PAUL SCHERRER INSTITUT

Thomas Schietinger :: Paul Scherrer Institut

Outline of a Porthos baseline concept

Porthos Machine Working Group Meeting, 19 February 2021

Machine choices

Three major choices to be made:

1) **Repetition rate and bunch separation**
   - RF energy losses mandate a shorter bunch spacing (than the current 28 ns).
   - Baseline concept: shorten bunch spacing to 21 ns with a faster kicker (from 56 ns to 42 ns period).
   - Alternative option: 14 ns bunch spacing using zero-crossings in 56 ns kicker period (only for 3 bunches?).

2) **Electron beam energy (linac upgrade)**
   - Baseline concept: upgrade to 7 GeV by adding 3 more C-band stations.
   - Further upgrade, e.g. with an X-band Porthos linac, to 8 or 9 GeV very attractive but will require building extensions and therefore probably too expensive (Porthos upgrade?).

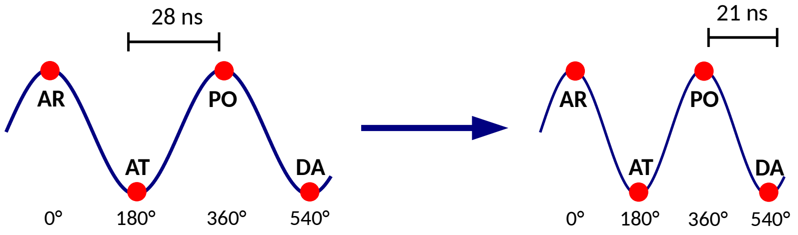
3) **Undulator type and configuration**
   - Interundulator chicanes are a given (CHIC concept).
   - Hybrid undulator concepts found to be not attractive.
   - Two competing undulator concepts: pure Apple-X undulator (baseline) or planar undulator with phase retarder to enable some polarization control.

Resonant kicker upgrade

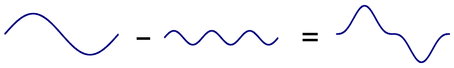
Kicker upgrade options:

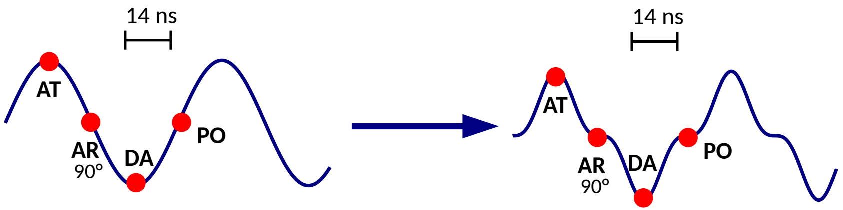
Two possibilities to upgrade the kicker to avoid or mitigate the problems associated with shorter bunch separations:

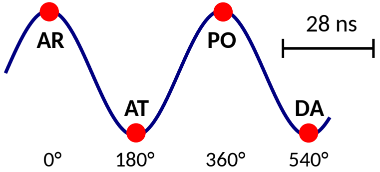
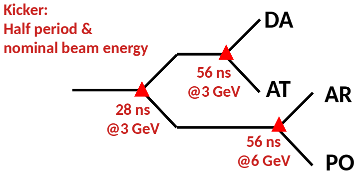
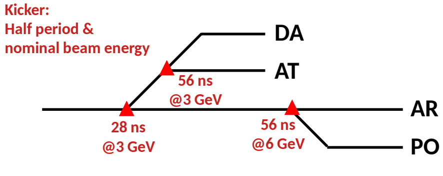
- **Faster oscillation**
  - The emergence of GaN transistors means that higher voltages are now possible than 10 years ago (our current system is based on Si MOSFET and pushed that technology to the limit).
  - A faster kicker with the same active length will be challenging but should be possible (Martin).



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





<table>
<tr><th>Bunch spacing / allocation</th><th>Bunch placement at first kicker</th><th>Topology</th><th>Actual layout (schematic)</th></tr>
<tr><td>28 ns
Status quo with four bunches, all on-crest</td><td></td><td></td><td></td></tr>
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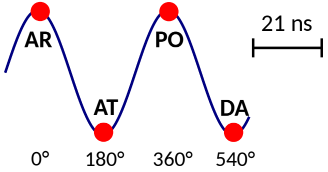
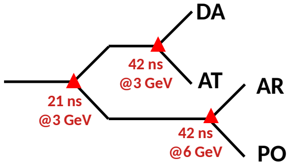
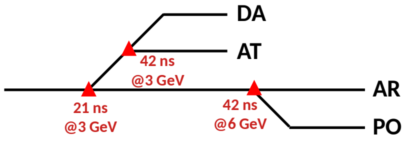
Status quo with four bunches, but faster kicker</td><td></td><td></td><td></td></tr>
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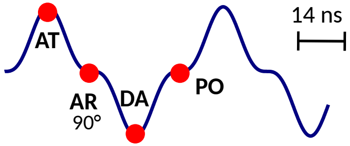
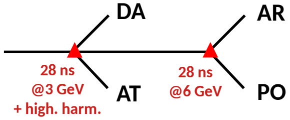
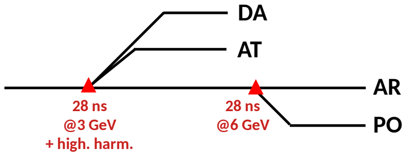
Using inflection points at zero crossings to go straight.</td><td></td><td></td><td></td></tr>
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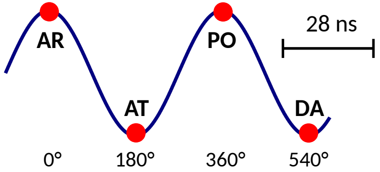
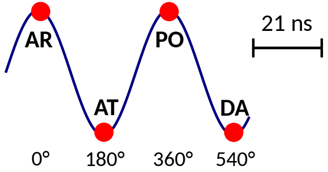
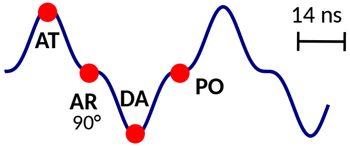
Bunch spacing / allocation	Bunch placement at first kicker	Evaluation (pulsed magnets, RF, other)
28 ns Status quo with four bunches, all on-crest		• Maximum stability for all bunches. • 6 GeV kicker doable (twice stronger but twice lower frequency). • New kicker and electronics need to be designed. • Other diagnostics and (LLRF) control systems will not suffer. • **Unacceptable loss of RF power at 84 ns separation.** • Maximum RF tunability, minimum wakefield effects.
21 ns, fast kicker Status quo with four bunches, but **faster** kicker		• 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!
14 ns, inflection Using inflection points at zero crossings to go straight.		• 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.

Feedback 14 ns vs. 21 ns bunch spacing

Assuming that the decision for the bunch spacing will be between 14 ns and 21 ns, the system responses so far are:

- **RF/LLRF** (Z. Geng, P. Craievich):
  - Higher energy loss at 21 ns (presentation Qiao, 27 October 2020). Example C-band loss: 129 MeV (21 ns) vs. 73 MeV (14 ns) (compare to 200 MeV at 28 ns).
  - Tuning range (RF step) considerably reduced at 14 ns (e.g. S-band phase: ±0.5° versus ±0.2°)
  - Higher wakefield effects at 14 ns (no quantitative estimate yet).
- **Laser** (A. Trisorio):
  - In general preference for multiples of 14 ns for the bunch spacing.
  - 21 ns is possible, but requires a separate laser for each beam line (one laser will not be able to serve two or more arbitrary beam lines).
- **Resonant kicker** (M. Paraliev): both cases require some technological development. Beyond that:
  - 21 ns: can use existing beam topology (incl. Lambertson, septum)
  - 14 ns: three-way Lambertson/septum needed – how to remerge the beams? Many uncertainties.
- **Diagnostics** (except BPMs) (R. Ischebeck):
  - Difference is only relevant for detectors that actually have a time constant in that range.
  - Readout challenges to be discussed with AEK – Porthos would represent a good opportunity to overhaul all our readout electronics (the designs date back to 2010). Clearly 14 ns will be more challenging than 21 ns.
- **BPM** (B. Keil):
  - No quantitative statements possible without considerable work (and specifications)
  - Qualititative estimate: at 21 ns there is a chance to re-use the existing hardware, at 14 ns we will most likely need to replace the hardware (where bunch seperation is needed).
- **Timing & Synchronization** (C. Sydlo):
  - The bunch spacing makes no difference.
  - In principle, once we have a digital laser lock (end of 2021), the timing can be set with almost arbitrary precision (0.1 fs).
  - For some systems, spacing given by the rep. rate of the amplification chain (typically 7 ns)

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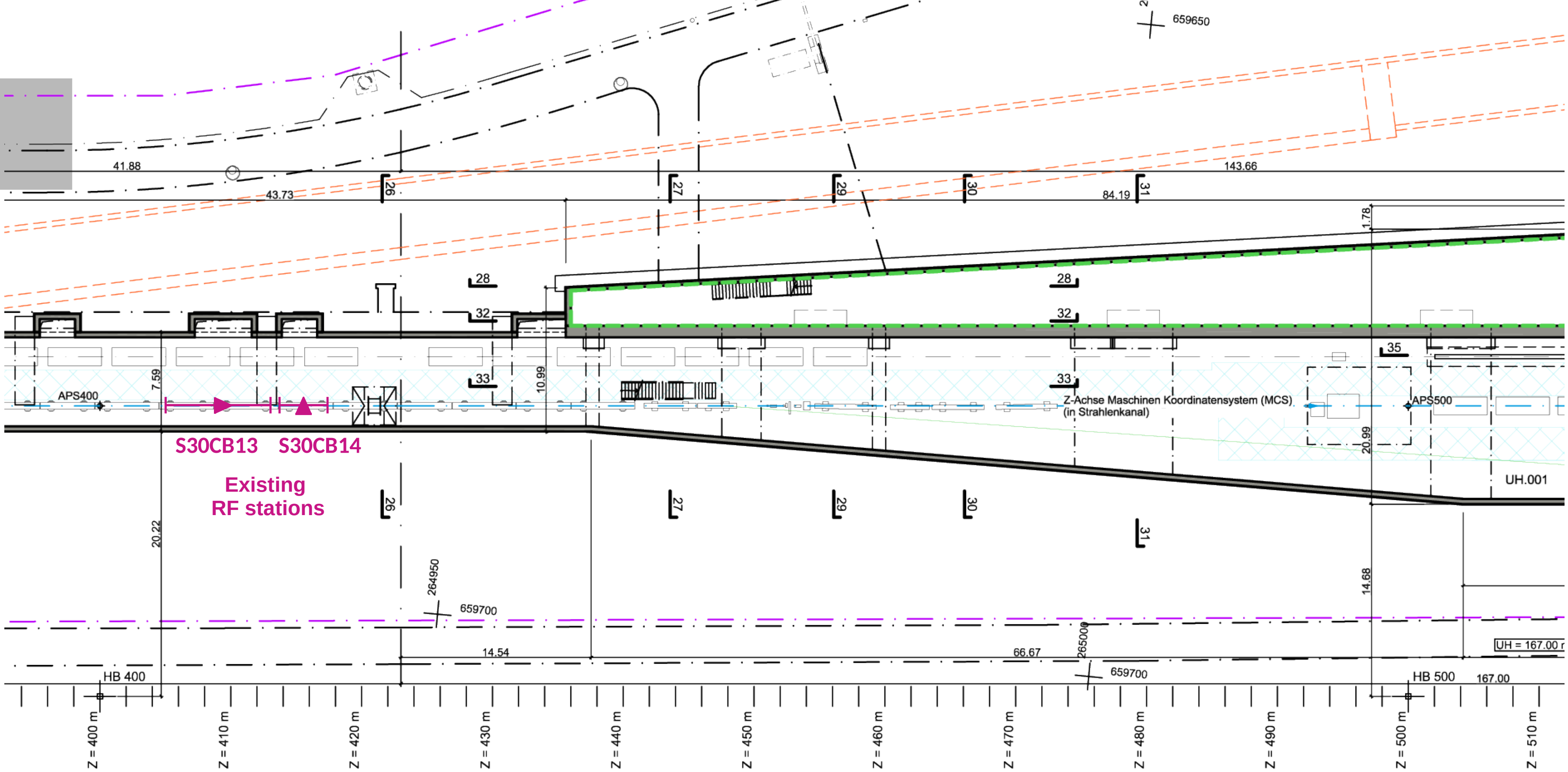
→ Overall preference for 21 ns bunch spacing

Linac upgrade

Porthos switchyard: current situation

PSI drawing
No. 2R-393601 (2019)



Porthos switchyard: beam separation

PSI drawing
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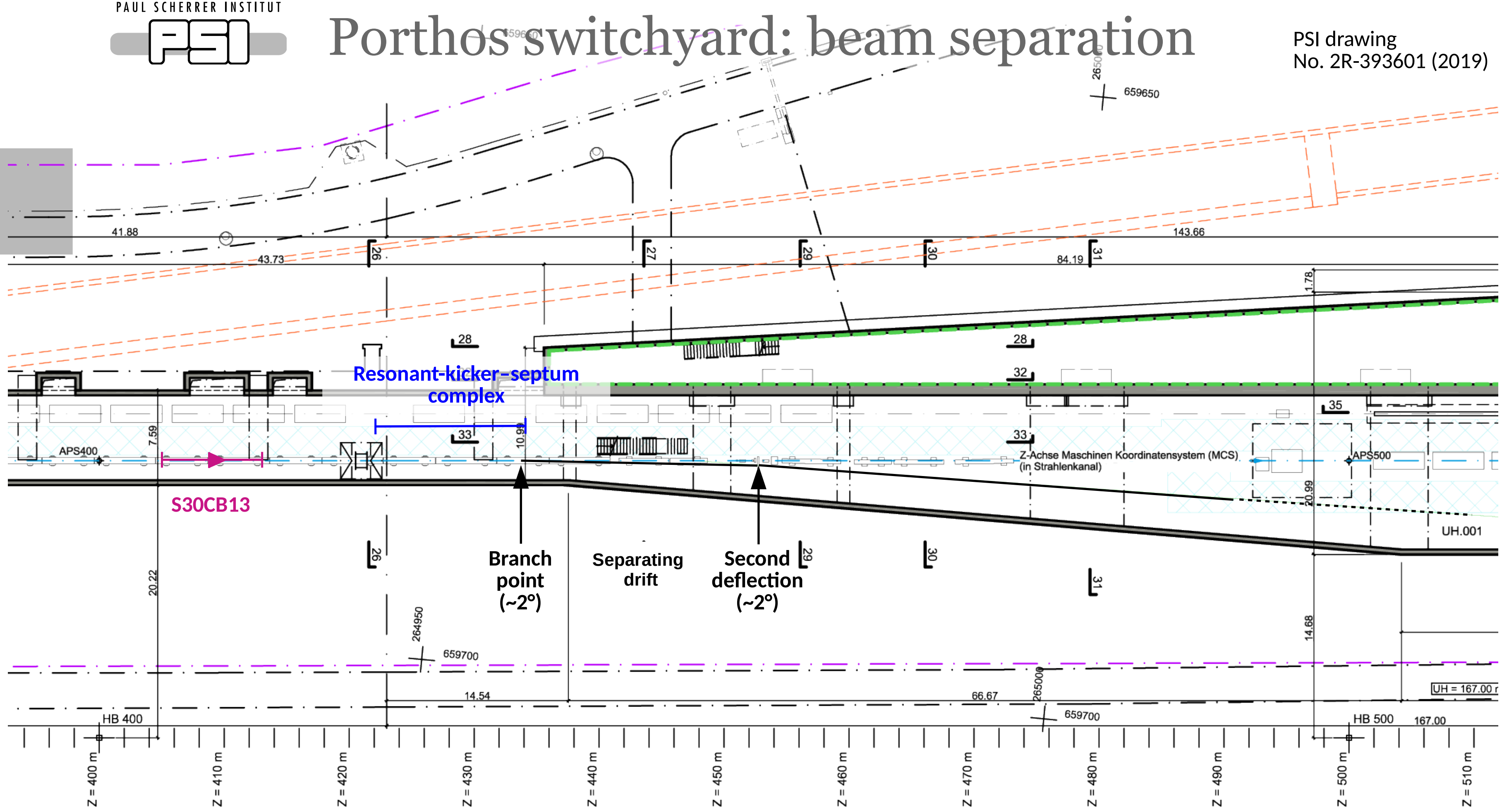

Three additional C-band stations

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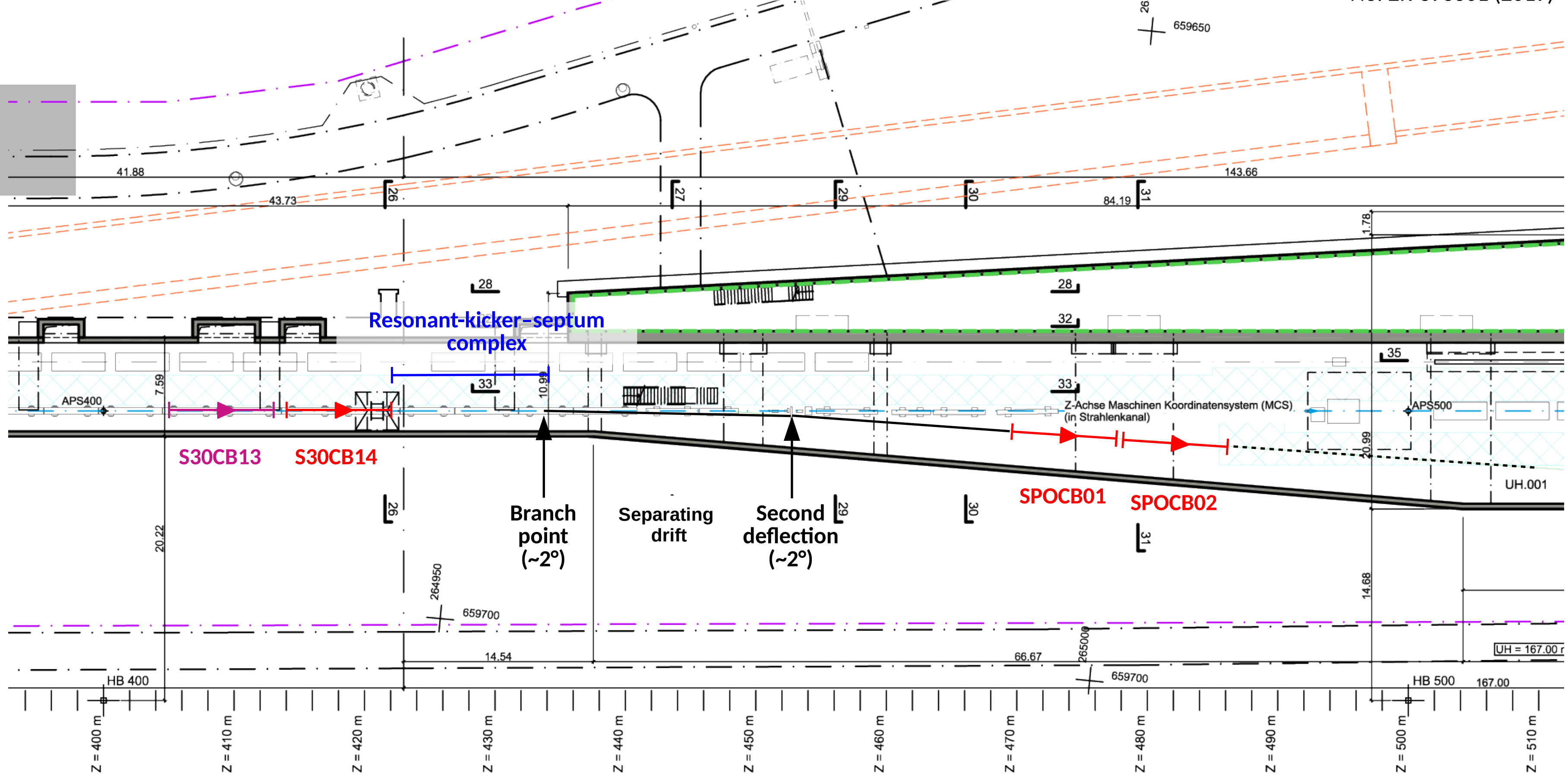

Three additional C-band stations

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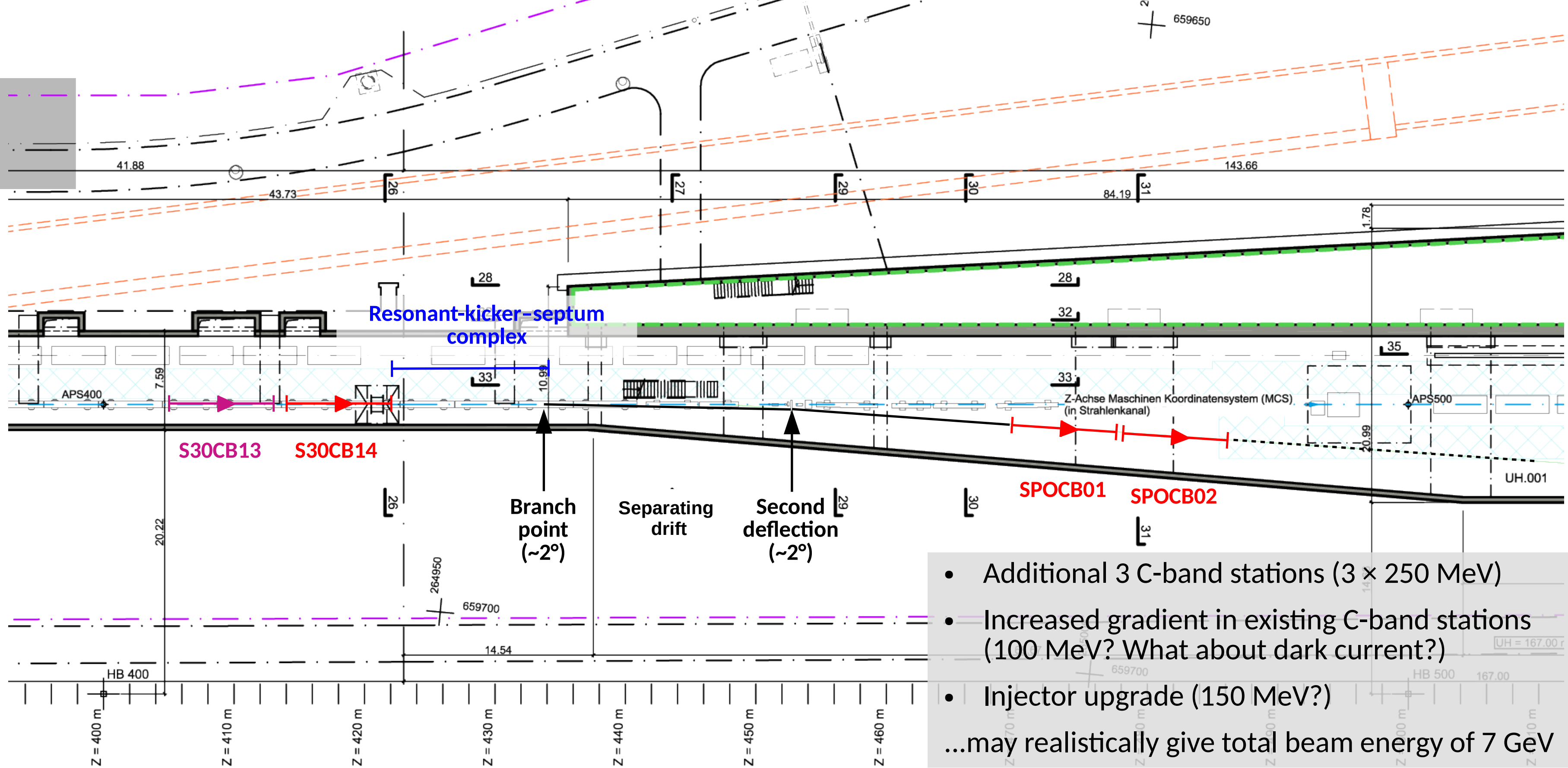


- Additional 3 C-band stations (3 × 250 MeV)
- Increased gradient in existing C-band stations (100 MeV? What about dark current?)
- Injector upgrade (150 MeV?)

...may realistically give total beam energy of 7 GeV

Undulator design

Undulator 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.	✓

2-stage configuration

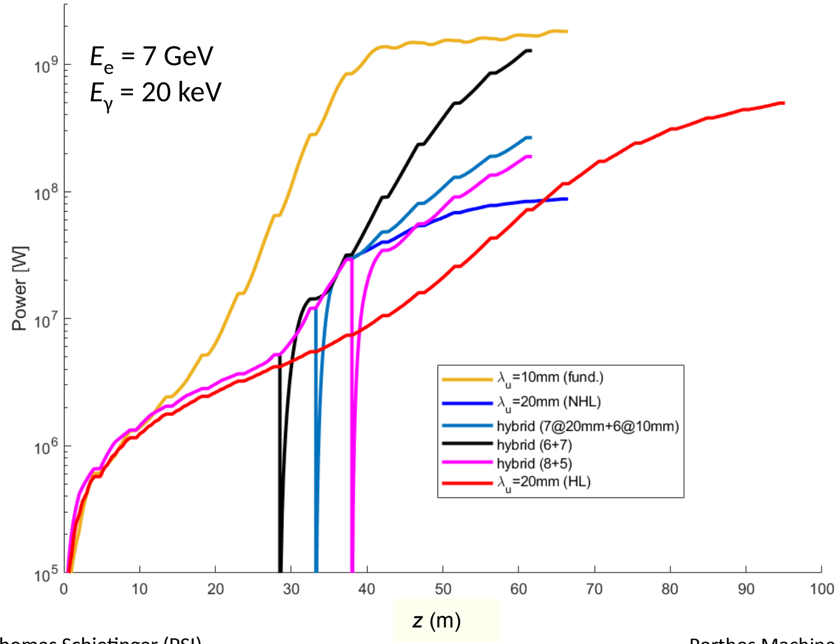
Electron beam parameters: E = 7 GeV, I = 2 kA, Q = 200 pC, ε = 300 nm, σ_E = 1 MeV

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



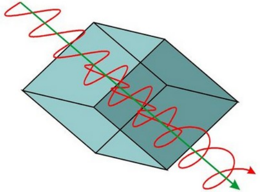
Hybrid configuration:

- 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).

Arguments pro and contra phase retarder



Arguments favoring a phase retarder solution (mostly from E. Ferrari):

- **Cost:** fixed polarization undulators are much less expensive than variable polarization ones
- **Field quality:** can be made much better with fixed polarization
- **Mechanical simplicity:** no need for complex undulator movements prone to failure when doing dichroism experiments
- **Gap control:** we will most likely run at a fixed (maximum?) K anyway and may even go to fixed-gap undulators.
- **Polarization losses** due to transmission to the beamline: even with a circularly polarized source, at the end you end up with ellipitically polarized light at the experiment (LCLS-II went for vertically polarized undulators for hard X-rays to benefit from the better transmission to the beamlines).

Arguments against a phase retarder solution (favoring a hybrid solution instead) (mostly from G. Aeppli):

- **Insufficient flexibility:** phase retarders quickly reach a limit when it comes to broad-band mode, sub-femtosecond pulses etc., needed for complex experiments.
  - In particular **bandwidth** is a big limitation (but efficiency increases when operating in high-brightness mode or after a monochromator)
- Full polarization control is **only needed up to 10 keV** – for higher energies can still use a fixed-polarization afterburner or…
- …in the long run, we could have one hard-X-ray line focusing on high photon energies with linear polarization for biology, chemistry and imaging, and a second one limited to 12 keV with fancier options (polarized light, CHIC) used for “physics” – but in this case, Aramis should cover the high energies → complete linac overhaul?

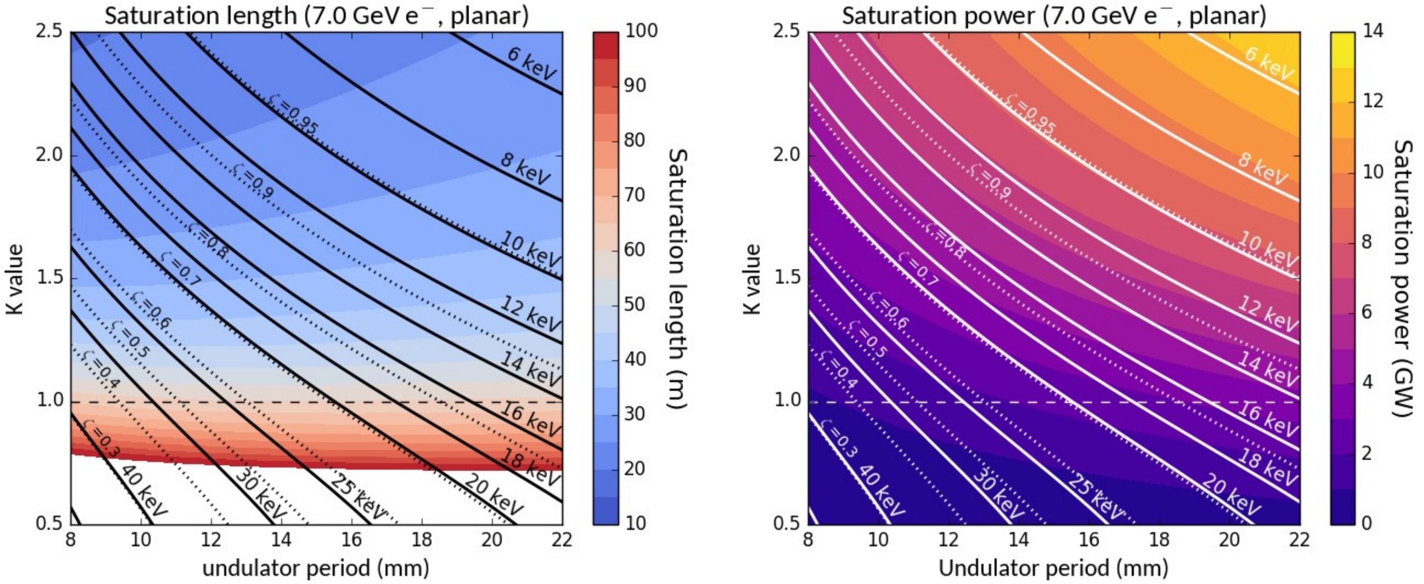
Ming Xie estimates (planar, fixed energy)

- 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)

$$\frac{\epsilon_n}{\gamma} \leq \frac{\lambda}{2\pi} \Rightarrow \hat{\epsilon} \equiv \frac{2\pi\epsilon_n}{\gamma\lambda} \leq 1 \qquad \zeta \approx \frac{1.1\hat{\epsilon}^{1/4}}{1+0.15\hat{\epsilon}^{9/4}}$$

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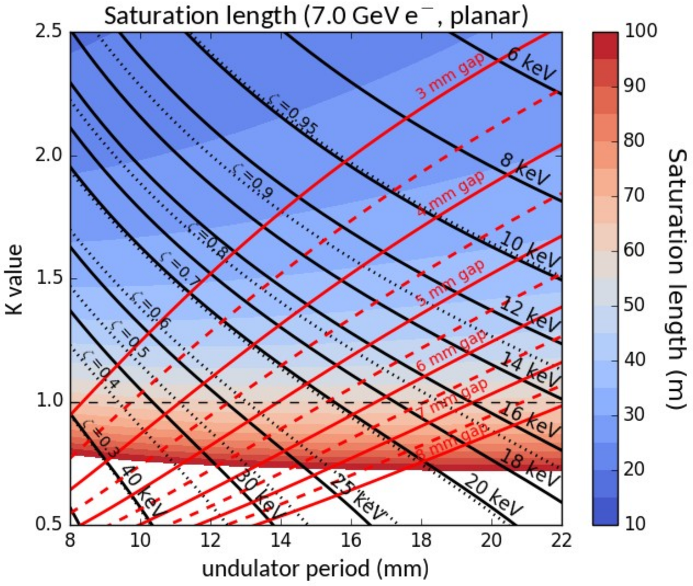
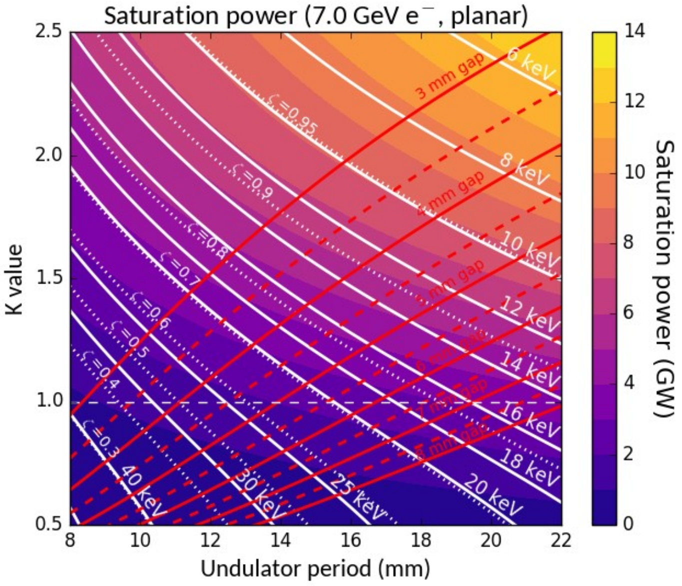
- Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad.(2018) 25, 686-705)

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

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





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

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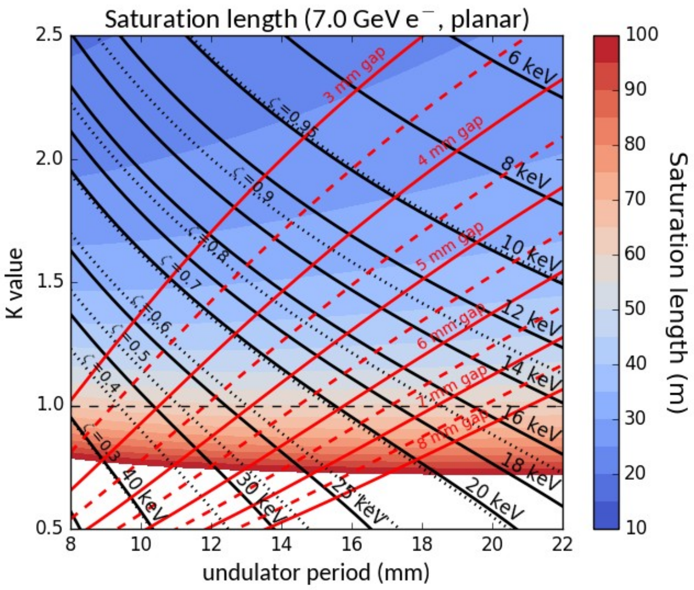

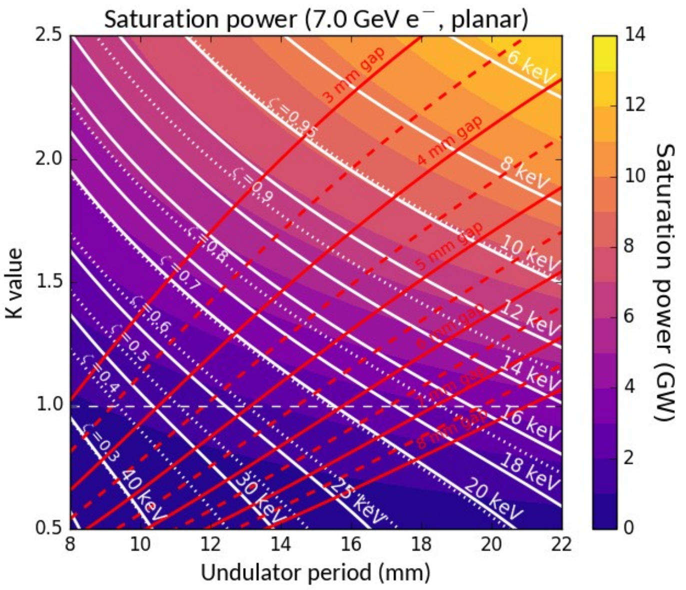

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We want ζ ≥ 0.7.

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

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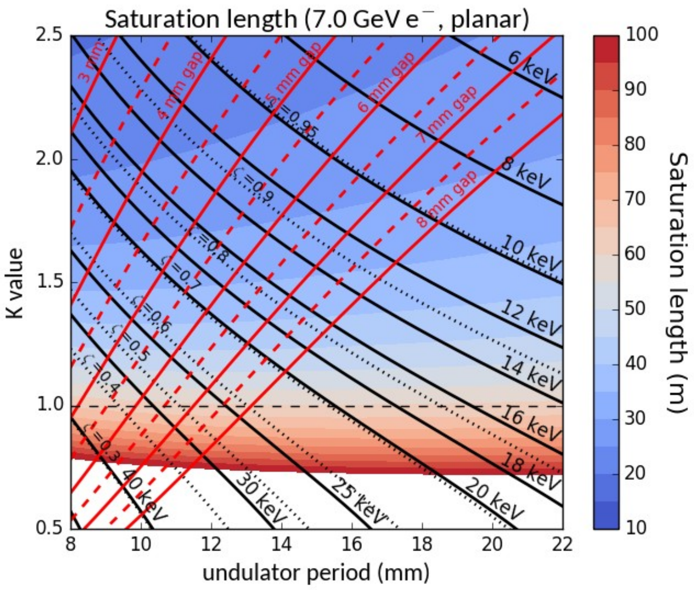
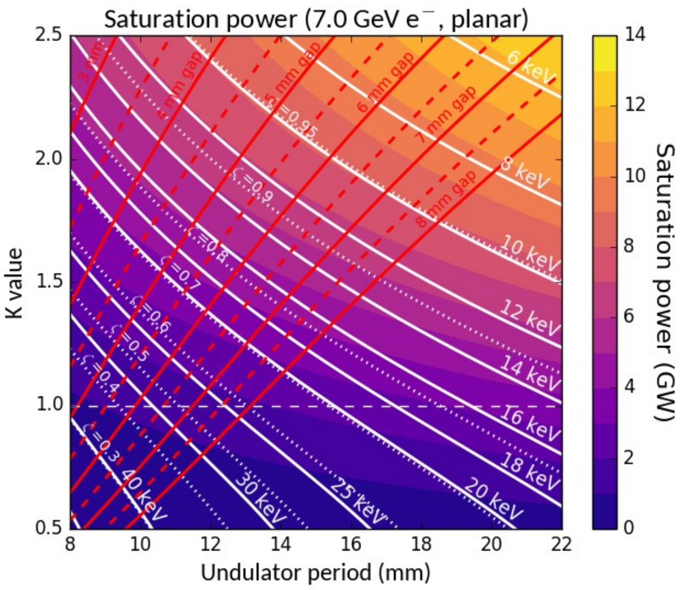
To be evaluated the smallest gap we can aim for (losses, wakefields,...)





The path to higher photon energies

- Let's assume 7 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:

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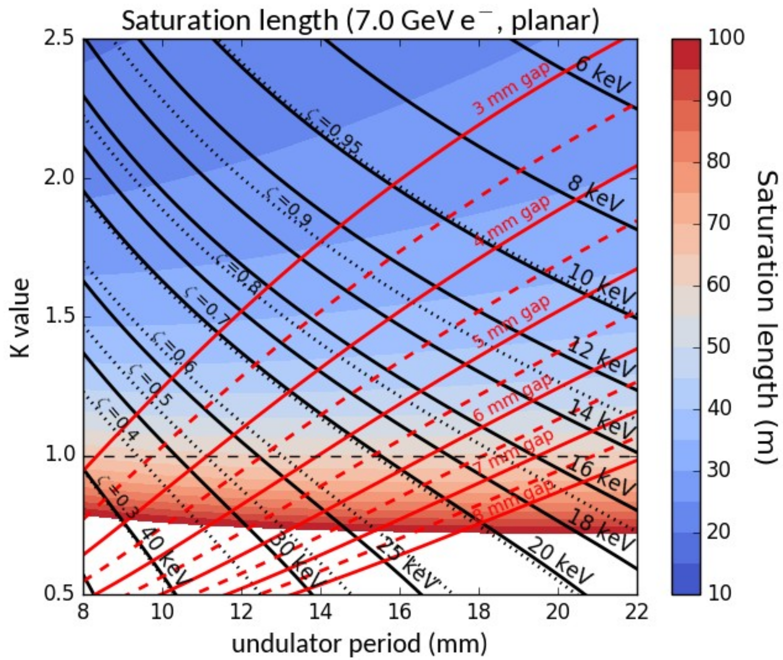

Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

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  - **available undulator space (saturation length)**

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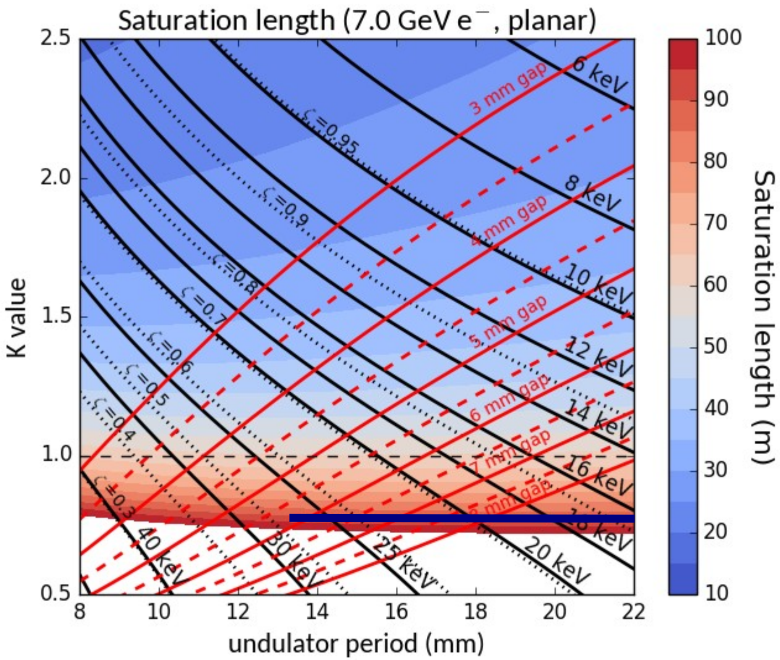

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  - **loss of coherence**

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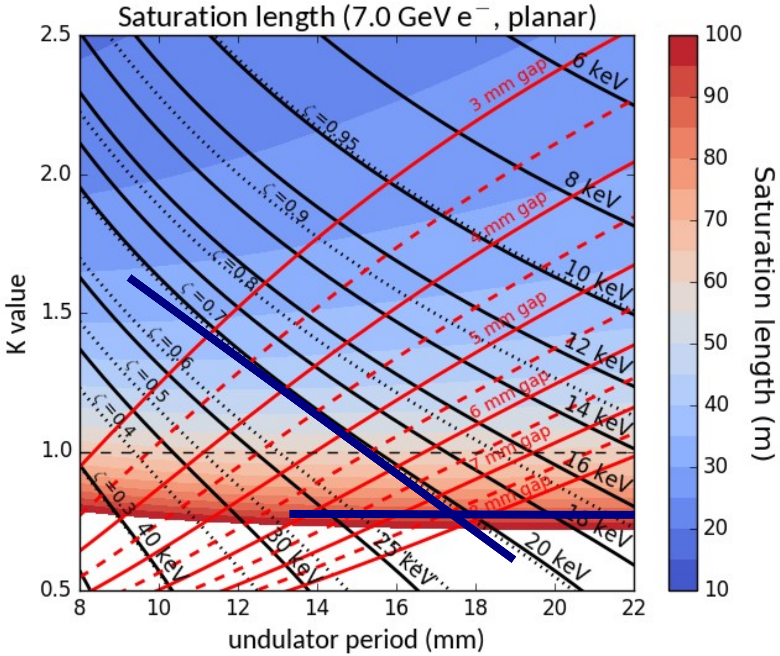

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  - loss of coherence
  - **achievable undulator strength (K at minimal gap)**

Electron beam parameters:
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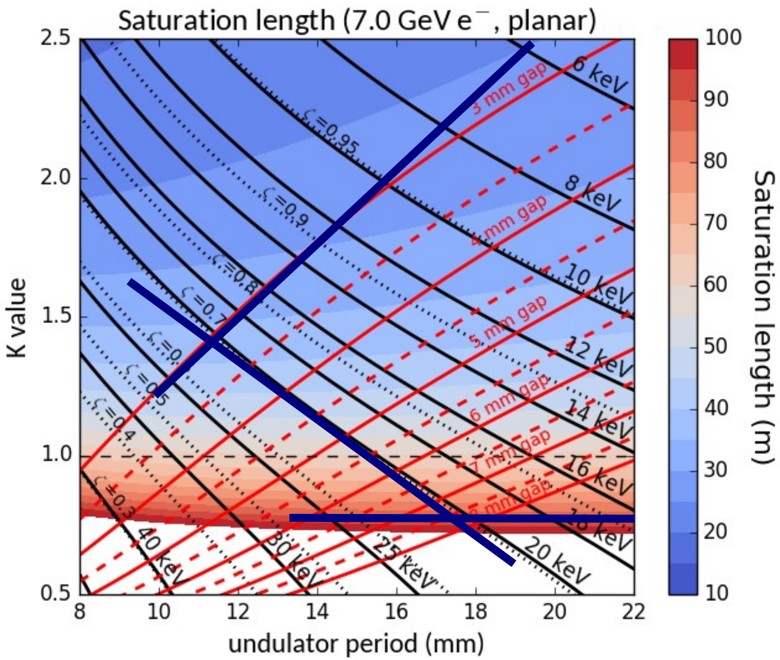

Undulator K vs. gap: permanent magnet (example Aramis U15, M. Calvi et al., J. Synchrotron Rad. (2018) 25, 686-705)

The path to higher photon energies

- Let's assume 7 GeV beam energy available and permanent magnet undulators.
- Our parameter space is limited by three boundaries, given by:
  - available undulator space (saturation length)
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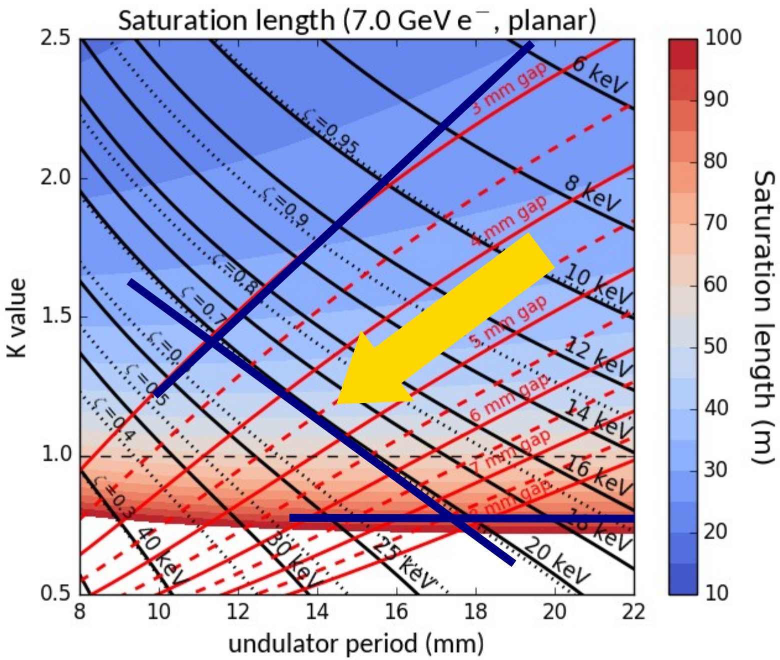
- **Higher photon energies call for:**
  - **smaller undulator period**
  - ***smaller* K values**



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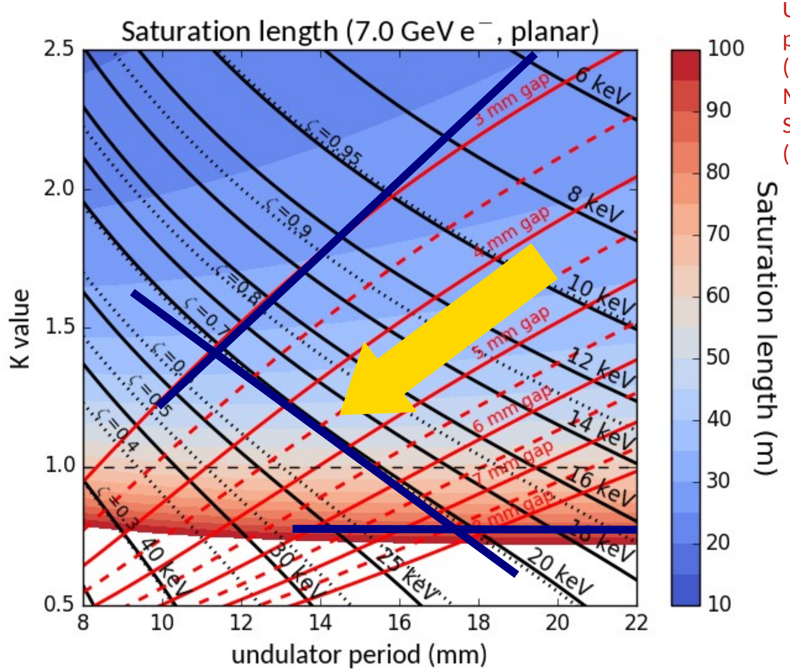
- The main obstacle towards higher photon energies is **the loss of coherence!**
  - i.e. at 7 GeV, 300 nm, no point in going to 10 mm undulator period!

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



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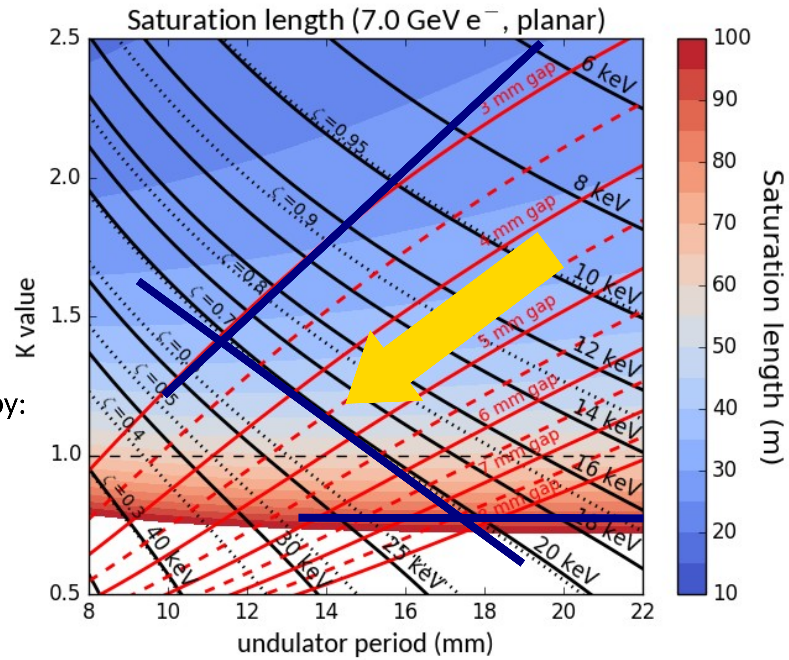

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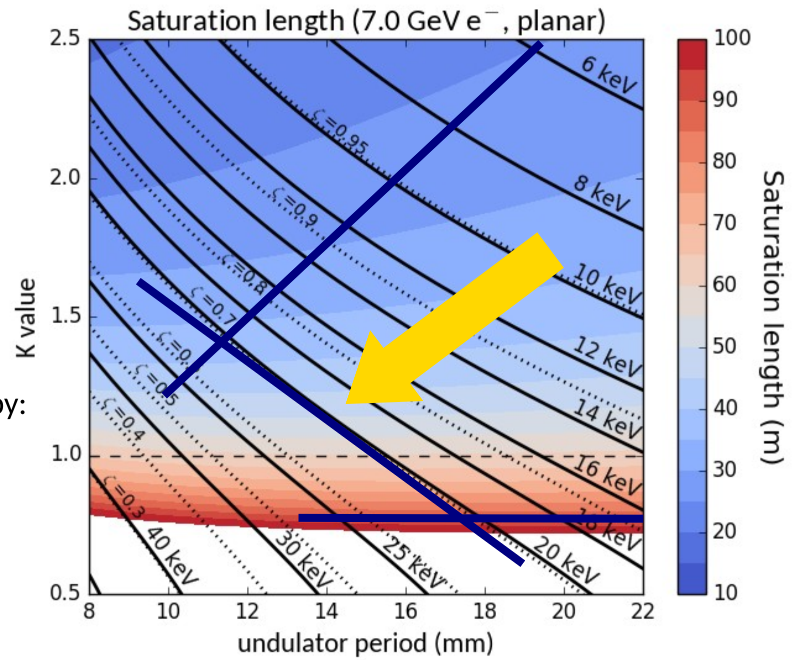

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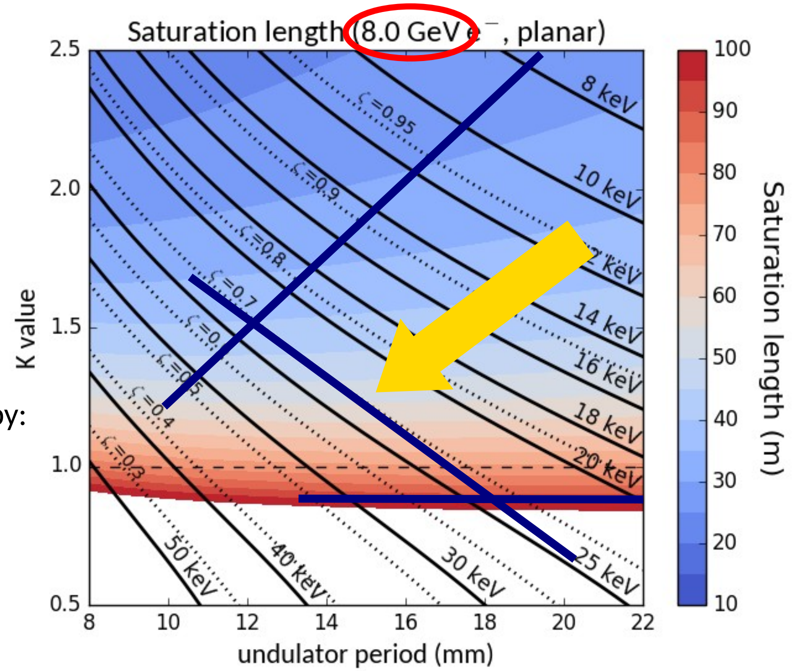

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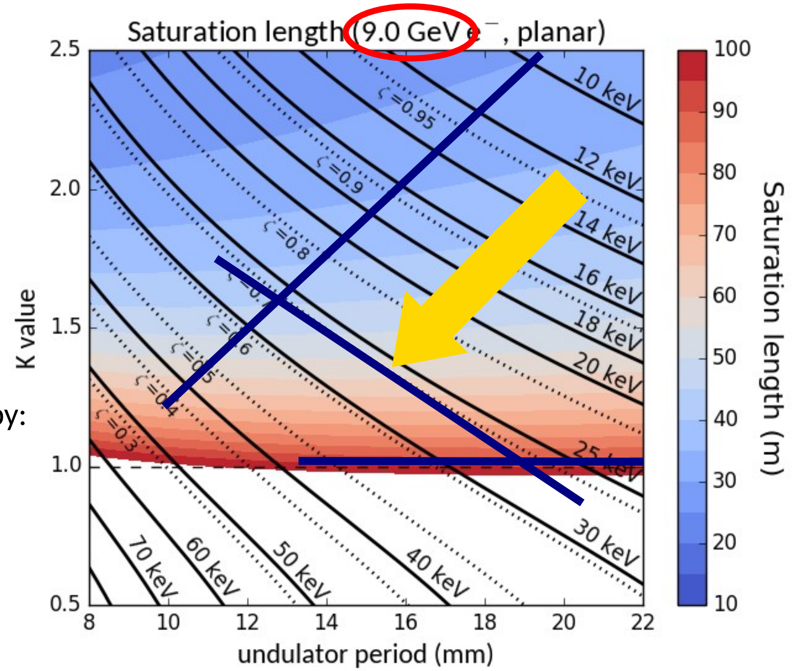

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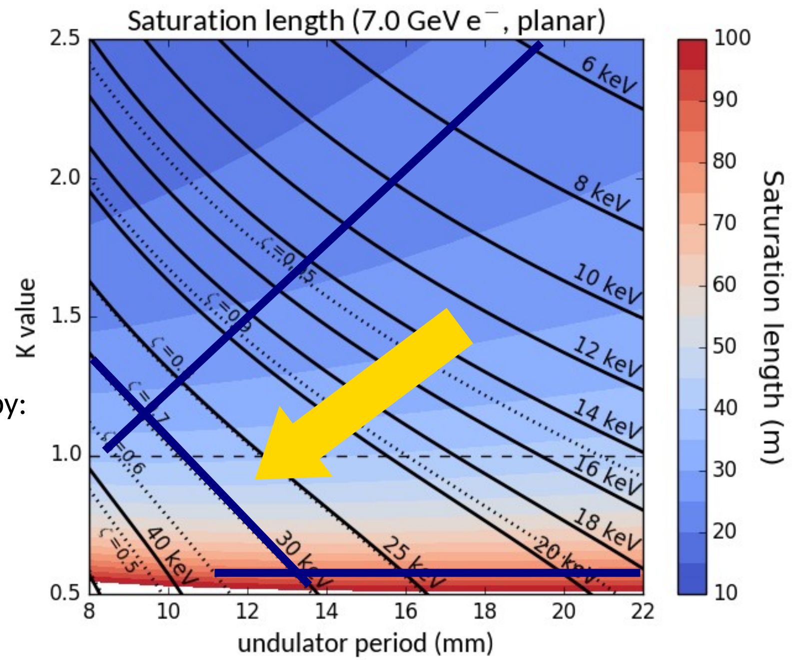
- The main obstacle towards higher photon energies is **the loss of coherence!**

- **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



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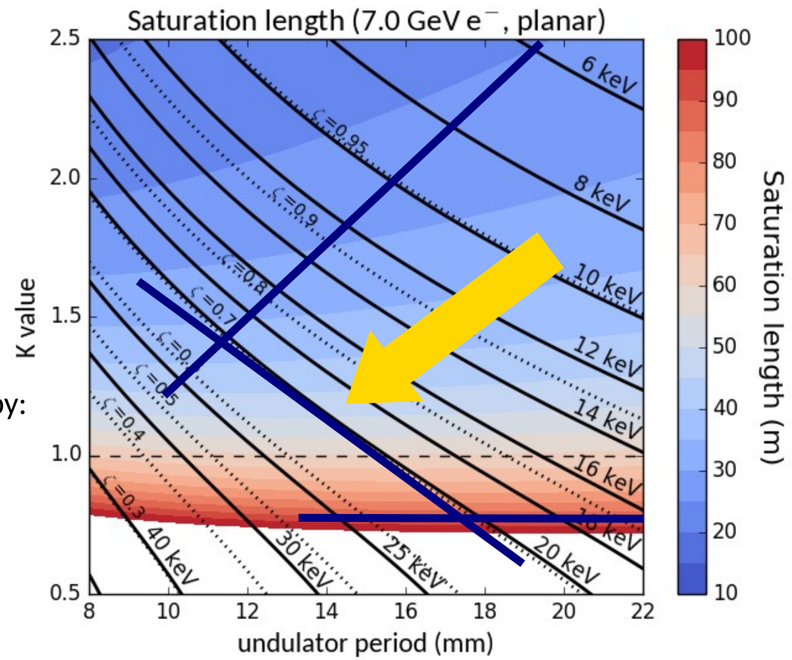

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Electron beam parameters:
I = 2 kA, **ε = 400 nm**, σ_E = 1 MeV, β = 10 m

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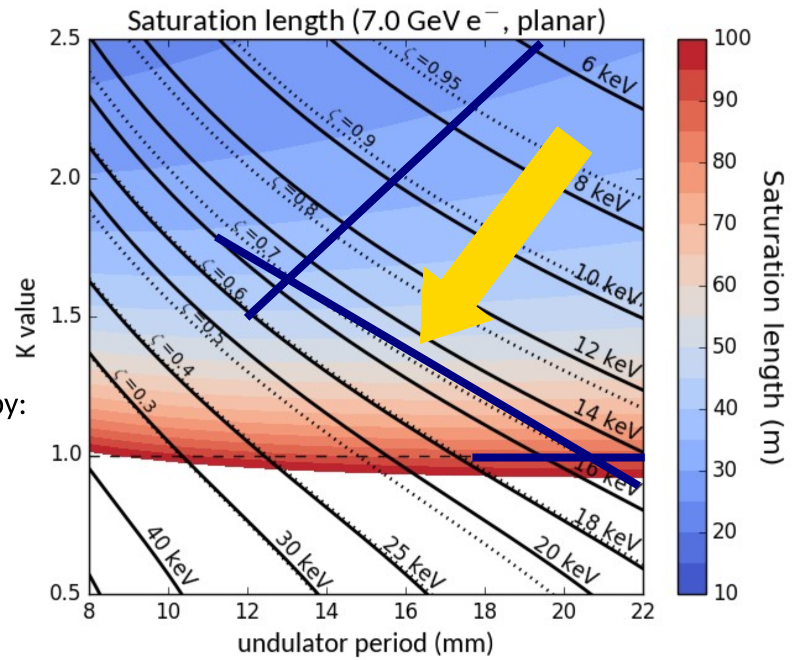

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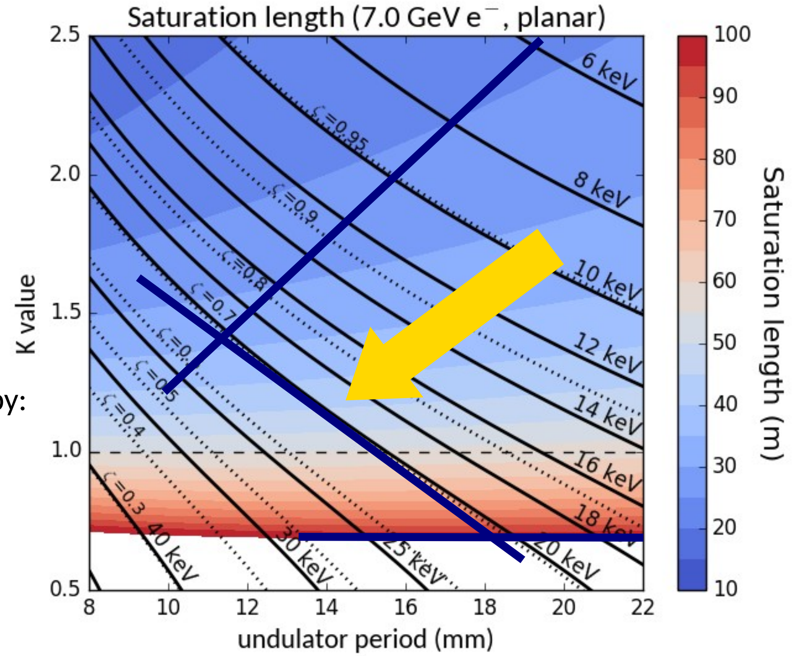
Electron beam parameters:
I = 2 kA, ε = 300 nm, **σ_E = 0 MeV,** β = 10 m

- 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 effect of energy spread is relatively small.**
  (Only affects saturation length, no effect on coherence.)



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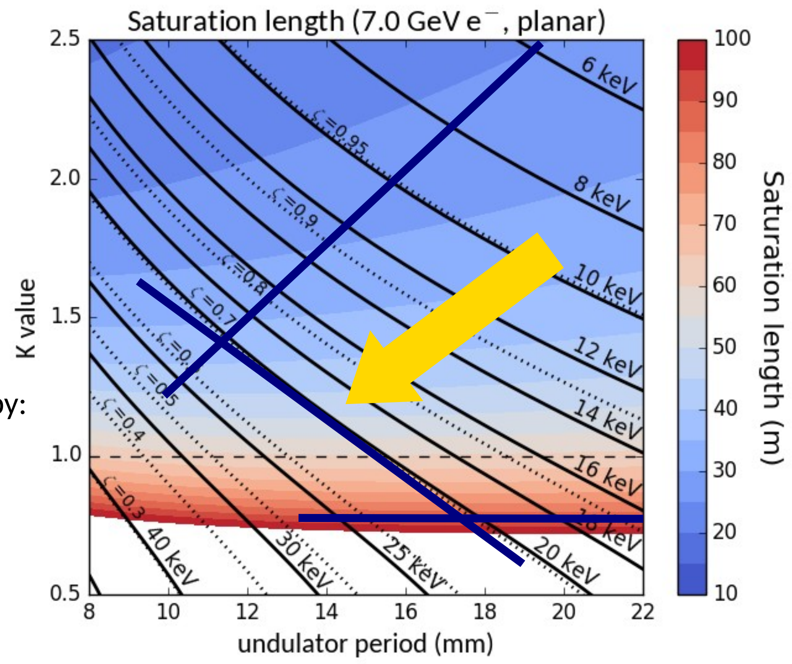

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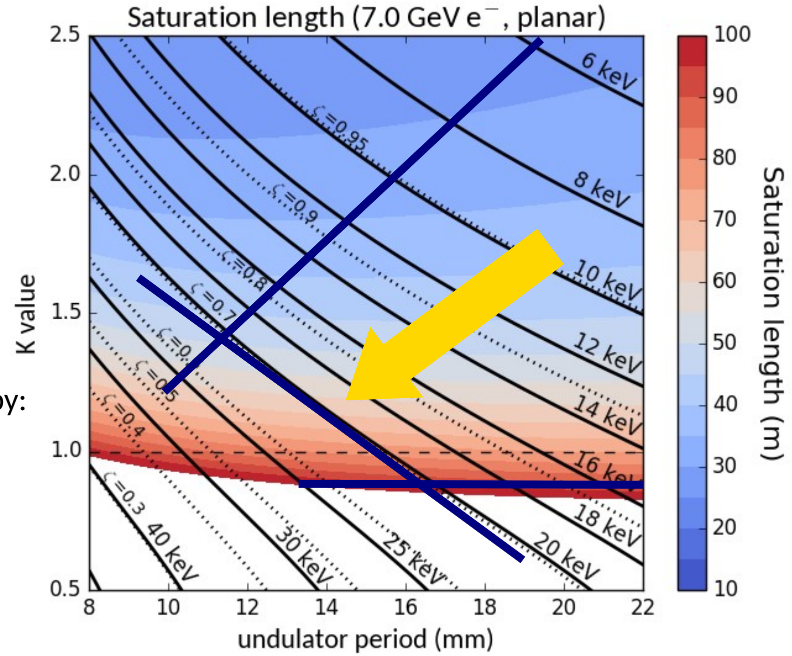
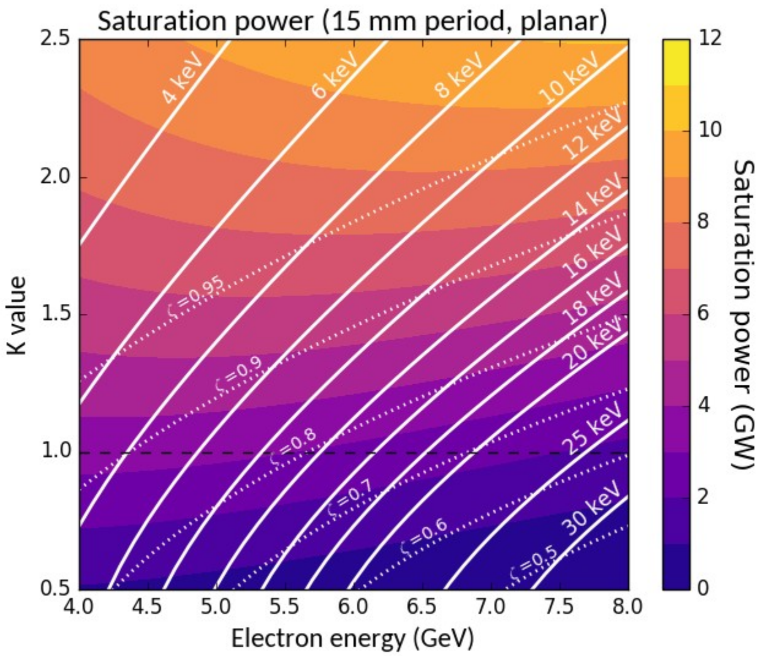


The case for high K

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!



Cryogenic Apple-X with 15 mm period

– a good compromise?

- Can cover 10–20 keV (with polarization control!) at 7 GeV beam energy under the assumption of 300 nm emittance and K values analogous to the SLS cryo U14.
- Lower energies easily accessible with lower photon energies (very low energies may require coordination with Aramis).
- But is it feasible?

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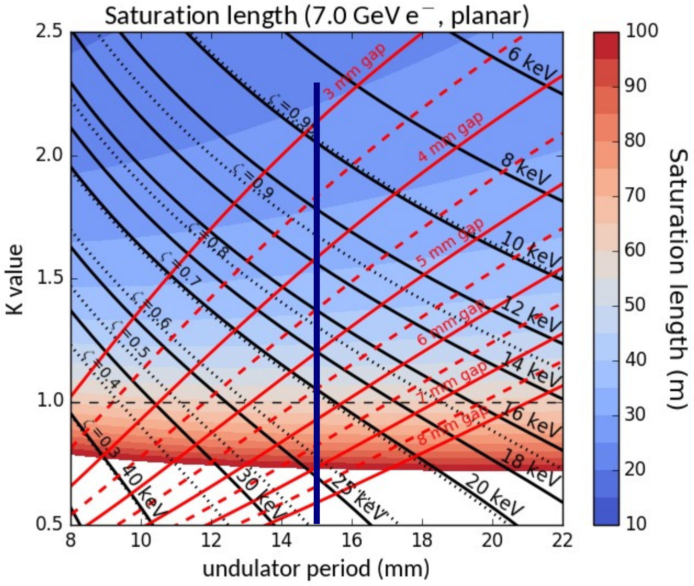
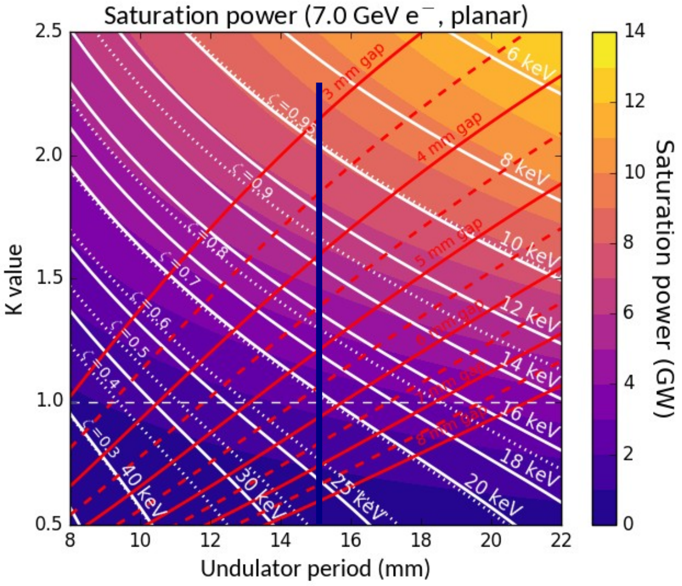
Undulator K vs. gap: cryogenic permanent magnet (example SLS cryo U14, M. Calvi et al., J. Phys.: Conf. Series 425 (2013) 032017)





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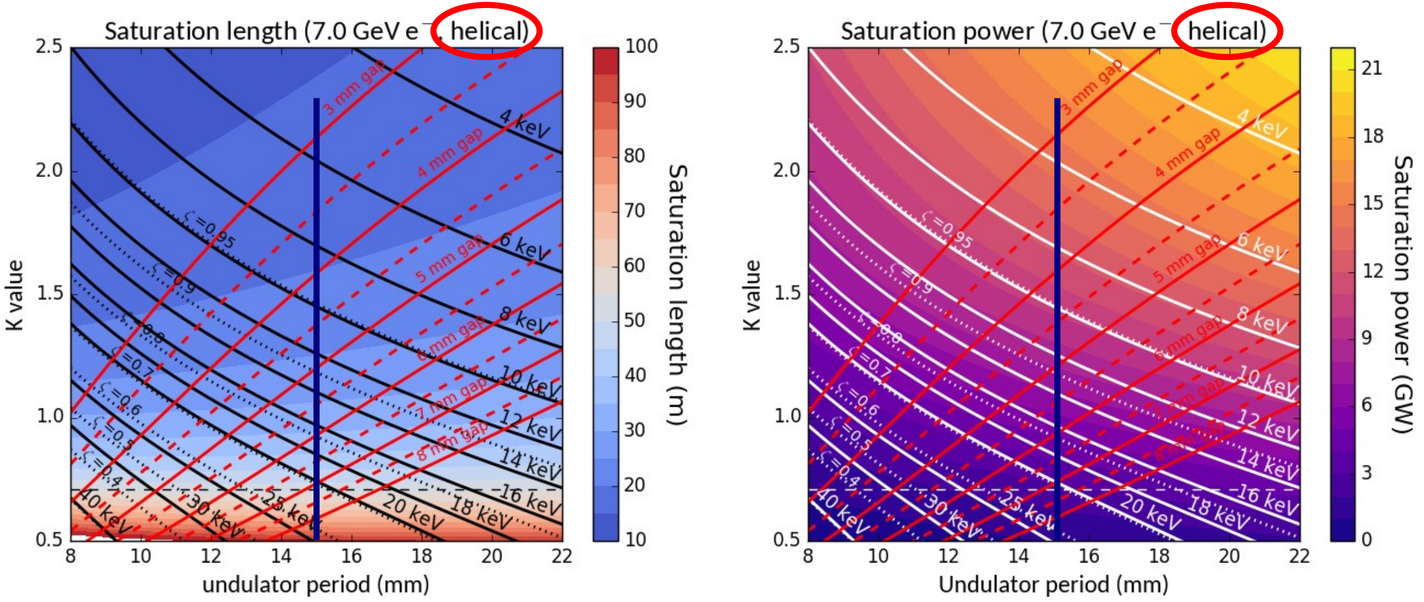

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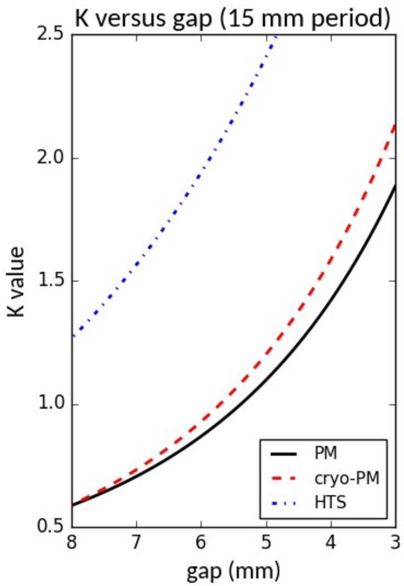

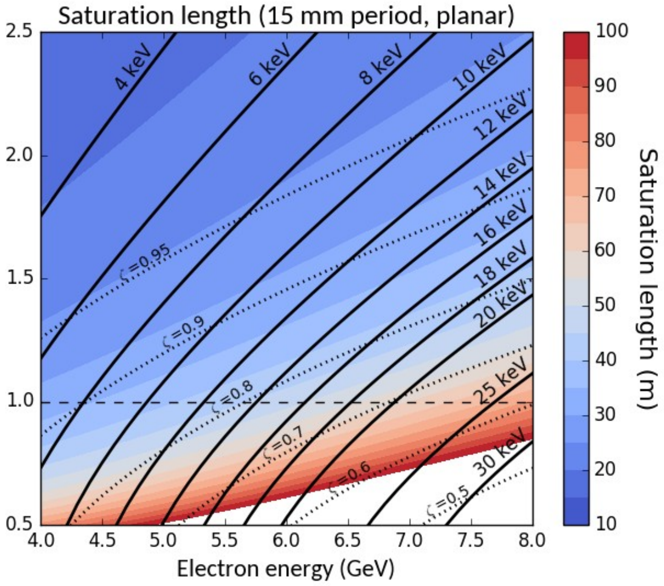

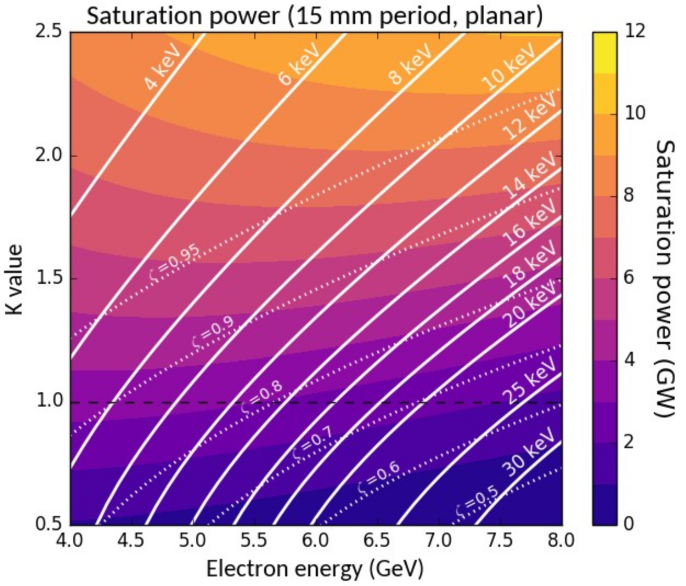

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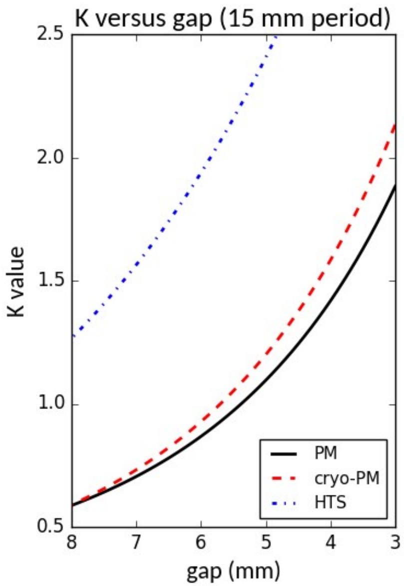
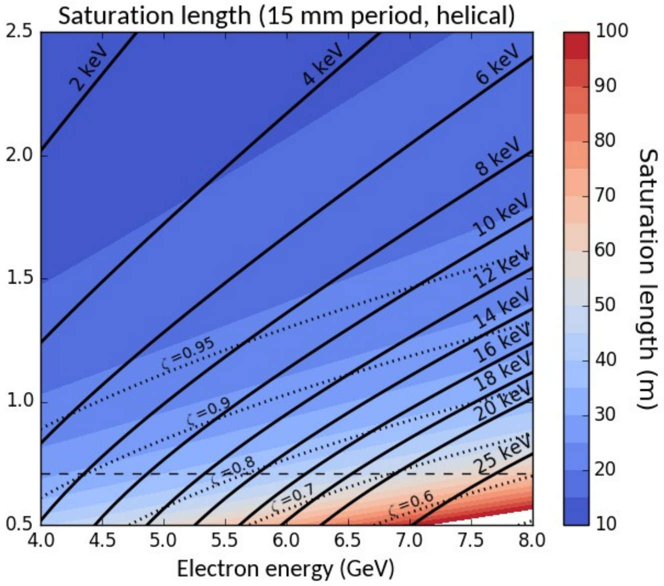
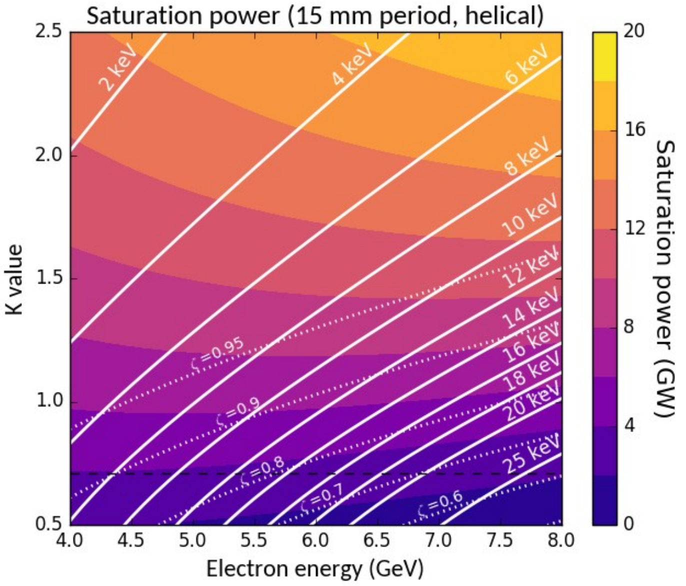


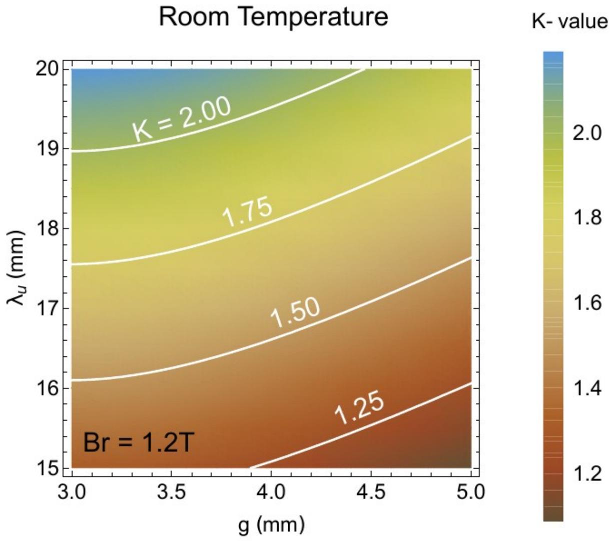


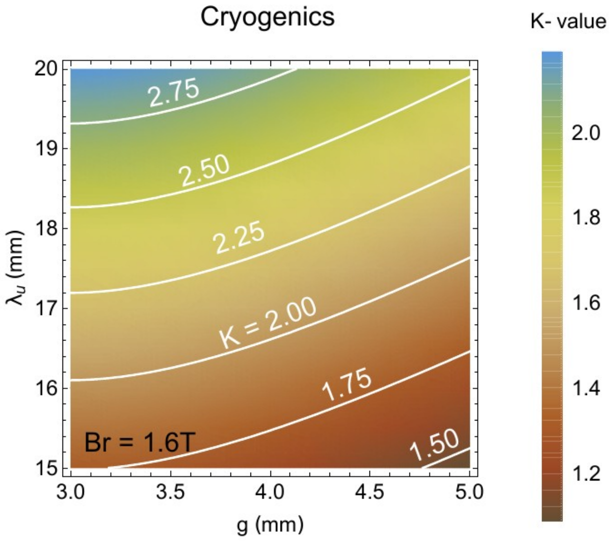


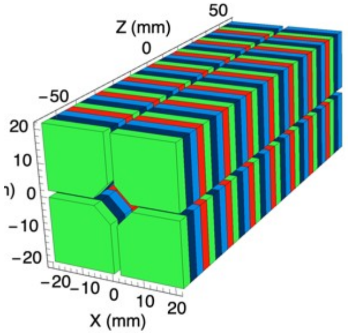
Apple-X 15–20 mm period, calculations

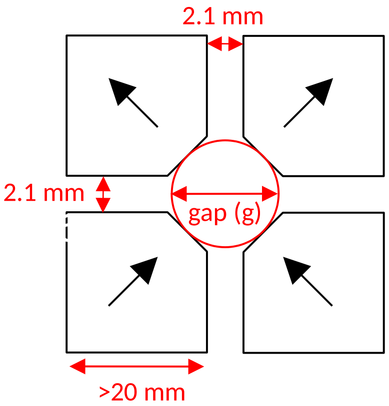
Marco Calvi

- 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…
- Maximum K (at 3 mm gap) would be about 1.35 at room temperature, 1.75 at cryogenic temperature.
- No full parameterization for K(gap) available yet.
- To be pursued in more detail.









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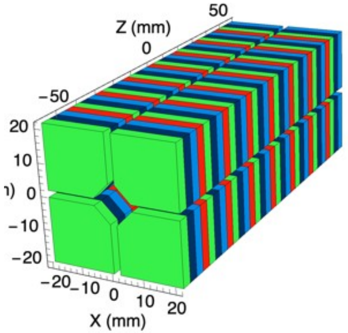
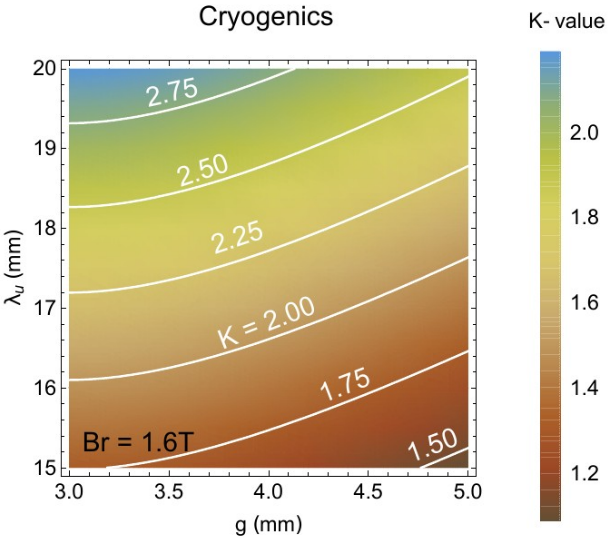
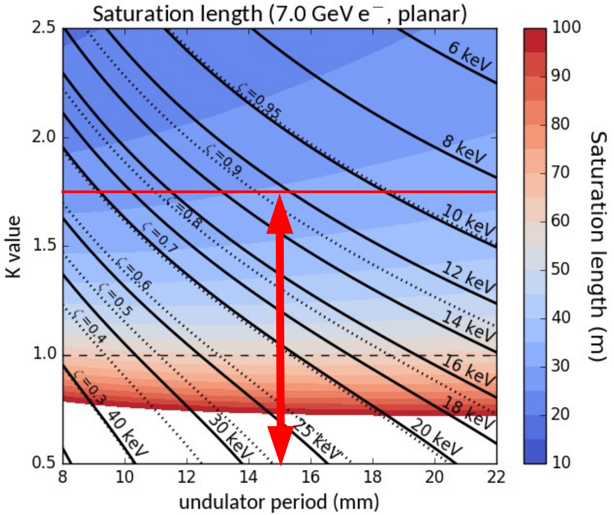
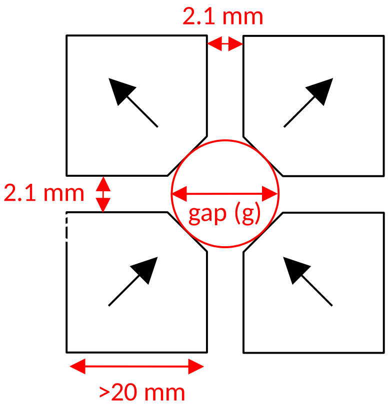
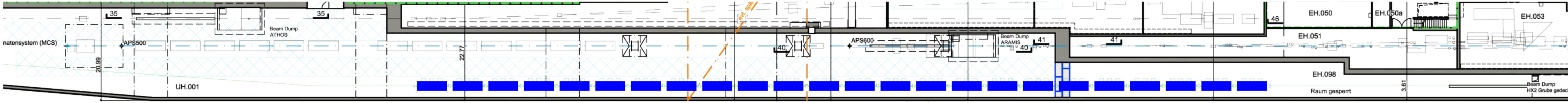








Porthos undulator line: original provision

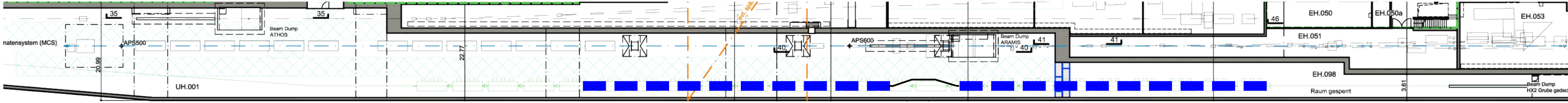


Original provision: 24 × 4.75 m = 114 m undulator line

Beam dump
(7 GeV)

PSI drawing
No. 2R-393601 (2019)

Porthos undulator line: possible configuration



Space for future Porthos linac
(e.g. X-band) or
beam manipulation devices

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

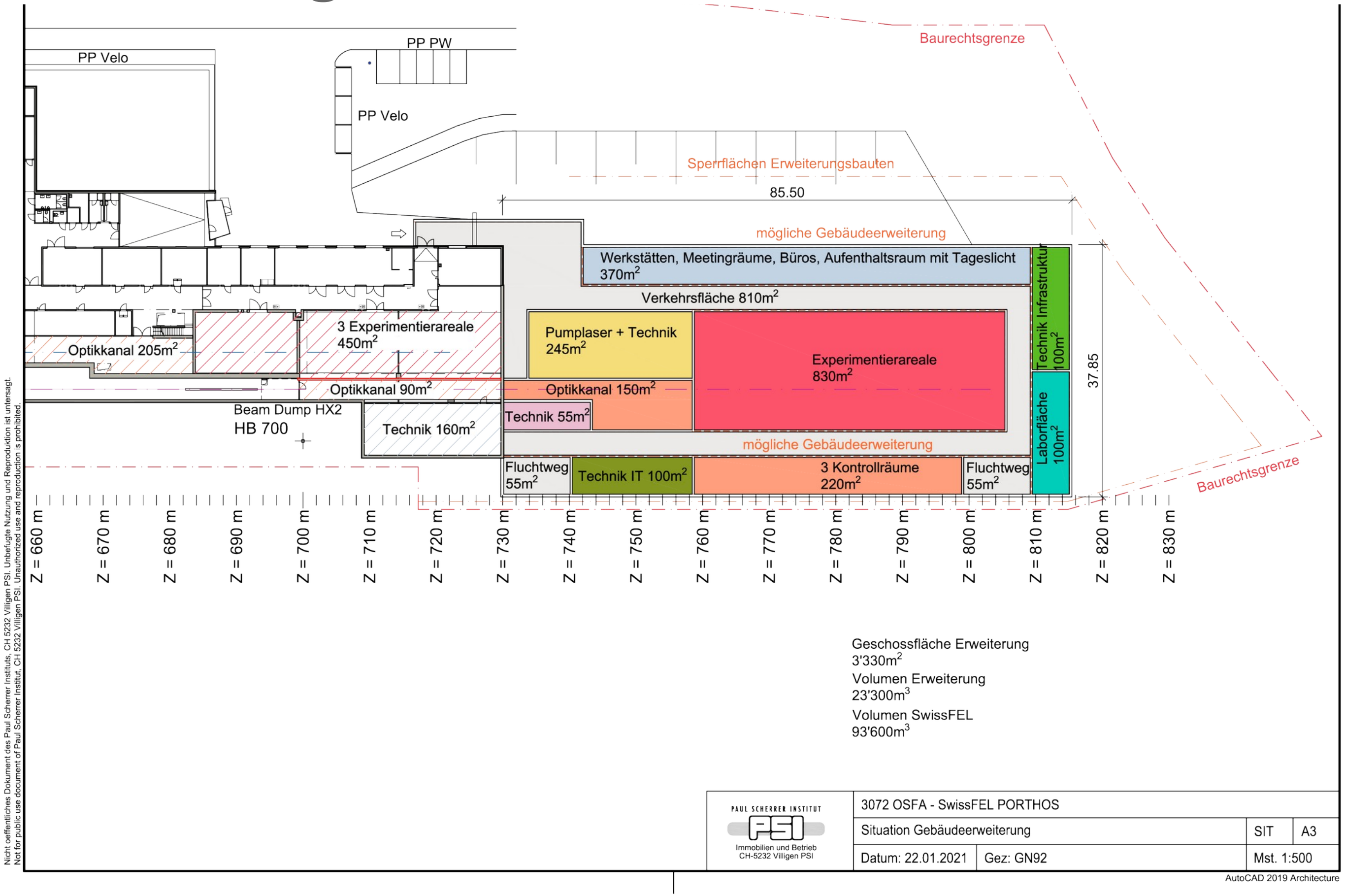
Beam dump
(7 GeV)

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 m3 (about 35% of existing OSFA!)
- First cost estimate is 35–40 MCHF.
- Careful: building costs cannot be changed later!



Very first, very rough budget estimate

- 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** (3 C-band stations, injector upgrades): **9 MCHF**
  - **Electron beamline components** (vacuum, diagnostics etc.): **5 MCHF**
  - **Machine total: 50 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: 125 MCHF

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Conclusions

- **Rough baseline concepts** identified for the three main parts of the Porthos machine:
  - **Resonant kicker** for bunch separation: faster kicker with 21 ns bunch spacing
  - **Linac upgrade:** 3 additional C-band stations in linac-3 and Porthos arm, injector upgrade
  - **Undulator:** 60 m of 15 mm Apple-X undulators
- With this, can start designing a 100-Hz, 7-GeV machine delivering 4–18 keV, maybe 20 keV photons, with **full polarization control.**
- **Feasibility of Apple-X undulators** (with stringent field quality requirements at hard X-rays) still to be demonstrated.
  - Therefore fall-back solution with planar undulators and phase retarder.
- Very first **budget estimate** based on main components costs: **120 MCHF** – a reasonable envelope?
- Note: The only robust way to reach higher photon energies is by increasing the electron energy!
  - Starting at 6 GeV, *SwissFEL will never be competitive in that area!* (It was not our goal.)
  - SwissFEL Porthos will be **unique** in terms of **polarization control** up to very high photon energies.

Next steps (roadmap process)

- Tonight (16:30): **meeting with directorate** to discuss RI priorities for PSI
  - SwissFEL Porthos or TATTOOS/HIMB, or both?
- early March 2021: **Internal deadline for PSI evaluation** (two-page fact sheet with supporting material)
- 21 April 2021 **ETH council meeting:** first discussion of project ideas.
  ⇒ for this a two-page fact sheet is needed! (close to what actually goes into the roadmap)
- early July 2021 **ETH closed session** ("Klausur"): in-depth discussion of projects
- September 2021 **Notification of SNF** on ETH projects planned for the '23 roadmap
- January 2022 **Submission of final requests to SNF for evaluation**

Roadmap process (general)

- The process towards the roadmap 2023 is expected to be very similar to the process that led to the last roadmap (2019).
- From the “Leitfaden” to the roadmap 2019, as well as an SBFI communication from 3 Feb. 2020, we may infer the following timeline (translated to the 2025–28 ERI period):

Phase	Date	Procedural steps
Preparatory phase	during 2020	SCNAT prepares discipline specific roadmaps
	Dec. 2020–Feb. 2021	SERI prepares the roadmap process.
Phase I	March–Dec. 2021	First assessment by ETH board and swissuniversities for facilities in their respective areas – requires a **two-page fact sheet**
Phase II	Jan.–Aug. 2022	Scientific evaluation by SNF – requires a **conceptual design report!** Only the highest ranked facilities proceed to the next level
Phase III	Jan.–Dec. 2022	In-depth assessment of technical and financial feasibility, again by ETH board and swissuniversities for their respective facilities
Phase IV	Jan.–Aug. 2023	SERI finalizes the roadmap report and presents it to the federal council.
Decisions	Dec. 2024	Federal council presents ERI dispatch with recommended support for facilities to parliament, which votes on the dispatch. (The decision to actually build or upgrade a facility still rests with the ETH board or swissuniversities.)
Implementation	2025–2028	Realization by ETH institutions / universities

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Thank you