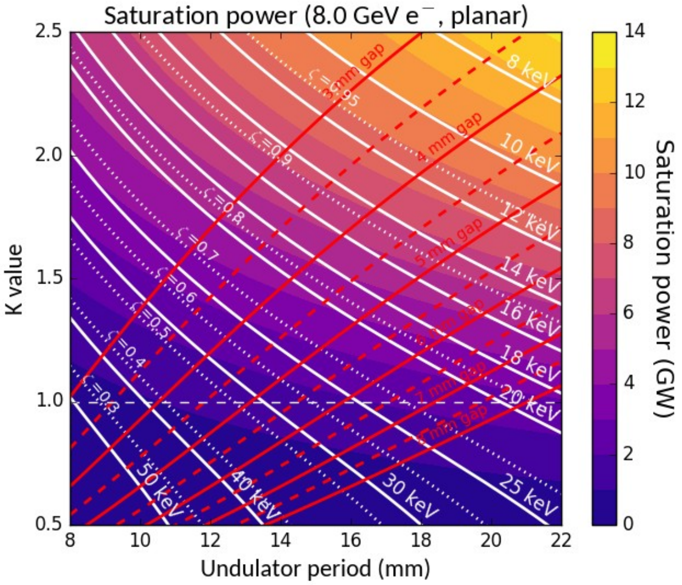

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We want ζ ≥ 0.7.

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

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

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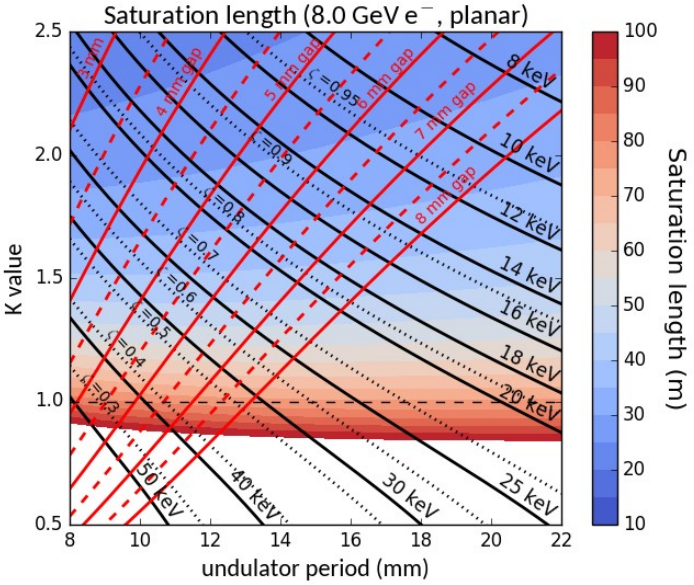
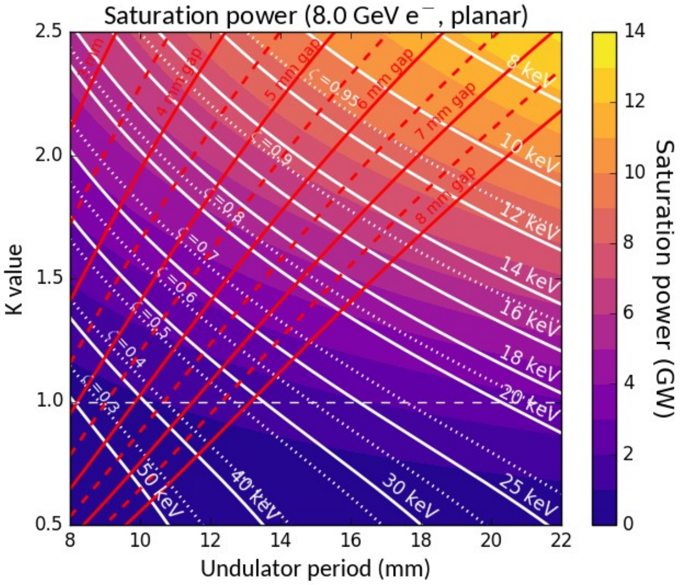
To be evaluated the smallest gap we can aim for (losses, wakefields,…)

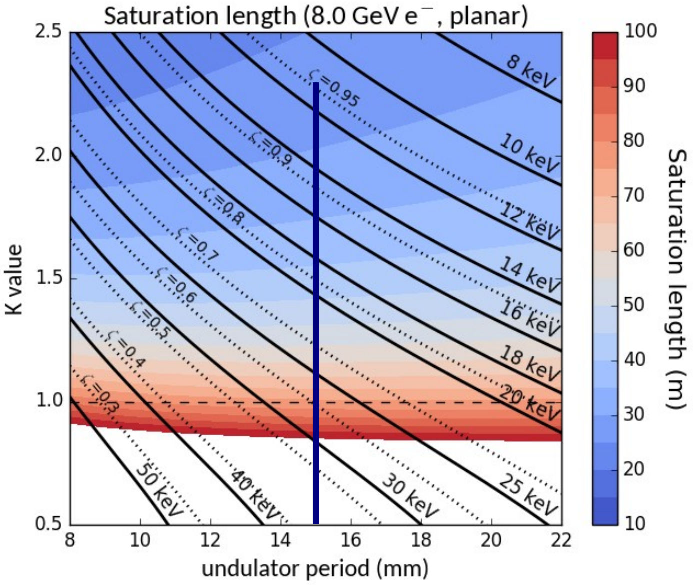


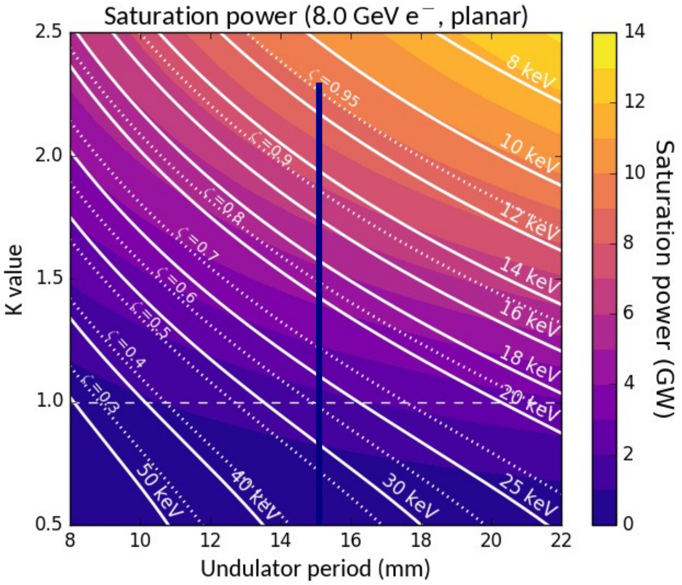


Apple-X with 15 mm period – a good compromise?

- Can cover up 25 keV (with polarization control!) at 8 GeV beam energy under the assumption of 300 nm emittance.
- Lower energies easily accessible with lower photon energies (very low energies may require coordination with Aramis).
- *But is it feasible?*

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



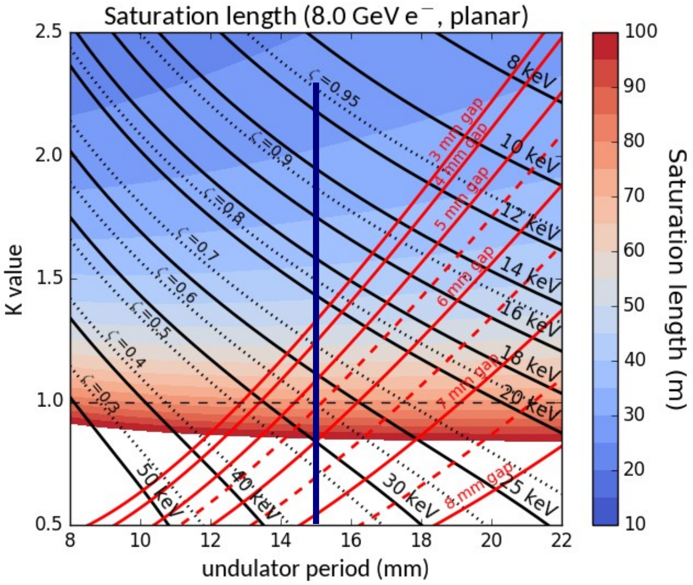


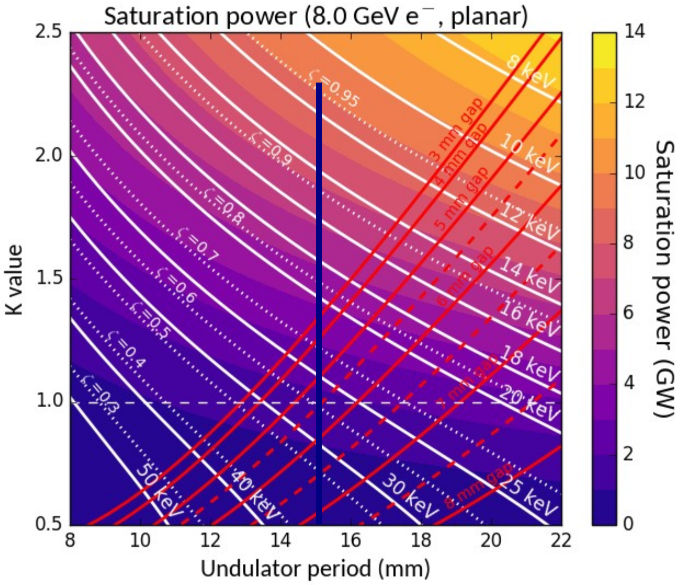
Room-temp. Apple-X with 15 mm period

- Yes! Initial studies indicate that an Apple-X with such small period may be feasible.
- Can cover 20–25 keV (with polarization control!) at 8 GeV beam energy under the assumption of 300 nm emittance and gaps down to 3–4 mm.
- Lower photon energies easily accessible with lower electron energies (very low energies may require coordination with Aramis).

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

- Undulator vs. gap: **room-temperature in-vacuum APPLE-X** (simulation data, M. Calvi, private communication).





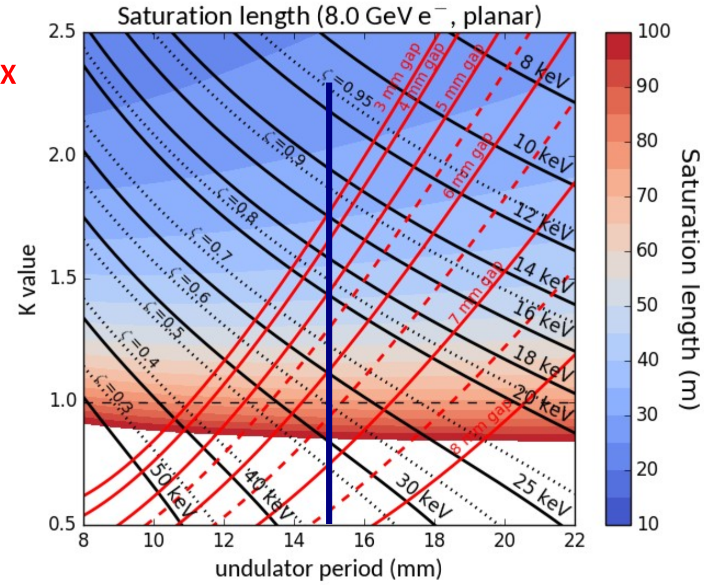
Cryogenic Apple-X with 15 mm period

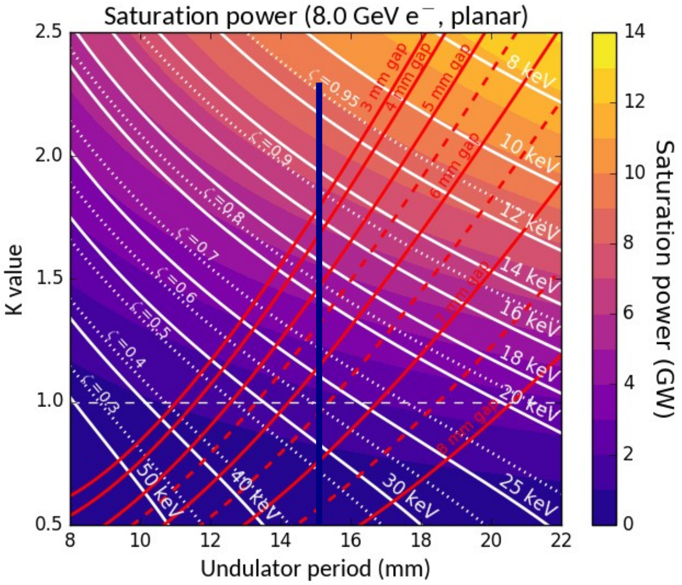
– more flexibility with higher K!

- Much more flexibility (but more technical complexity) with a cryogenic Apple-X
- Can cover 14–25 keV (with polarization control!) at 8 GeV beam energy under the assumption of 300 nm emittance and more relaxed gaps around 5–6 mm. Significantly higher pulse energies at lower photon energies.
- Lower photon energies easily accessible with lower electron energies (very low energies may require coordination with Aramis).

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

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

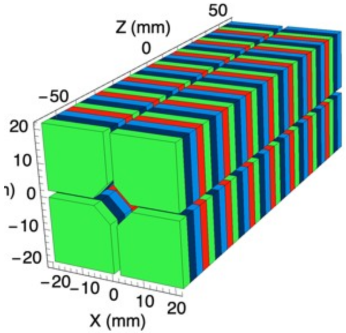


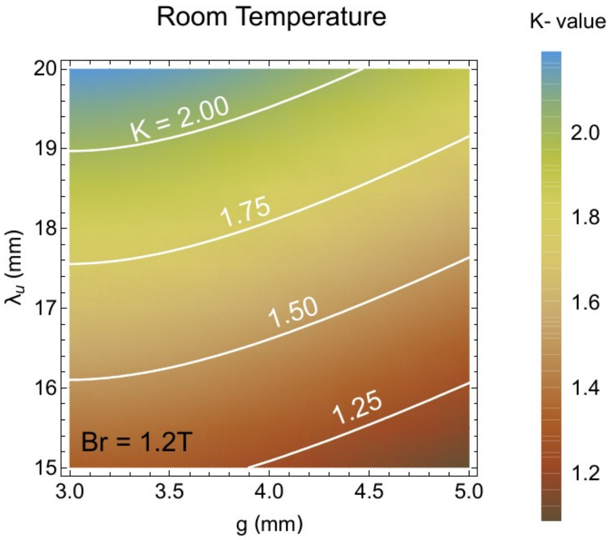


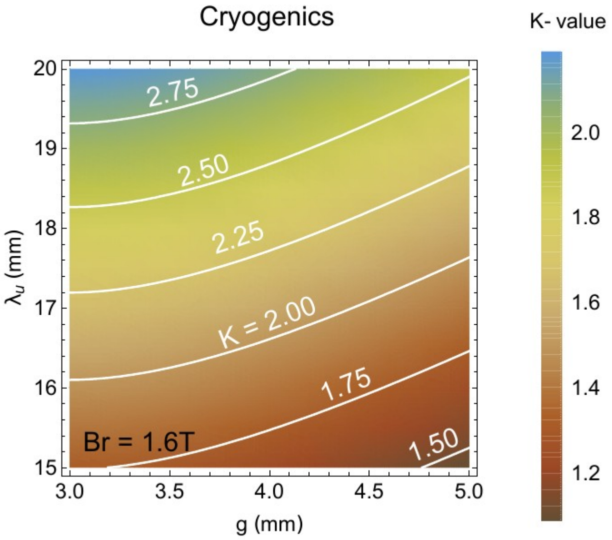
Apple-X 15–20 mm period, calculations

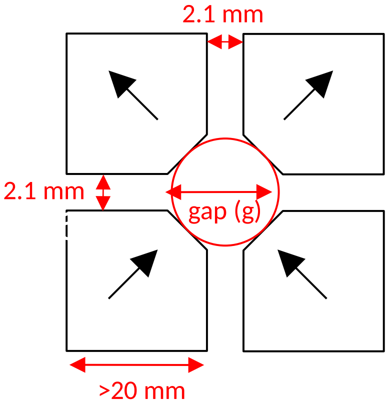
Marco Calvi

- Magnetic calculations by M. Calvi show that for an Apple-X the K values cannot be made quite as high as was achieved for Aramis U15 (room temperature permanent magnet) or SLS U14 (cryogenic permanent magnet), but still competitive…
- Assumed materials are NbFeB and PrFeB.
- Maximum K (at 3 mm gap) would be about 1.35 at room temperature, 1.75 at cryogenic temperature.
- To be looked at in more detail!
- Possible collaboration with Soleil, HZB, who pursue the same technology!

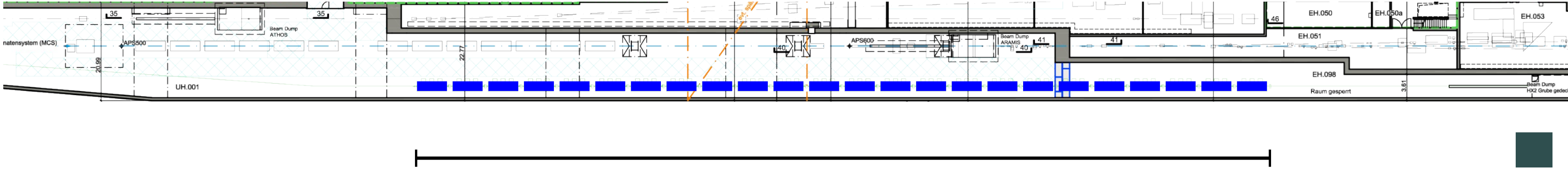








Porthos undulator line: original provision

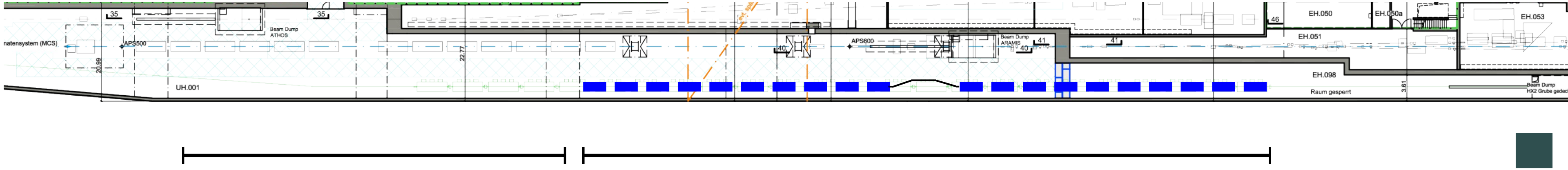


Original provision: 24 × 4.75 m = 114 m undulator line

Beam dump
(certified to
7 GeV)

PSI drawing
No. 2R-393601 (2019)

Porthos undulator line: possible configuration



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)

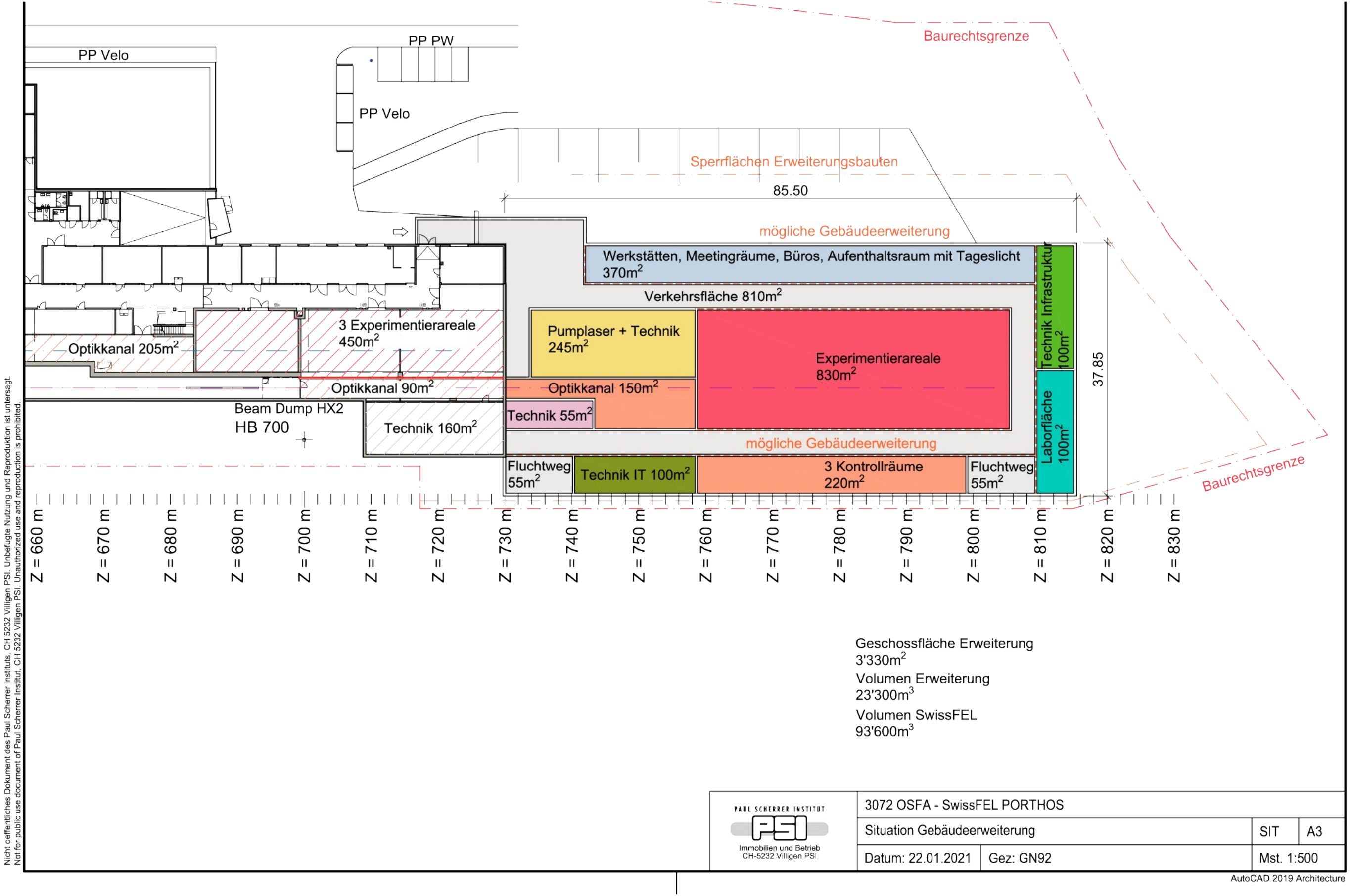
Beam dump
(certified to
7 GeV)

PSI drawing
No. 2R-393601 (2019)

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!

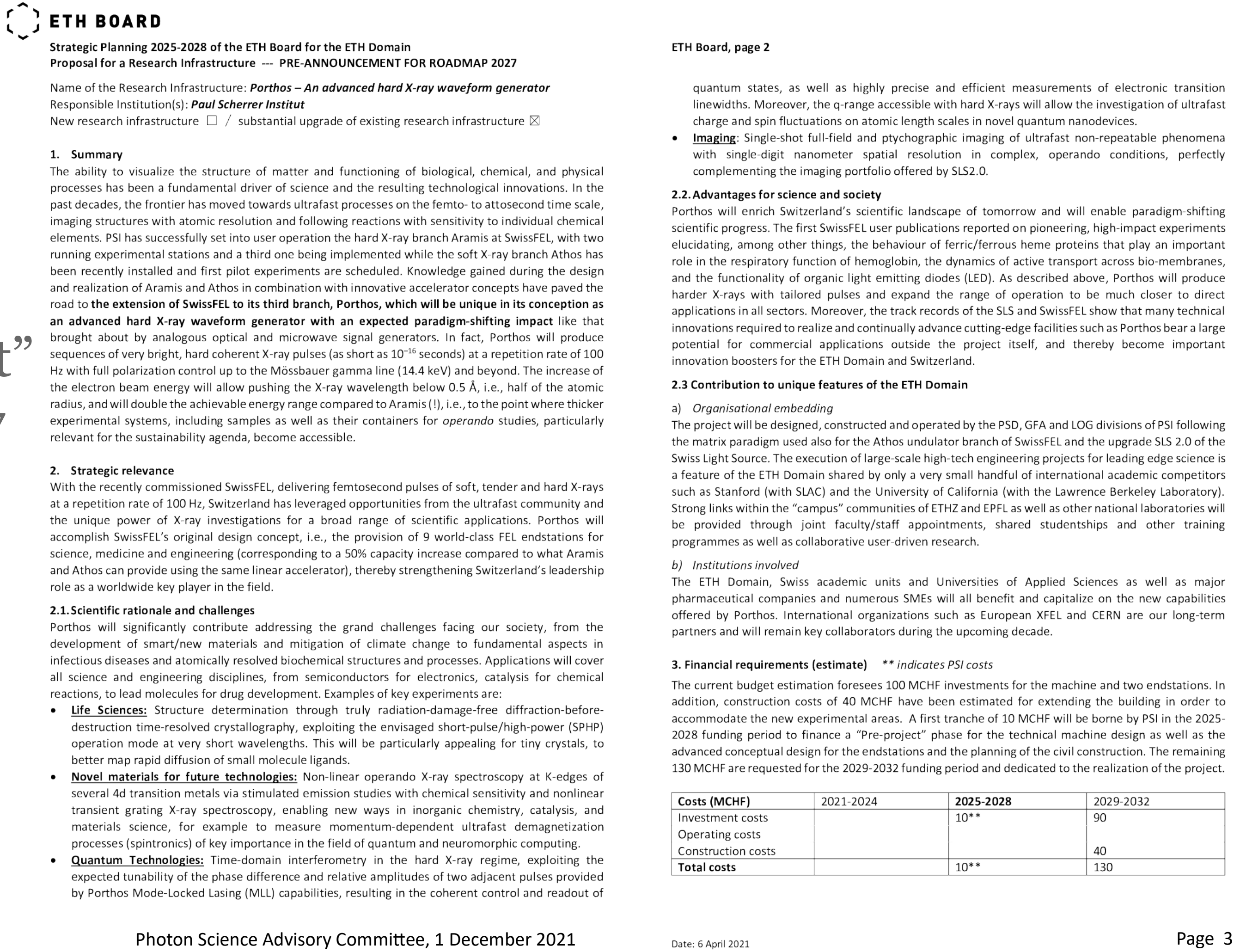


First, rough budget estimate (all items ±20%)

- 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

“Pre-announcement” for Roadmap 2027 submitted to ETH Board



ETH BOARD

Strategic Planning 2025-2028 of the ETH Board for the ETH Domain
Proposal for a Research Infrastructure --- PRE-ANNOUNCEMENT FOR ROADMAP 2027

Name of the Research Infrastructure: ***Porthos – An advanced hard X-ray waveform generator***
Responsible Institution(s): ***Paul Scherrer Institut***
New research infrastructure ☐ / substantial upgrade of existing research infrastructure ☒

1. Summary

The ability to visualize the structure of matter and functioning of biological, chemical, and physical processes has been a fundamental driver of science and the resulting technological innovations. In the past decades, the frontier has moved towards ultrafast processes on the femto- to attosecond time scale, imaging structures with atomic resolution and following reactions with sensitivity to individual chemical elements. PSI has successfully set into user operation the hard X-ray branch Aramis at SwissFEL, with two running experimental stations and a third one being implemented while the soft X-ray branch Athos has been recently installed and first pilot experiments are scheduled. Knowledge gained during the design and realization of Aramis and Athos in combination with innovative accelerator concepts have paved the road to **the extension of SwissFEL to its third branch, Porthos, which will be unique in its conception as an advanced hard X-ray waveform generator with an expected paradigm-shifting impact** like that brought about by analogous optical and microwave signal generators. In fact, Porthos will produce sequences of very bright, hard coherent X-ray pulses (as short as 10^{-16} seconds) at a repetition rate of 100 Hz with full polarization control up to the Mössbauer gamma line (14.4 keV) and beyond. The increase of the electron beam energy will allow pushing the X-ray wavelength below 0.5 Å, i.e., half of the atomic radius, and will double the achievable energy range compared to Aramis (!), i.e., to the point where thicker experimental systems, including samples as well as their containers for *operando* studies, particularly relevant for the sustainability agenda, become accessible.

2. Strategic relevance

With the recently commissioned SwissFEL, delivering femtosecond pulses of soft, tender and hard X-rays at a repetition rate of 100 Hz, Switzerland has leveraged opportunities from the ultrafast community and the unique power of X-ray investigations for a broad range of scientific applications. Porthos will accomplish SwissFEL's original design concept, i.e., the provision of 9 world-class FEL endstations for science, medicine and engineering (corresponding to a 50% capacity increase compared to what Aramis and Athos can provide using the same linear accelerator), thereby strengthening Switzerland's leadership role as a worldwide key player in the field.

2.1. Scientific rationale and challenges

Porthos will significantly contribute addressing the grand challenges facing our society, from the development of smart/new materials and mitigation of climate change to fundamental aspects in infectious diseases and atomically resolved biochemical structures and processes. Applications will cover all science and engineering disciplines, from semiconductors for electronics, catalysis for chemical reactions, to lead molecules for drug development. Examples of key experiments are:

- **Life Sciences:** Structure determination through truly radiation-damage-free diffraction-before-destruction time-resolved crystallography, exploiting the envisaged short-pulse/high-power (SPHP) operation mode at very short wavelengths. This will be particularly appealing for tiny crystals, to better map rapid diffusion of small molecule ligands.
- **Novel materials for future technologies:** Non-linear operando X-ray spectroscopy at K-edges of several 4d transition metals via stimulated emission studies with chemical sensitivity and nonlinear transient grating X-ray spectroscopy, enabling new ways in inorganic chemistry, catalysis, and materials science, for example to measure momentum-dependent ultrafast demagnetization processes (spintronics) of key importance in the field of quantum and neuromorphic computing.
- **Quantum Technologies:** Time-domain interferometry in the hard X-ray regime, exploiting the expected tunability of the phase difference and relative amplitudes of two adjacent pulses provided by Porthos Mode-Locked Lasing (MLL) capabilities, resulting in the coherent control and readout of quantum states, as well as highly precise and efficient measurements of electronic transition linewidths. Moreover, the q-range accessible with hard X-rays will allow the investigation of ultrafast charge and spin fluctuations on atomic length scales in novel quantum nanodevices.
- **Imaging**: Single-shot full-field and ptychographic imaging of ultrafast non-repeatable phenomena with single-digit nanometer spatial resolution in complex, operando conditions, perfectly complementing the imaging portfolio offered by SLS2.0.

ETH Board, page 2

2.2. Advantages for science and society

Porthos will enrich Switzerland's scientific landscape of tomorrow and will enable paradigm-shifting scientific progress. The first SwissFEL user publications reported on pioneering, high-impact experiments elucidating, among other things, the behaviour of ferric/ferrous heme proteins that play an important role in the respiratory function of hemoglobin, the dynamics of active transport across bio-membranes, and the functionality of organic light emitting diodes (LED). As described above, Porthos will produce harder X-rays with tailored pulses and expand the range of operation to be much closer to direct applications in all sectors. Moreover, the track records of the SLS and SwissFEL show that many technical innovations required to realize and continually advance cutting-edge facilities such as Porthos bear a large potential for commercial applications outside the project itself, and thereby become important innovation boosters for the ETH Domain and Switzerland.

2.3 Contribution to unique features of the ETH Domain

a) *Organisational embedding*

The project will be designed, constructed and operated by the PSD, GFA and LOG divisions of PSI following the matrix paradigm used also for the Athos undulator branch of SwissFEL and the upgrade SLS 2.0 of the Swiss Light Source. The execution of large-scale high-tech engineering projects for leading edge science is a feature of the ETH Domain shared by only a very small handful of international academic competitors such as Stanford (with SLAC) and the University of California (with the Lawrence Berkeley Laboratory). Strong links within the “campus” communities of ETHZ and EPFL as well as other national laboratories will be provided through joint faculty/staff appointments, shared studentships and other training programmes as well as collaborative user-driven research.

b) *Institutions involved*

The ETH Domain, Swiss academic units and Universities of Applied Sciences as well as major pharmaceutical companies and numerous SMEs will all benefit and capitalize on the new capabilities offered by Porthos. International organizations such as European XFEL and CERN are our long-term partners and will remain key collaborators during the upcoming decade.

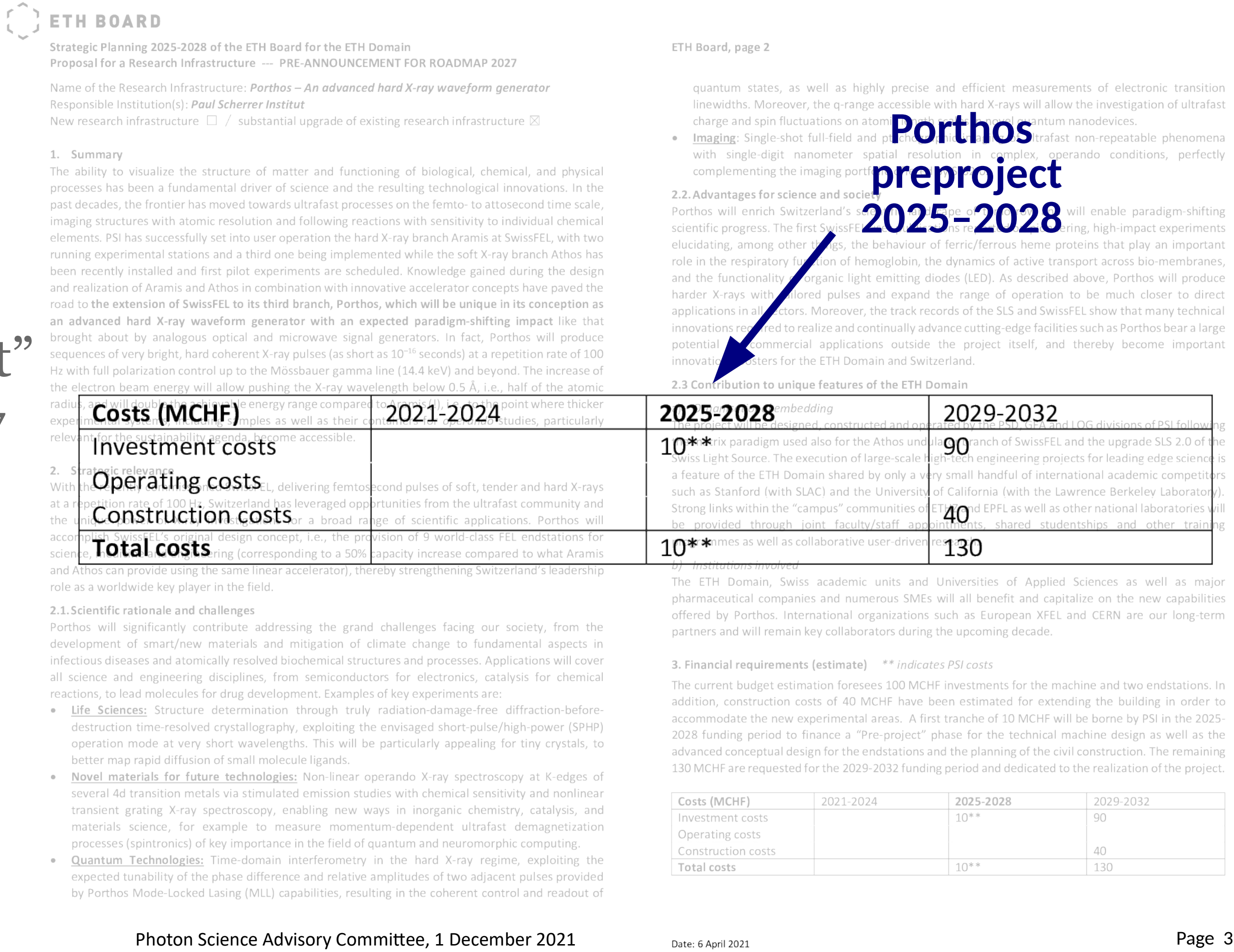
3. Financial requirements (estimate) *** indicates PSI costs*

The current budget estimation foresees 100 MCHF investments for the machine and two endstations. In addition, construction costs of 40 MCHF have been estimated for extending the building in order to accommodate the new experimental areas. A first tranche of 10 MCHF will be borne by PSI in the 2025-2028 funding period to finance a “Pre-project” phase for the technical machine design as well as the advanced conceptual design for the endstations and the planning of the civil construction. The remaining 130 MCHF are requested for the 2029-2032 funding period and dedicated to the realization of the project.

Costs (MCHF)	2021-2024	**2025-2028**	2029-2032
Investment costs		10**	90
Operating costs			
Construction costs			40
Total costs		10**	130

Date: 6 April 2021

"Pre-announcement" for Roadmap 2027 submitted to ETH Board



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ETH Board, page 2

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2.3 Contribution to unique features of the ETH Domain

a) Organisational embedding

The project will be designed, constructed and operated by the PSD, GFA and LOG divisions of PSI following the matrix paradigm used also for the Athos undulator branch of SwissFEL and the upgrade SLS 2.0 of the Swiss Light Source. The execution of large-scale high-tech engineering projects for leading edge science is a feature of the ETH Domain shared by only a very small handful of international academic competitors such as Stanford (with SLAC) and the University of California (with the Lawrence Berkeley Laboratory). Strong links within the "campus" communities of ETHZ and EPFL as well as other national laboratories will be provided through joint faculty/staff appointments, shared studentships and other training programmes as well as collaborative user-driven research.

b) Institutions involved

The ETH Domain, Swiss academic units and Universities of Applied Sciences as well as major pharmaceutical companies and numerous SMEs will all benefit and capitalize on the new capabilities offered by Porthos. International organizations such as European XFEL and CERN are our long-term partners and will remain key collaborators during the upcoming decade.

3. Financial requirements (estimate) *** indicates PSI costs*

The current budget estimation foresees 100 MCHF investments for the machine and two endstations. In addition, construction costs of 40 MCHF have been estimated for extending the building in order to accommodate the new experimental areas. A first tranche of 10 MCHF will be borne by PSI in the 2025-2028 funding period to finance a "Pre-project" phase for the technical machine design as well as the advanced conceptual design for the endstations and the planning of the civil construction. The remaining 130 MCHF are requested for the 2029-2032 funding period and dedicated to the realization of the project.

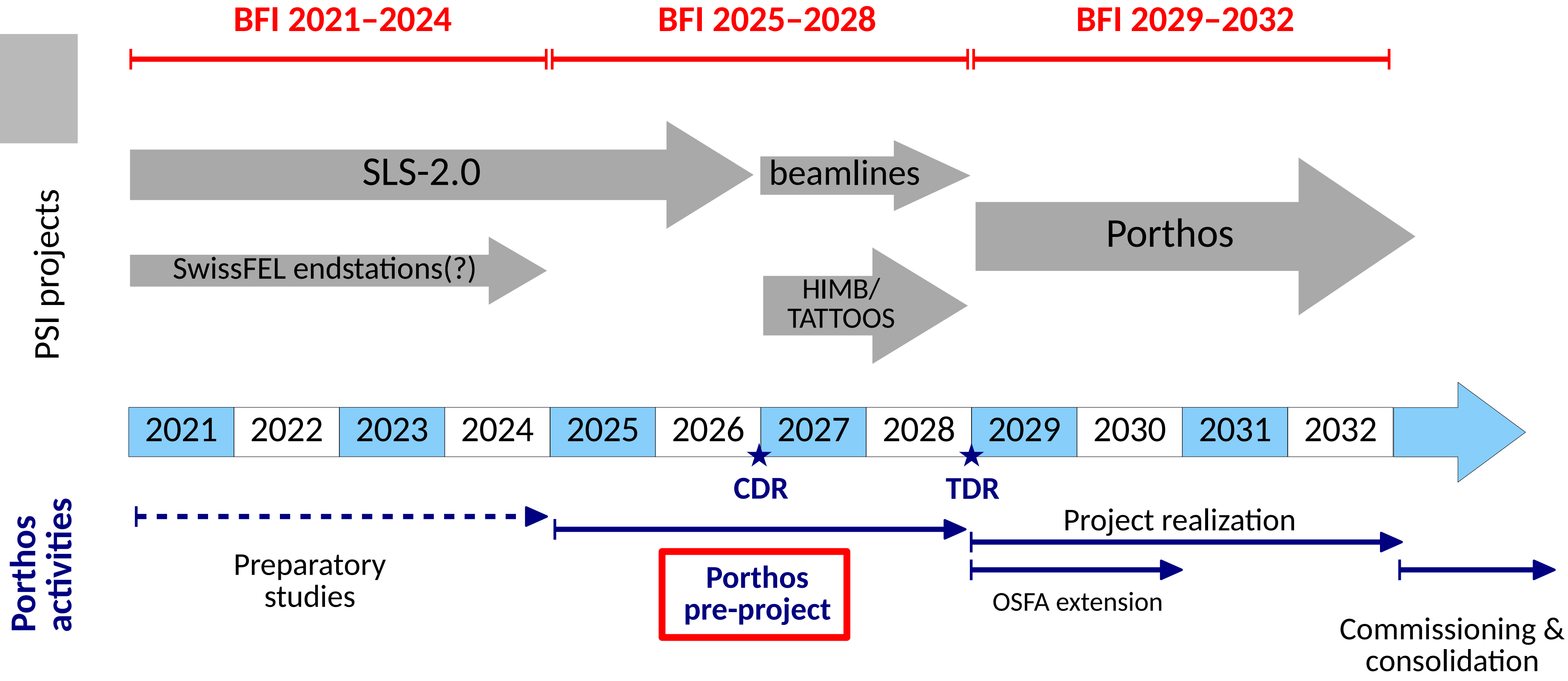
Costs (MCHF)	2021-2024	**2025-2028**	2029-2032
Investment costs		10**	90
Operating costs			
Construction costs			40
Total costs		10**	130

Date: 6 April 2021

Costs (MCHF)	2021-2024	**2025-2028**	2029-2032
Investment costs		10**	90
Operating costs			
Construction costs			40
Total costs		10**	130

Porthos preproject 2025–2028

New Porthos timeline



BFI 2021–2024

BFI 2025–2028

BFI 2029–2032

PSI projects

SLS-2.0

beamlines

SwissFEL endstations(?)

HIMB/
TATTOOS

Porthos

2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032

CDR

TDR

Porthos activities

Preparatory
studies

**Porthos
pre-project**

Project realization

OSFA extension

Commissioning &
consolidation

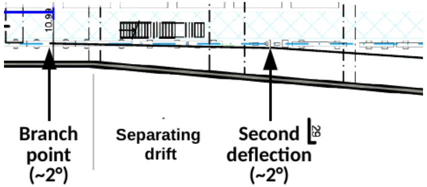
Porthos pre-project 2025–2028

Possible directions to explore during a pre-project:

Porthos pre-project

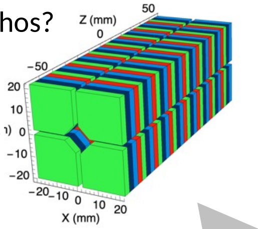
Early realization of extraction and transfer line

- Can we profit from an extraction line for equipment testing?
- Synergy with P^3 project (CERN-FCC)



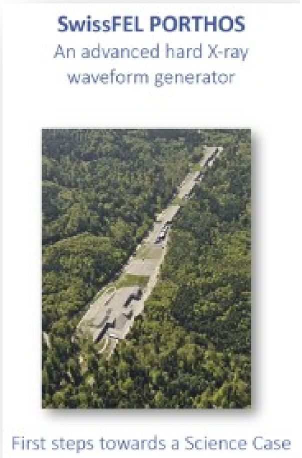
Cryo-APPLE-X undulator

- Is Cryo-APPLE-X the right choics for Porthos?
- Can we build and test a prototype?
- Can we improve on the state of the art?



Photonics / Photon Science

- Photon beam transport (optics, mirrors etc.)
- Possible seeding options
- Re-assessment of beamline portfolio
- CDR for one or two beamlines



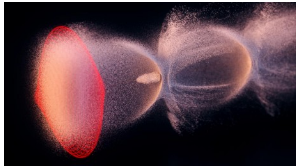
SwissFEL PORTHOS

An advanced hard X-ray waveform generator

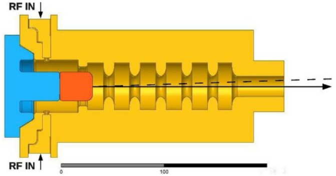
First steps towards a Science Case

New acceleration schemes

- Can Porthos profit from recent advances in acceleration techniques to increase the electron energy?
- Comparison between C-band, X-band, cryo-C-band
- Plasma acceleration??



Ultra-low emittance gun



- Can we enhance the photon energy reach by going even lower in emittance?
- How to reduce the energy spread?
- Synergy with I.FAST effort on new electron sources (SW & TW C-band guns).

Conclusion

- Convincing **science case** for a third SwissFEL beamline calls for:
  - High photon energy (20–25 keV)
  - Short pulses (5 fs or below)
  - Polarization control up to 14.4 keV
- **First baseline concept** towards this objective featuring:
  - Three-bunch distribution system with 21 ns bunch seperation
  - Various RF upgrades to increase the electron energy to 8 GeV
  - Cryogenic Apple-X undulators with 15 mm period
- A two page **“pre-announcement”** has been submitted to the ETH board for evaluation.
  - Porthos on track to be included on the 2023 infrastructure roadmap as a pre-project in the period 2025–28, and as a full project to be realized in the period 2029–32.
- **Brain storming** on various elements of a **Porthos pre-project** has started…

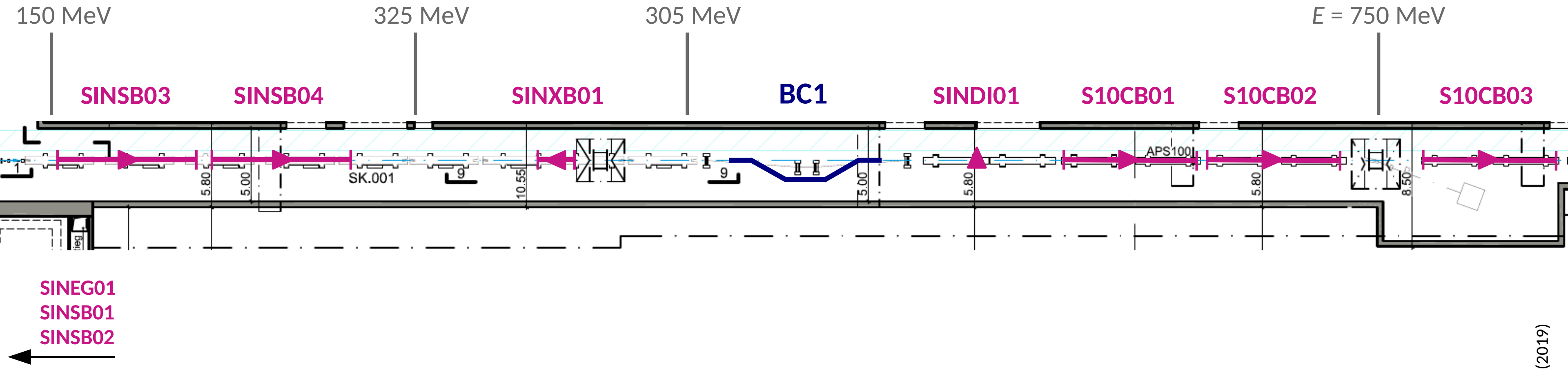
Porthos

Thank you for your attention!

Backup slides

RF upgrades I: injector/linac-1

Current situation



PSI drawing
No. 2R-393601 (2019)

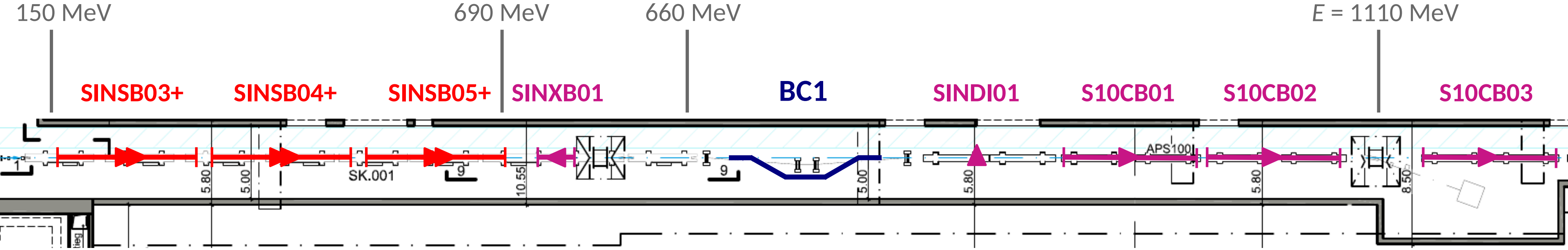
RF upgrades I: injector/linac-1

Option A: S-band upgrade

(Preferred option for RF section)

Energy gain: +360 MeV

Estimated cost: 2.6 MCHF



SINEG01
SINSB01
SINSB02
←

Upgrade SINSB03/04, new station SINSB05:

- New 3-m structures (FERMI type, 30 MV/m)
- S-band BOCs
- 180 MeV per S-band station
  (1 HV modulator/klystron serving two structures)

X-band upgrade to cope with higher compression energy?
⇒ BD simulations needed…

No changes after BC1

Option needs further study!…

PSI drawing
No. 2R-393601 (2019)

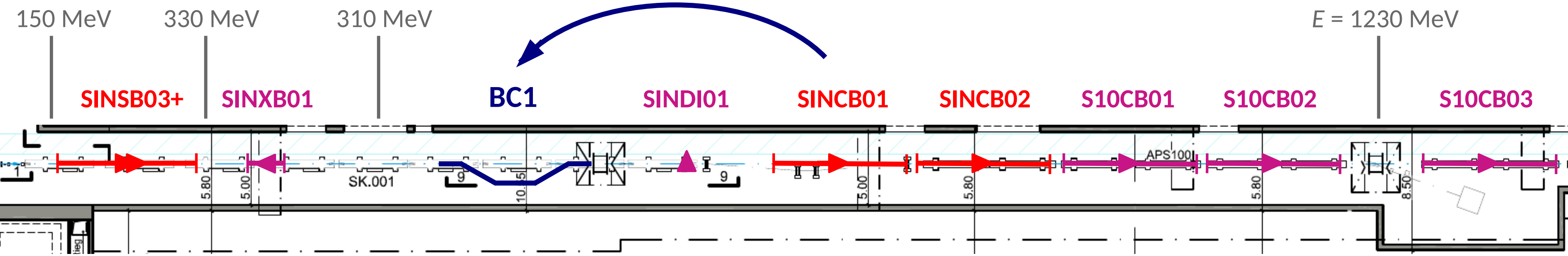
RF upgrades I: injector/linac-1

Option B: S-band and C-band upgrade

(Preferred option for beam dynamics team)

Energy gain: +480 MeV

Estimated cost: 4.1 MCHF



SINEG01
SINSB01
SINSB02

Upgrade SINSB03:

- New 3-m structures (FERMI type, 30 MV/m)
- S-band BOCs
- 180 MeV from a single S-band station (1 HV modulator/klystron serving two structures)

Move BC1 upstream by about 22 m

- Compression energy stays at ~330 MeV
- No X-band upgrade necessary
- **Long shutdown!**

2 additional C-band stations in linac-1

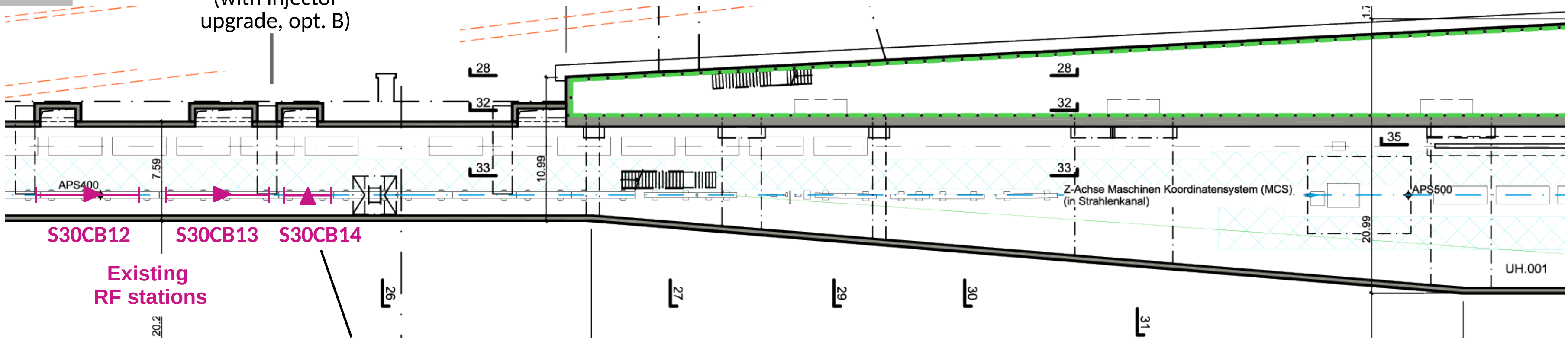
- 2 x 240 MeV = 480 MeV additional beam energy
- Stay at current acc. gradient for klystron stability (30 MV/m)

Option needs further study!...

PSI drawing
No. 2R-393601 (2019)

RF upgrades II: linac-3

Current situation



6480 MeV
(with injector
upgrade, opt. B)

S30CB12 **S30CB13** **S30CB14**

**Existing
RF stations**

transverse
deflecting
cavity

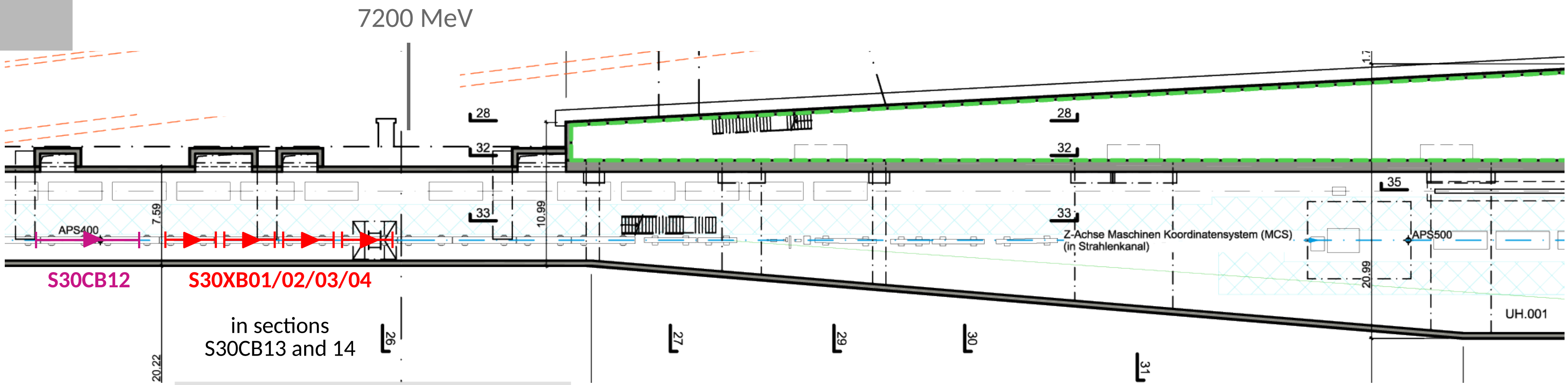
PSI drawing
No. 2R-393601 (2019)

RF upgrades II: linac-3

X-band upgrade

Energy gain: +720 MeV

Estimated cost: 10 MCHF



in sections
S30CB13 and 14

X-band linac:

- 4 X-band stations
- 240 MeV from each station
- Use S30CB13–16 spaces in klystron gallery for HV modulators and klystrons.

S30CB14 ⟼

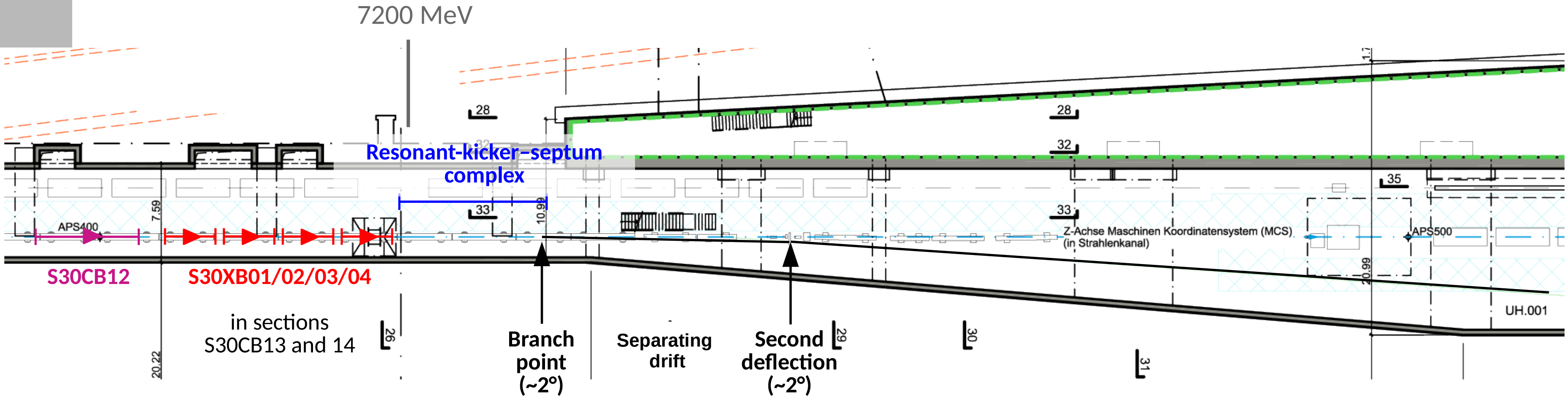
Transverse cavity to be moved to after undulator line

- Some additional cost (not factored in yet)

PSI drawing
No. 2R-393601 (2019)

RF upgrades II: linac-3

Resonant kicker and septum after X-band stations



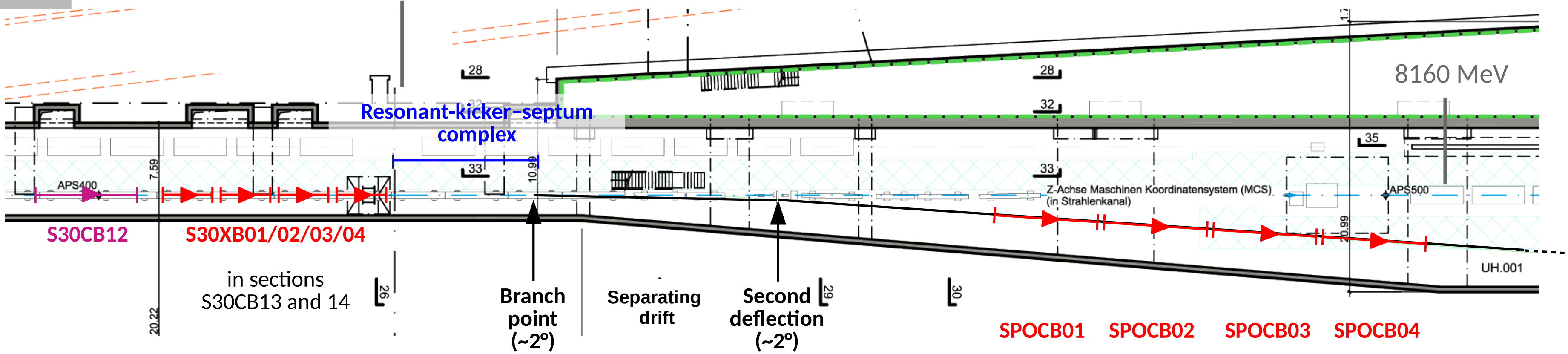
PSI drawing
No. 2R-393601 (2019)

RF upgrades III: Porthos arm

Porthos C-band linac

Energy gain: +960 MeV

Estimated cost: 8.2 MCHF (RF)
+ 2.5 MCHF (building)



7200 MeV

8160 MeV

Resonant-kicker–septum complex

S30CB12

S30XB01/02/03/04

in sections S30CB13 and 14

Branch point (~2°)

Separating drift

Second deflection (~2°)

SPOCB01 **SPOCB02** **SPOCB03** **SPOCB04**

Porthos C-band linac:

- 4 C-band stations giving 240 MeV each
- Stay at current acc. Gradient for klystron stability
- HV modulators and klystrons will require extension of klystron gallery!

PSI drawing
No. 2R-393601 (2019)

2-stage configuration

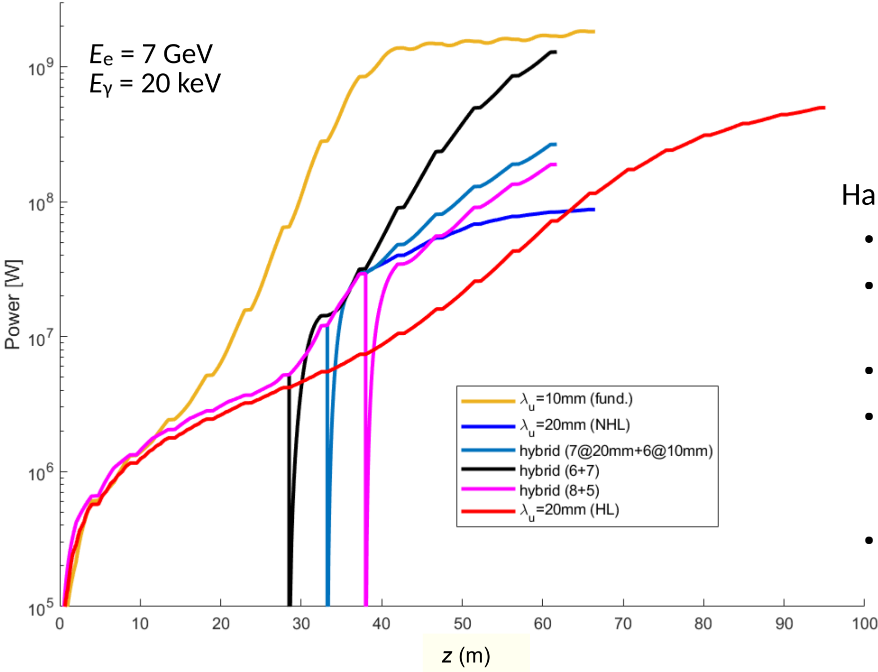
Electron beam parameters: E = 7 GeV, I = 2 kA, Q = 200 pC, ε = 300 nm, σ_E = 1 MeV

E. Prat

Hybrid setup:

λ_u = 20 mm, K = 2.18 (6.9 keV)
“Athos” type

λ_u = 10 mm, K = 1.62 (20.6 keV)
“HTS” type



Hybrid configuration:

- Amplification of 3rd harmonic with second stage.
- Varying number of undulators in first stage (6, 7 and 8). For each configuration the field of the 2nd stage is optimized (to match the third harmonic).
- Observation: Fastest growth with 6 undulators in the first stage (black curve). In this case it takes 7 modules in the 2nd section to reach 1 GW – only two modules less than in the case of only 10 mm undulators (yellow curve)…

Harmonic lasing:

- Amplification of 3rd harmonic in same stage.
- For λ_u = 20 mm tuned to 6.9 keV photon energy (0.18 nm) for the fundamental (power curve not shown).
- NHL: non-linear harmonic lasing, no suppression of the fundamental.
- HL: harmonic lasing where the fundamental is suppressed with phase shifters (one phase shifter after every meter of undulator).
  12 random configurations tried, the best is shown.
- Observation: NHL grows faster but does not reach 0.1 GW, HL needs more space but can grow to ~0.5 GW in 90 m (80 m of effective undulator length).

Against a phase retarder…

Vol. 16, No. 5, 2021

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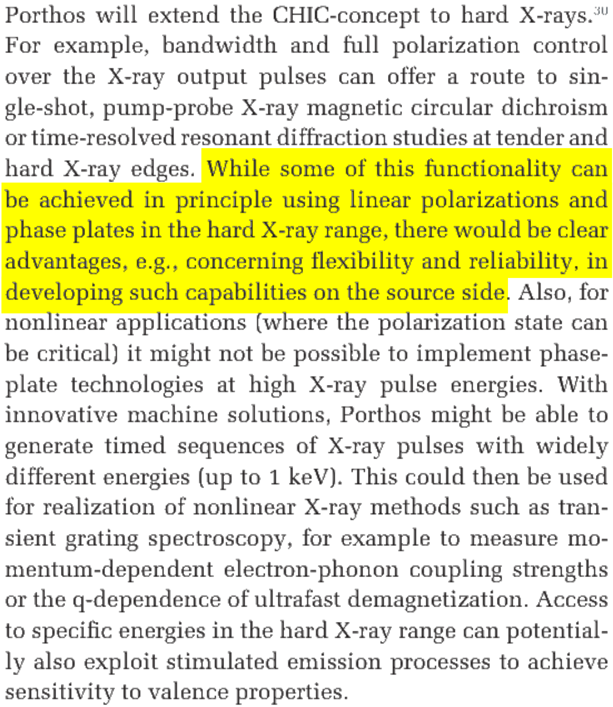
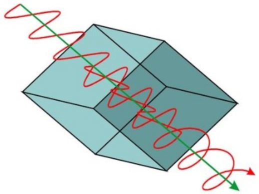
Photon Science Roadmap

for Research Infrastructures 2025–2028
by the Swiss Photon Community

Swiss Society for Photon Science



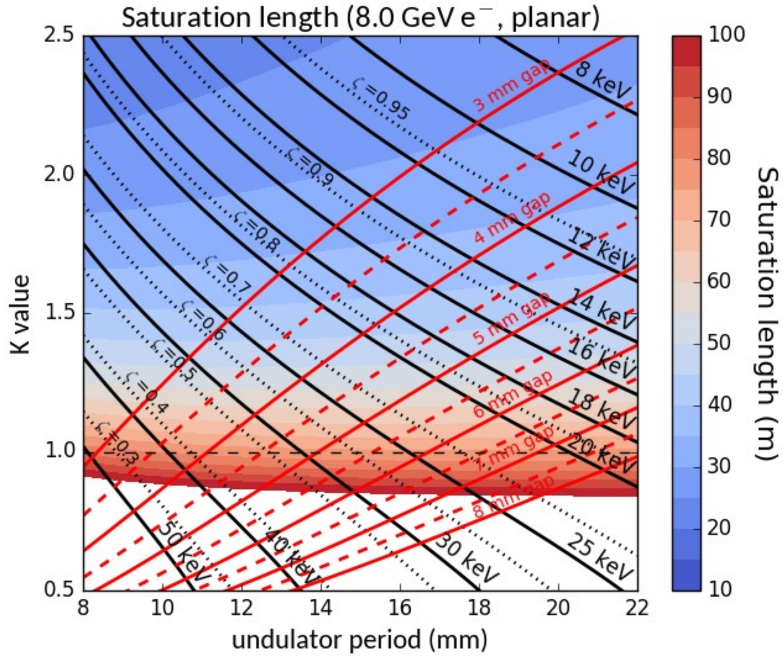
Porthos will extend the CHIC-concept to hard X-rays.[30] For example, bandwidth and full polarization control over the X-ray output pulses can offer a route to single-shot, pump-probe X-ray magnetic circular dichroism or time-resolved resonant diffraction studies at tender and hard X-ray edges. While some of this functionality can be achieved in principle using linear polarizations and phase plates in the hard X-ray range, there would be clear advantages, e.g., concerning flexibility and reliability, in developing such capabilities on the source side. Also, for nonlinear applications (where the polarization state can be critical) it might not be possible to implement phase-plate technologies at high X-ray pulse energies. With innovative machine solutions, Porthos might be able to generate timed sequences of X-ray pulses with widely different energies (up to 1 keV). This could then be used for realization of nonlinear X-ray methods such as transient grating spectroscopy, for example to measure momentum-dependent electron-phonon coupling strengths or the q-dependence of ultrafast demagnetization. Access to specific energies in the hard X-ray range can potentially also exploit stimulated emission processes to achieve sensitivity to valence properties.



The path to higher photon energies

- Let's assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

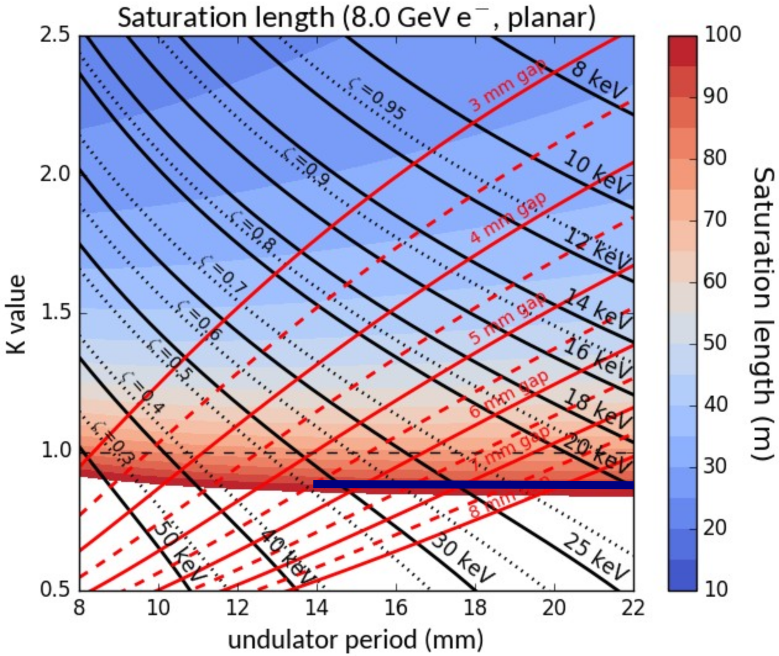


Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

- Let's assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - **– available undulator space (saturation length)**

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

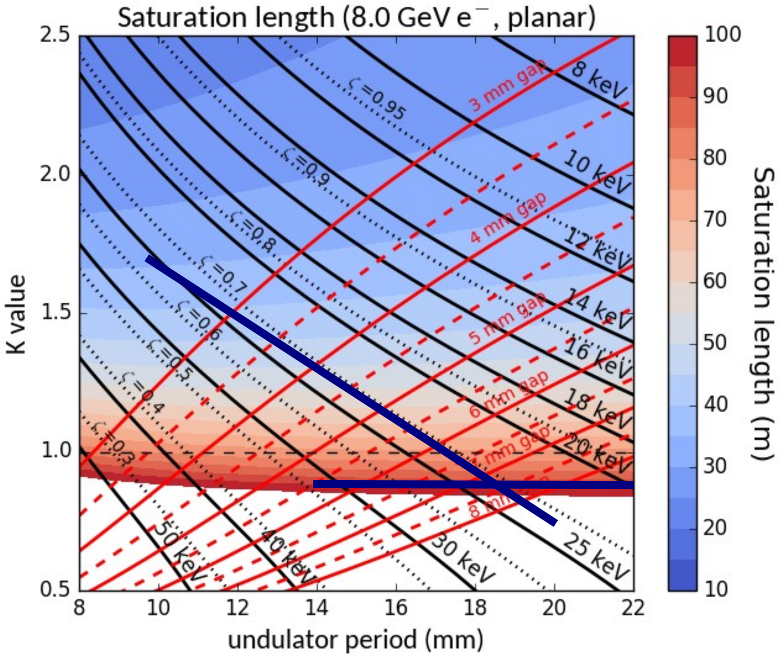


Undulator K vs. gap: **permanent magnet** (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - – available undulator space (saturation length)
  - **– loss of coherence**

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

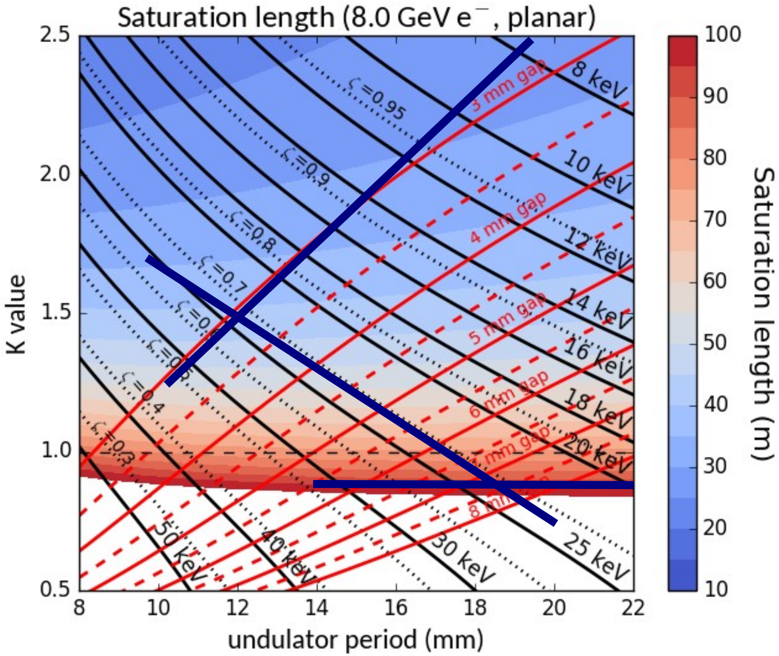


Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - **achievable undulator strength (K at minimal gap)**

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



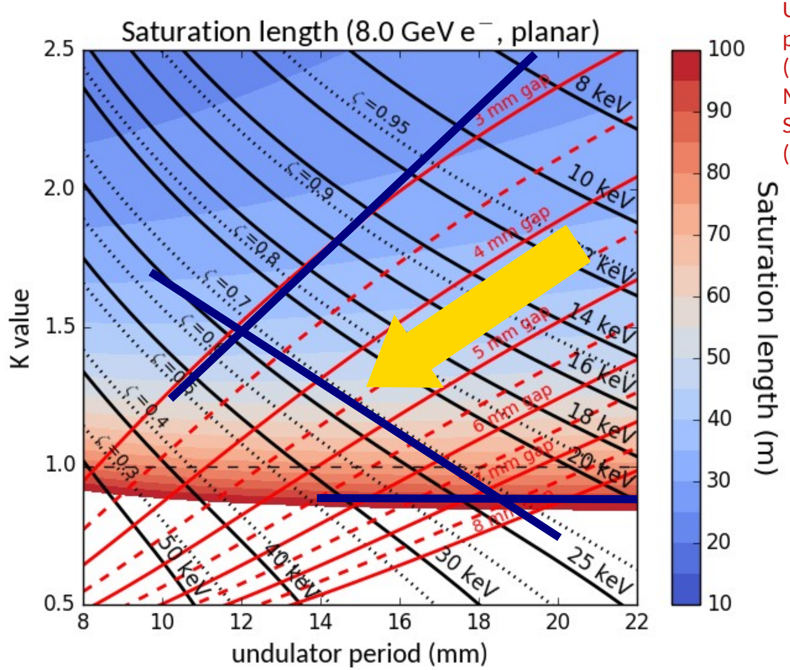
Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

- Let's assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m

- **Higher photon energies call for:**
  - **smaller undulator period**
  - ***smaller* K values**



Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

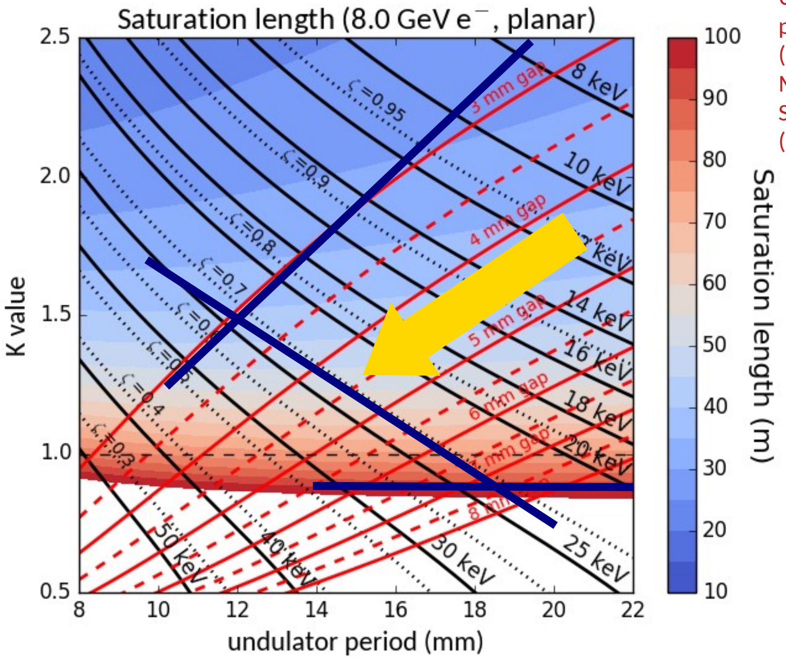
The path to higher photon energies

- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - smaller undulator period
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**
  - i.e. at 8 GeV, 300 nm, no point in going to 10 mm undulator period!

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

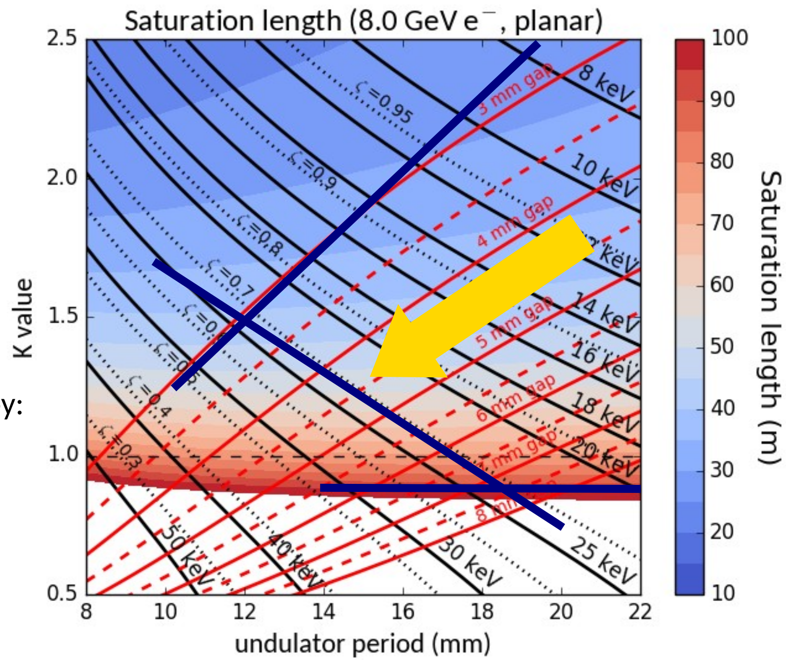
- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - smaller undulator period
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

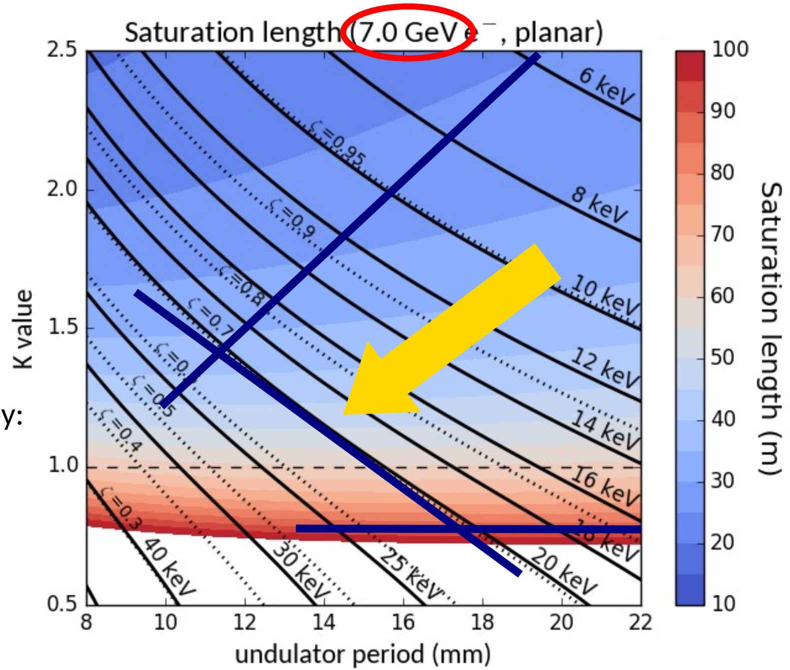
- Let's assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - – available undulator space (saturation length)
  - – loss of coherence
  - – achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - – smaller undulator period
  - – *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - **– increasing the beam energy!**

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



The path to higher photon energies

- Let's assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
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  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
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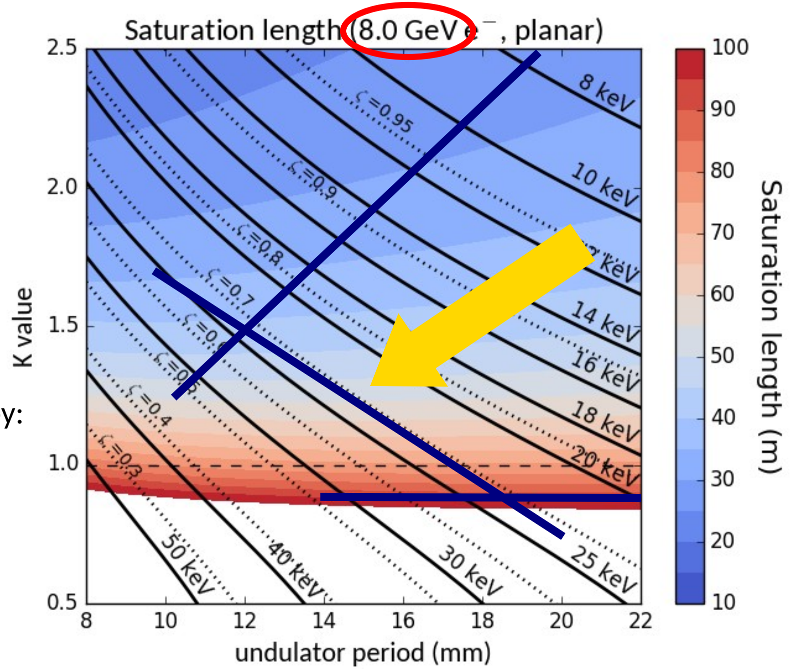
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - **increasing the beam energy!**

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



The path to higher photon energies

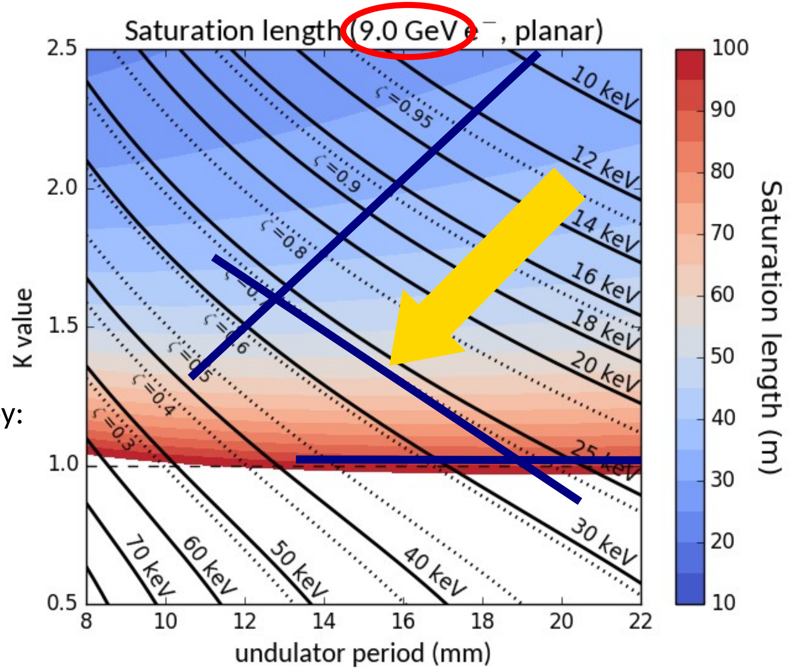
- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - smaller undulator period
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - **increasing the beam energy!**

Electron beam parameters:
I = 2 kA, ε = 300 nm, σ_E = 1 MeV, β = 10 m



The path to higher photon energies

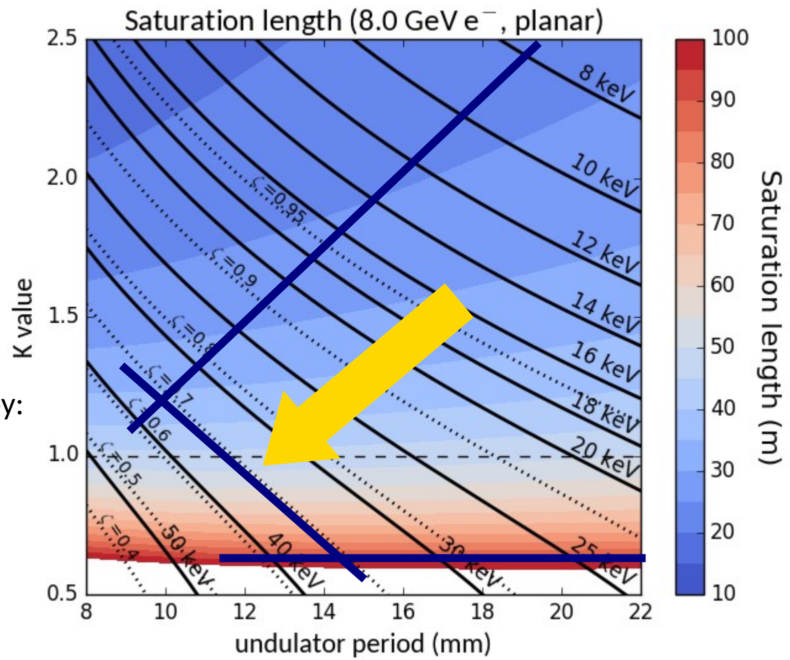
- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - smaller undulator period
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - increasing the beam energy, or
  - **further reducing the emittance**

Electron beam parameters:
I = 2 kA, **ε = 200 nm,** σ_E = 1 MeV, β = 10 m



The path to higher photon energies

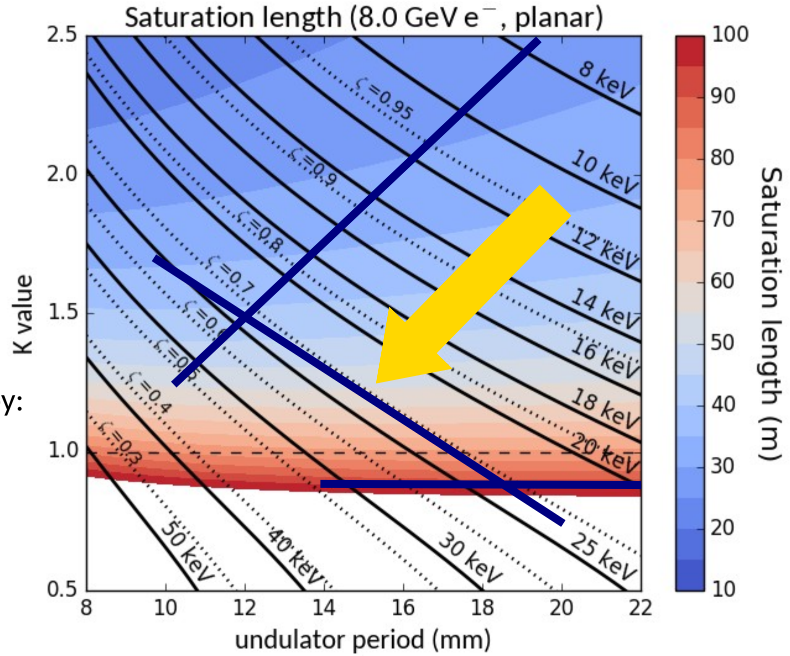
Electron beam parameters:
I = 2 kA, **ε = 300 nm,** σ_E = 1 MeV, β = 10 m

- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - – available undulator space (saturation length)
  - – loss of coherence
  - – achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - – smaller undulator period
  - – *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - – increasing the beam energy, or
  - **– further reducing the emittance**



The path to higher photon energies

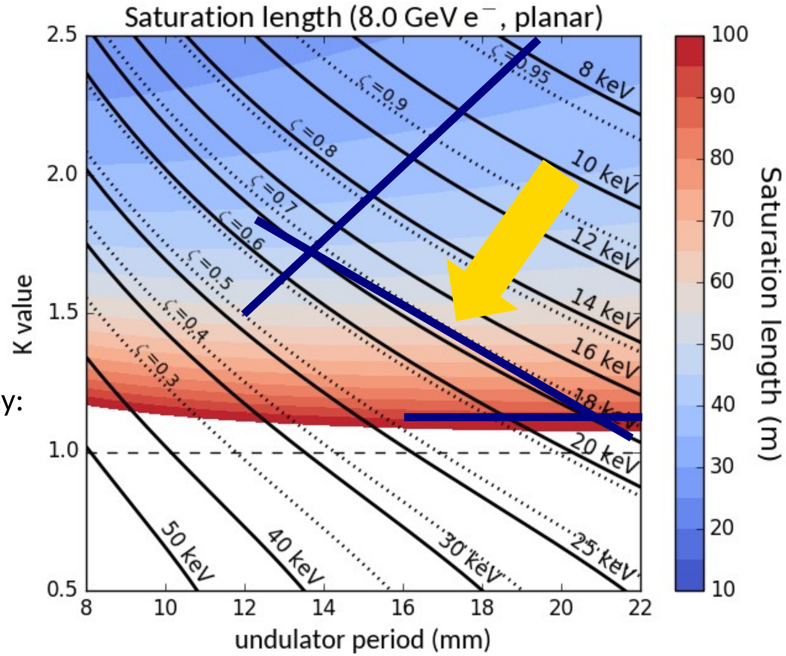
Electron beam parameters:
I = 2 kA, **ε = 400 nm,** σ_E = 1 MeV, β = 10 m

- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - smaller undulator period
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - increasing the beam energy, or
  - **further reducing the emittance**



The path to higher photon energies

- Let’s assume 8 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
  - loss of coherence
  - achievable undulator strength (K at minimal gap)

- Higher photon energies call for:
  - smaller undulator period
  - *smaller* K values

- The main obstacle towards higher photon energies is **the loss of coherence!**

- **The only ways** to reach higher photon energies are by:
  - increasing the beam energy, or
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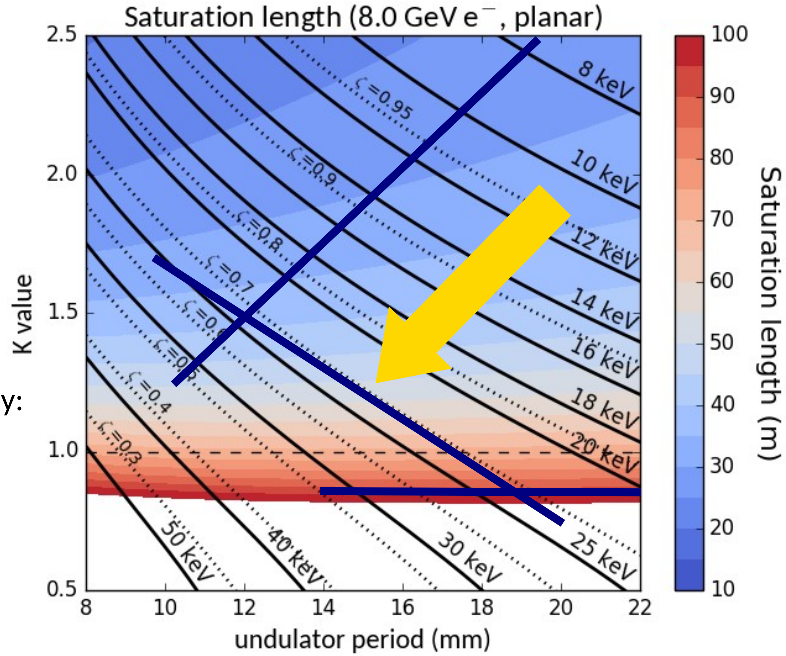
- **The effect of energy spread is relatively small.**
  (Only affects saturation length, no effect on coherence.)

Electron beam parameters:
I = 2 kA, ε = 300 nm, **σ_E = 0 MeV,** β = 10 m



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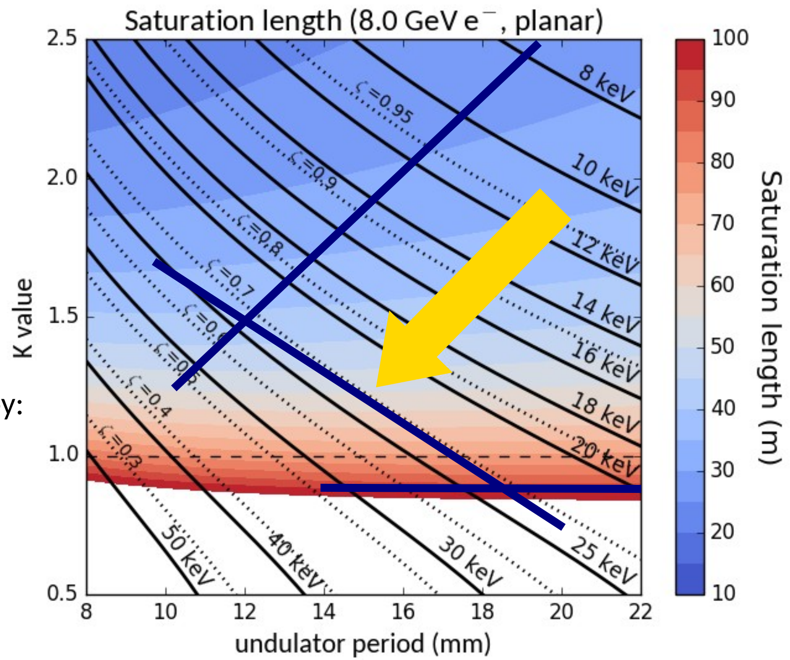
Electron beam parameters:
I = 2 kA, ε = 300 nm, **σ_E = 1 MeV,** β = 10 m



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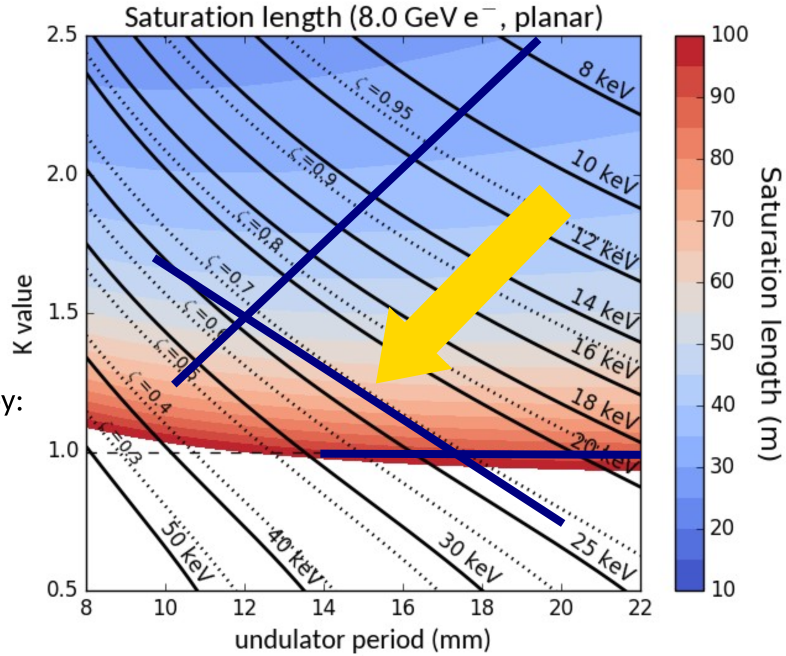
Electron beam parameters:
I = 2 kA, ε = 300 nm, **σ_E = 2 MeV,** β = 10 m



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!