PAUL SCHERRER INSTITUT

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Input from M. Calvi, S. Reiche, E. Prat

# Pathways to high photon energy

Porthos Machine Working Group Meeting, 15 December 2020

# Porthos requirements

- Gabriel Aeppli made it clear at the last SSB that Porthos must provide polarized light up to 12 keV
  - This requires a scaled APPLE-X undulator
  - Assumption is that the Athos undulator can be scaled to 20 mm period – to be verified! (Marco?)
- At the same time the majority of the photon science users ask for high photon flux at higher photon energies (at least 20 keV, better 25 keV)
  - A 20 mm APPLE-X cannot reach energies much above 12 keV.
  - We need a second undulator line to cover the high end of the photon energy spectrum.
  - It may profit from the first line as a subharmonic seed.
  - **How to find the best undulator period / technology for the second line?**

# Machine design options

Original approach:

- Machine design pursues three main options, all based on a linac extension to reach 7 GeV electron energy in both Aramis and Porthos branches (S. Reiche and team):
  - **APPLE-X undulator**
  - **HTS undulator technology**
  - **APPLE-X undulator with HTS afterburner**

*$\lambda_U$=2 cm, $K_{max}$=2, E = 7 GeV*

***Fundamental up to 13 keV, 3rd harmonic up to 22.5 keV***

*$\lambda_U$=1.5 cm, $K_{max}$=4, E = 7 GeV*

***Fundamental up to 19 keV, 3rd harmonic up to 27 keV***

*$\lambda_U$=2 cm, $K_{max}$=2, E = 7 GeV*

*$\lambda_U$=1.0 cm, $K_{max}$=2.5, E = 7 GeV*

***Up to 30 keV***

# 2-stage configuration

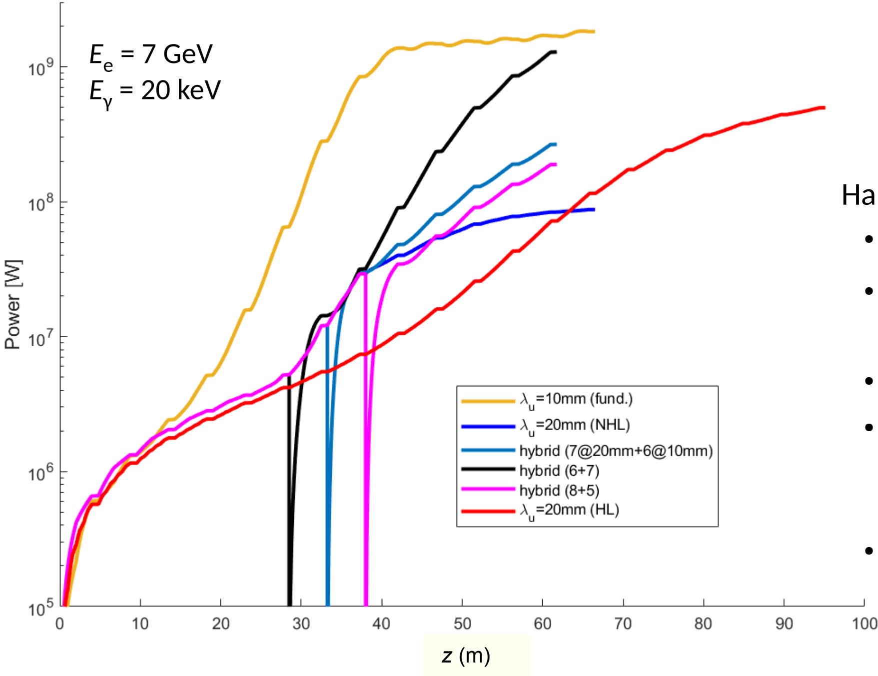
Electron beam parameters: E = 7 GeV, I = 2 kA,
Q = 200 pC, ε = 300 nm, $\sigma_E$ = 1 MeV

E. Prat

Hybrid setup:

$\lambda_u$ = 20 mm, K = 2.18 (6.9 keV)
“Athos” type

$\lambda_u$ = 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 $\lambda_u$ = 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).

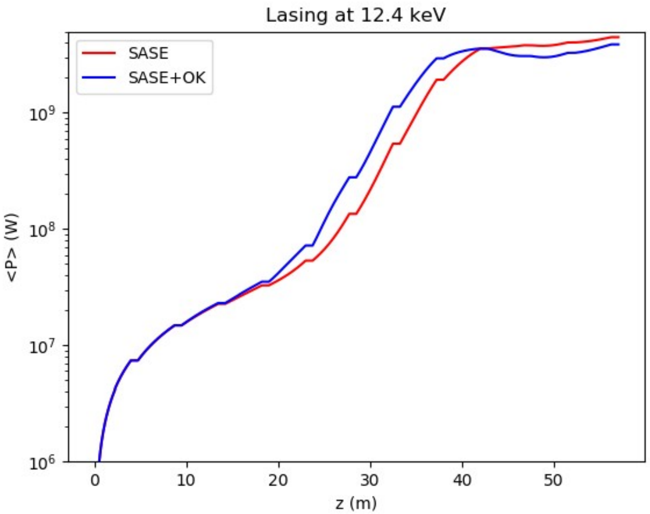
# Single-stage configuration

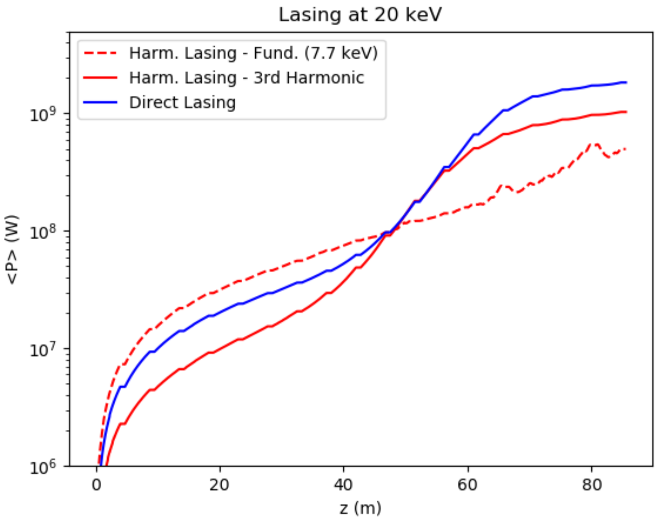
S. Reiche

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

$\lambda_u$ = 15 mm, K = 1–2.5
“Aramis” type

- CHIC between undulators (75 cm every 4 m)
- Optical klystron effect not helping a lot (conservative assumption for energy spread)
- Saturation after 40 m (12.4 keV) or 80–90 m (20 keV).
- In the case of 20 keV no gain from harmonic lasing (saturation length, maximum power)

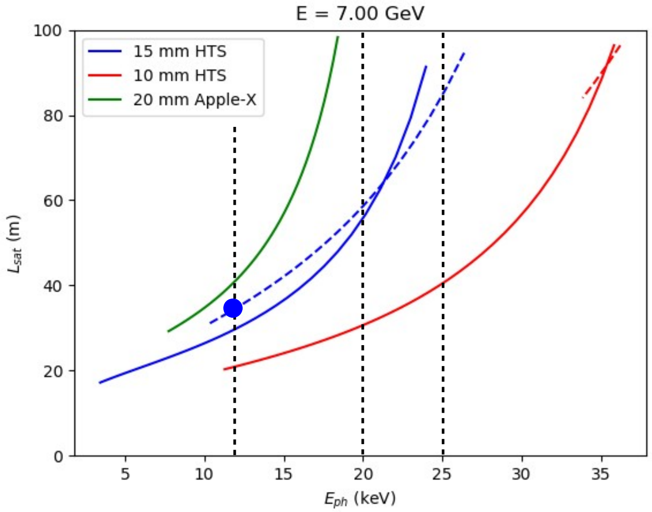




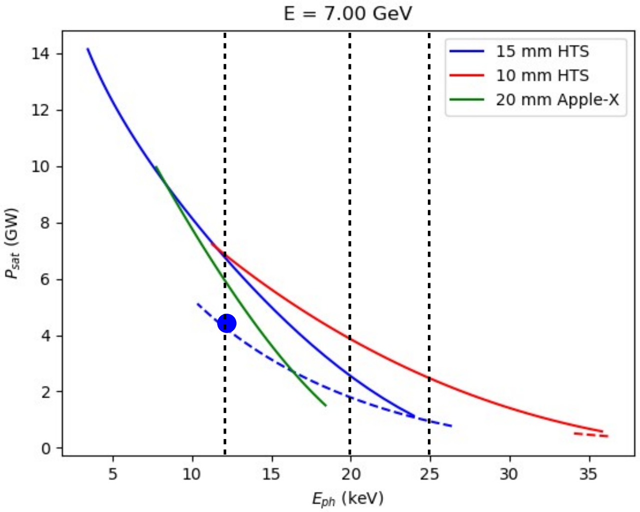
# Ming-Xie estimates for $E = 7$ GeV

S. Reiche

## Saturation length:



## Saturation power:



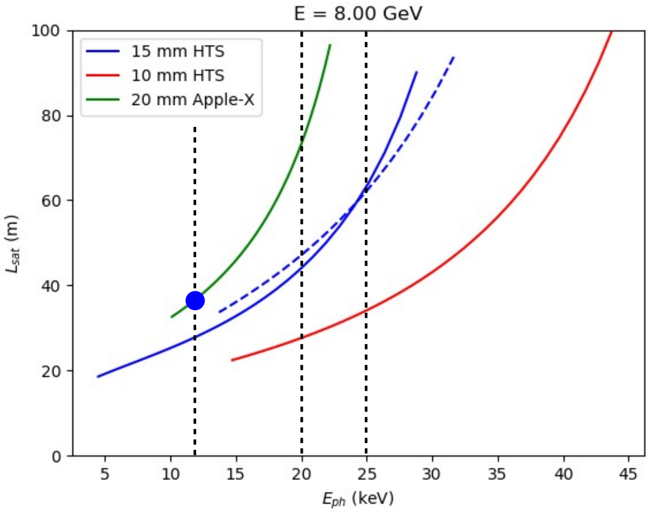
- Dashed lines: with harmonic lasing (some potential for HTS 15 mm at very high photon energies!)
- Gain length does not include drifts (e.g. for CHIC) → effective length about 20% longer

● Aramis now (with 6 GeV): 36 m, 4.5 GW at 12.4 keV

# Ming-Xie estimates for $E = 8$ GeV

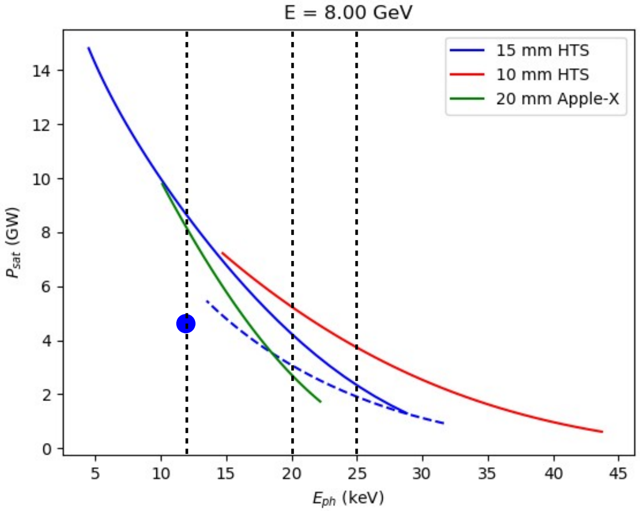
S. Reiche

## Saturation length:



- Dashed lines: with harmonic lasing (some potential for HTS 15 mm at very high photon energies!)
- Gain length does not include drifts (e.g. for CHIC) → effective length about 20% longer

## Saturation power:

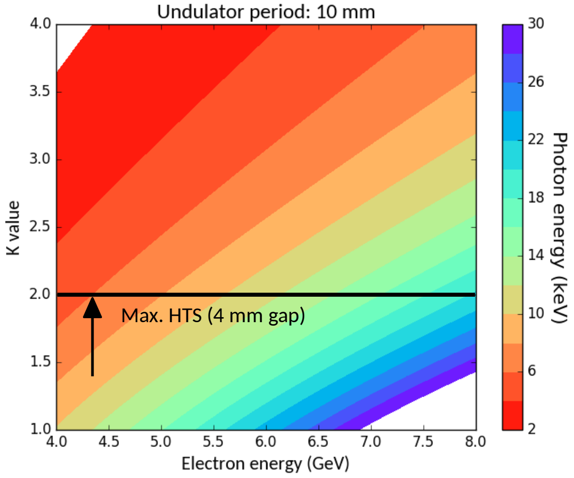


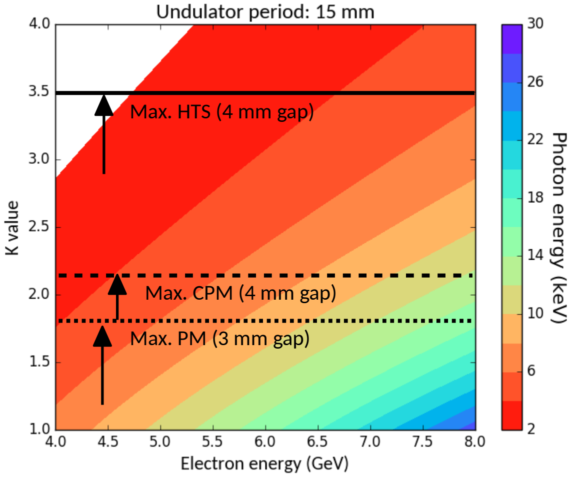
● Aramis now (with 6 GeV): 36 m, 4.5 GW at 12.4 keV

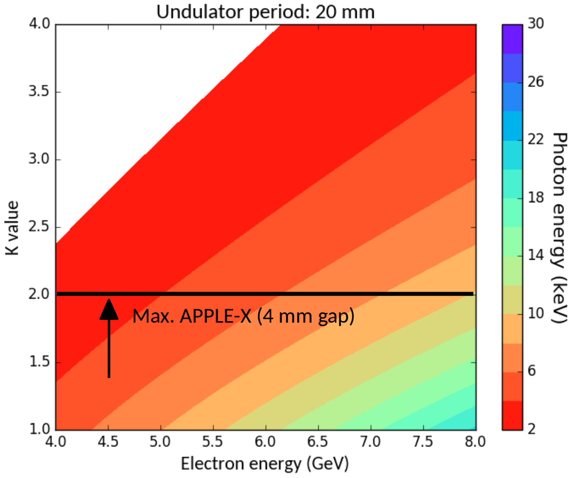
# Undulator types

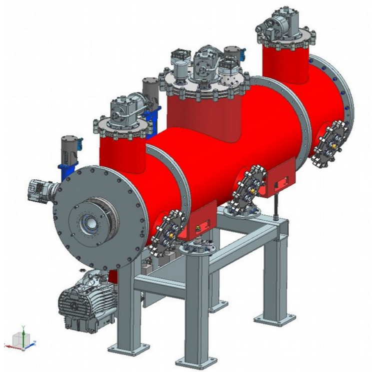
Photon energies 2–30 keV
(equal colors in all plots)

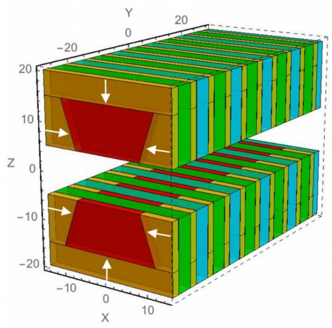
$$E_\gamma = \frac{2hc\gamma^2}{\lambda_u\left(1+\frac{K^2}{2}\right)}$$

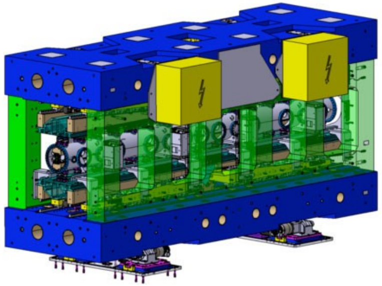


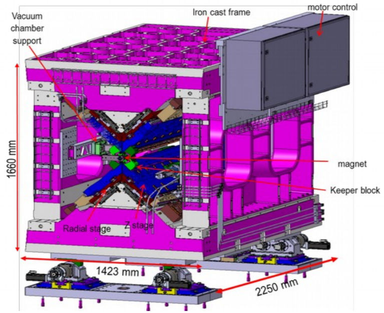












# Reaching high photon energies

$$E_\gamma = \frac{2hc\gamma^2}{\lambda_u\left(1+\frac{K^2}{2}\right)}$$

Photon energies 2–30 keV
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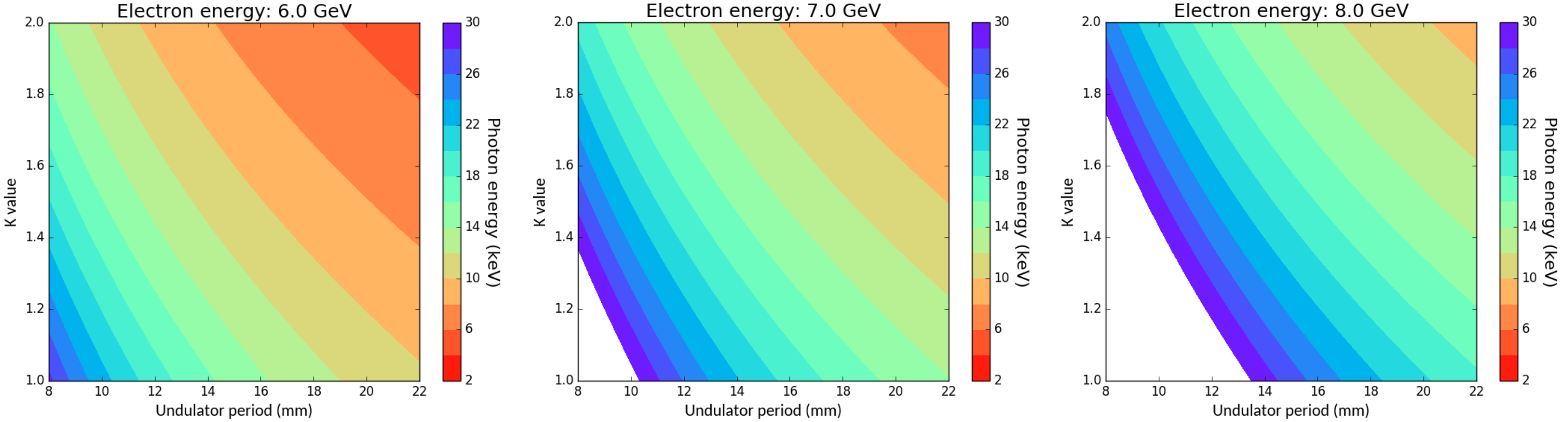

- Higher beam energy brings higher photon energies into reach.

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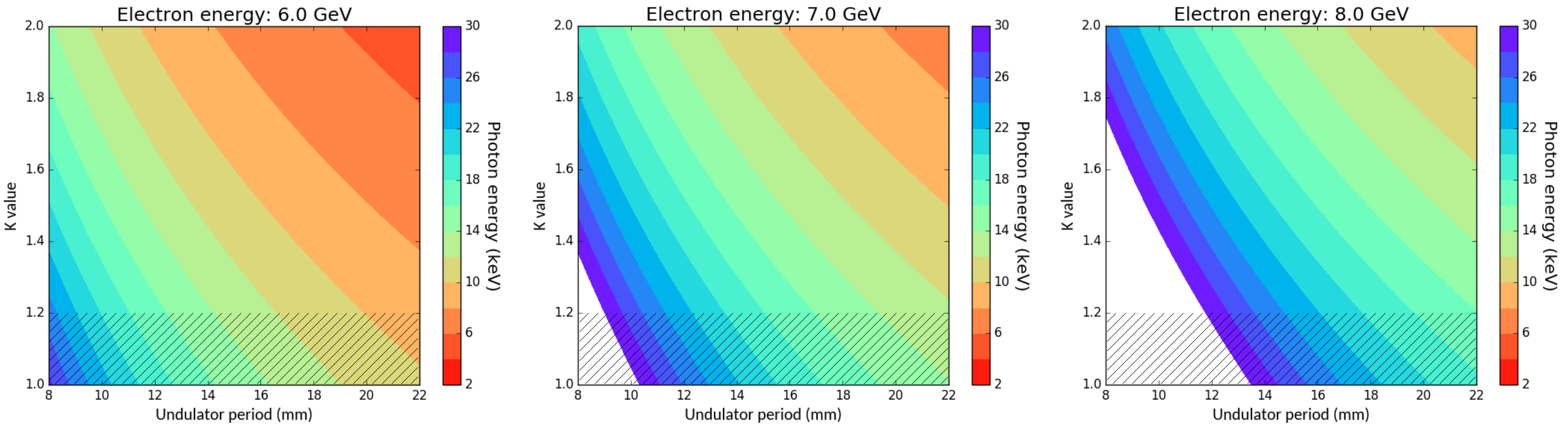


- Higher beam energy brings higher photon energies into reach.
- Highest photon energy demand low K values, but we should not go below 1.2 (to avoid insufficient coupling of photons to electrons)

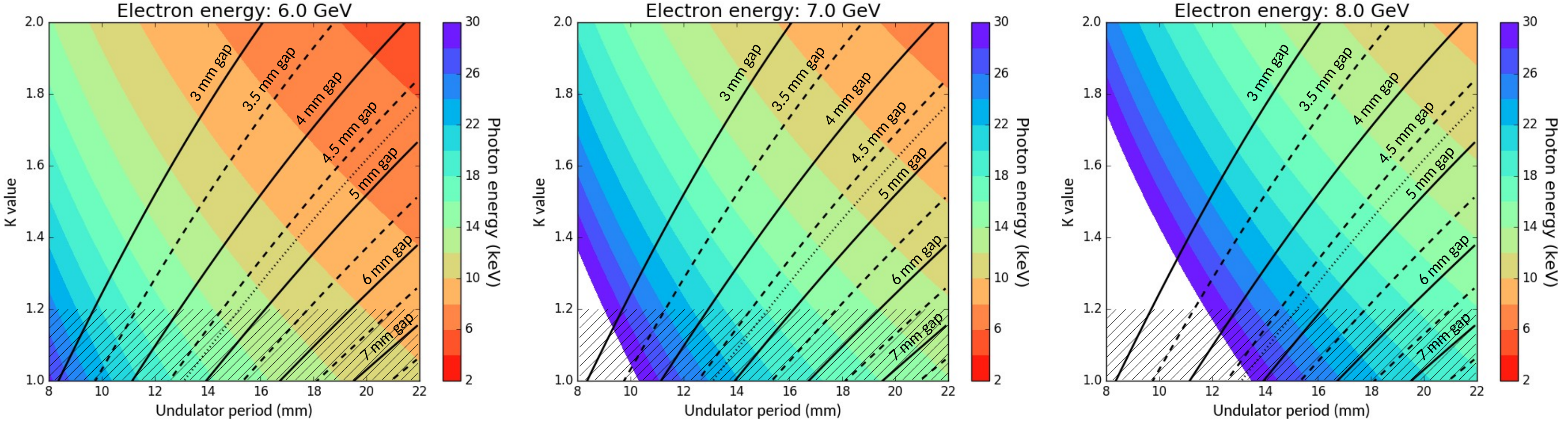
# Reaching high photon energies

$$E_\gamma = \frac{2hc\gamma^2}{\lambda_u\left(1+\frac{K^2}{2}\right)}$$

Photon energies 2–30 keV
(equal colors in all plots)

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

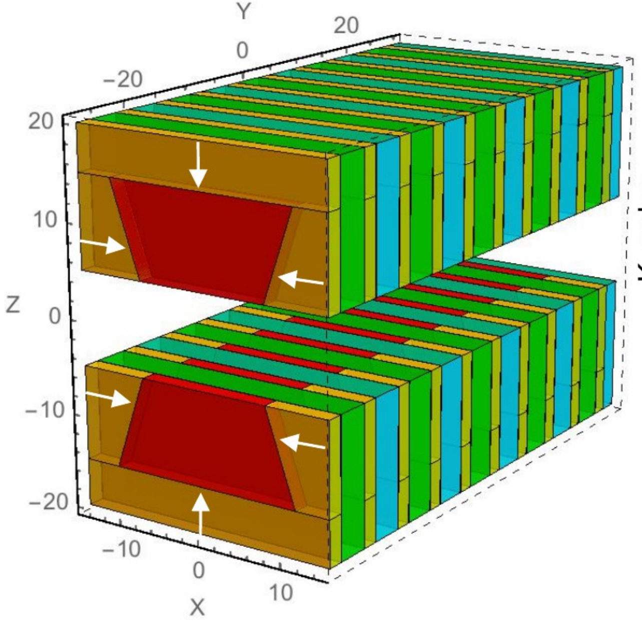
$K_0$, *a*, *b* from J. Synchrotron Rad.(2018) 25, 686-705 (Aramis U15)

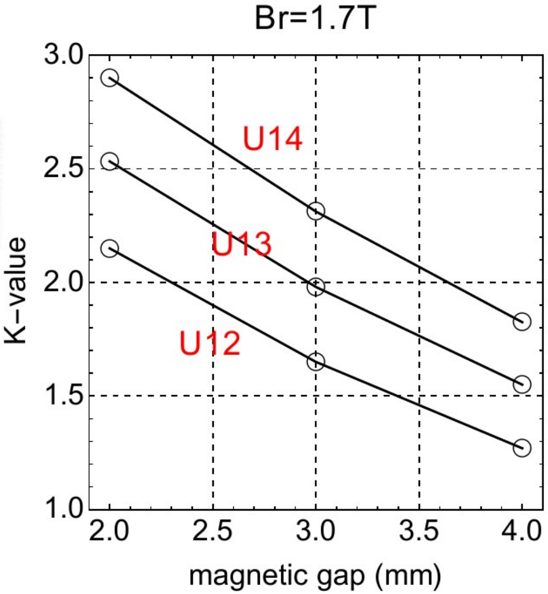


- Higher beam energy brings higher photon energies into reach.
- Highest photon energy demand low K values, but we should not go below 1.2 (to avoid insufficient coupling of photons to electrons)
- The choice of undulator period depends on the K values we can reach at a given period. This in turn depends on the gap we can operate at. Parameterization shown for Aramis U15 undulator.

# Cryogenic Permanent Magnet Undulator – a possible compromise?

Courtesy M. Calvi





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$K_0$, *a*, *b* from J. Phys.: Conf. Series 425 (2013) 032017 (SLS CPMU)

Photon energies 2–30 keV
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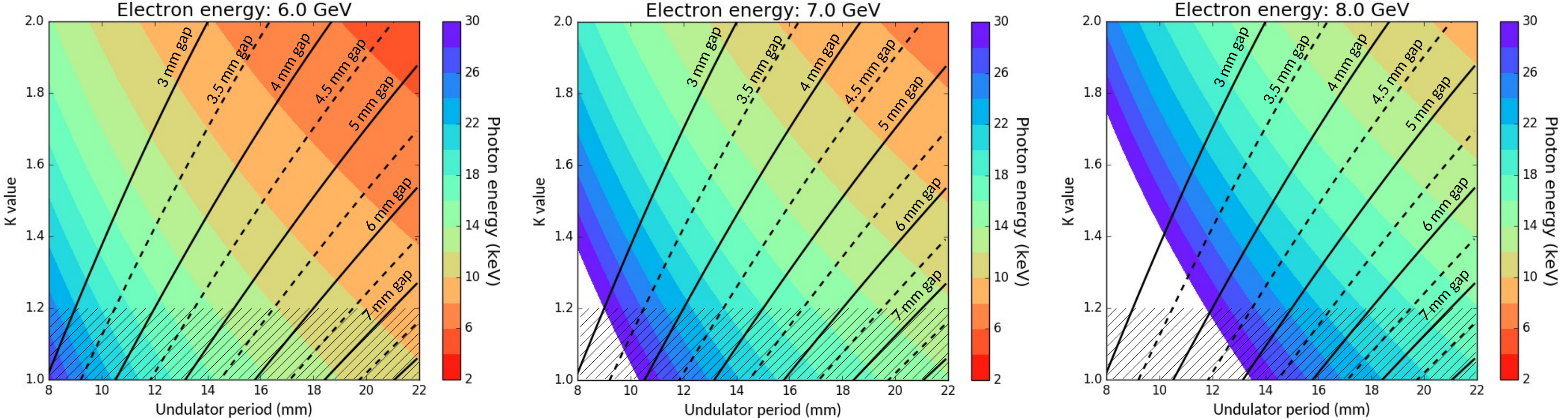

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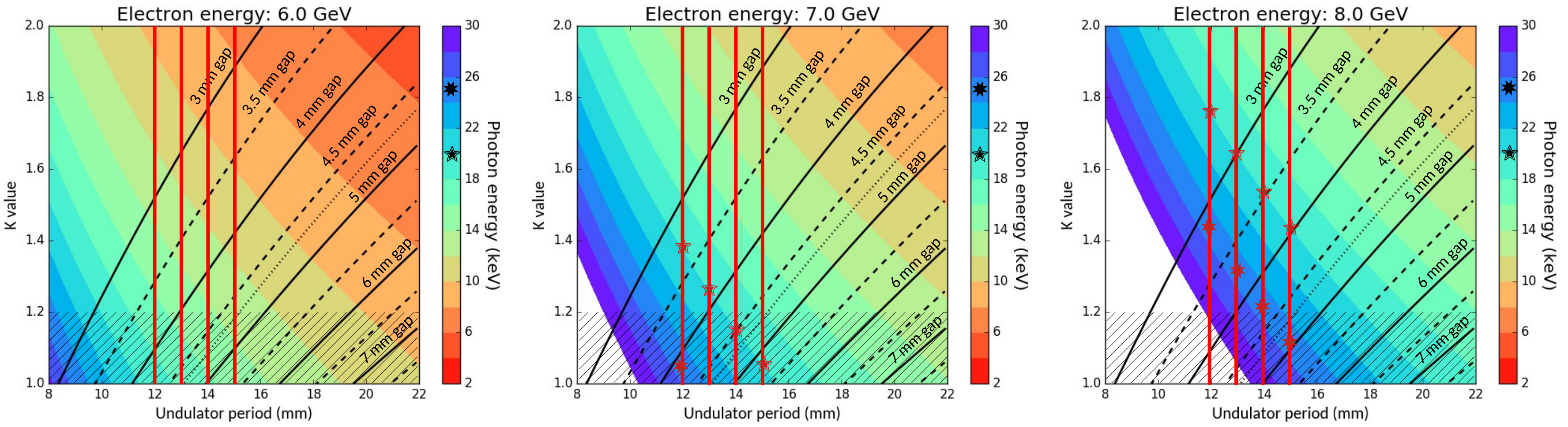

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Possible choices of undulator period (12–15 mm)

Target photon energies:
✭ 20 keV
✷ 25 keV

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Photon energies 2–30 keV
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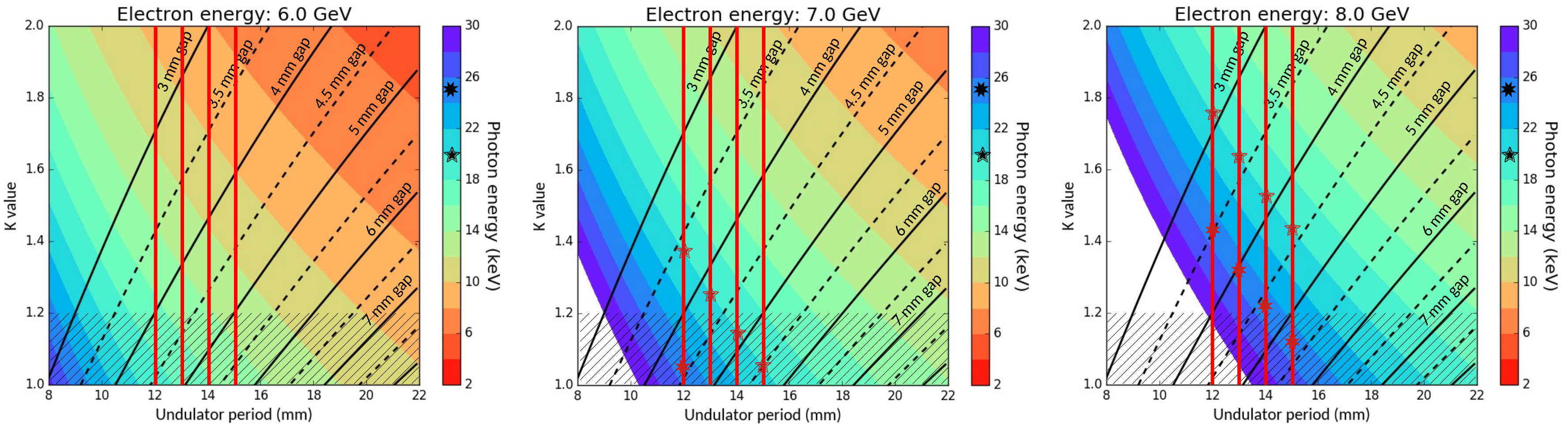

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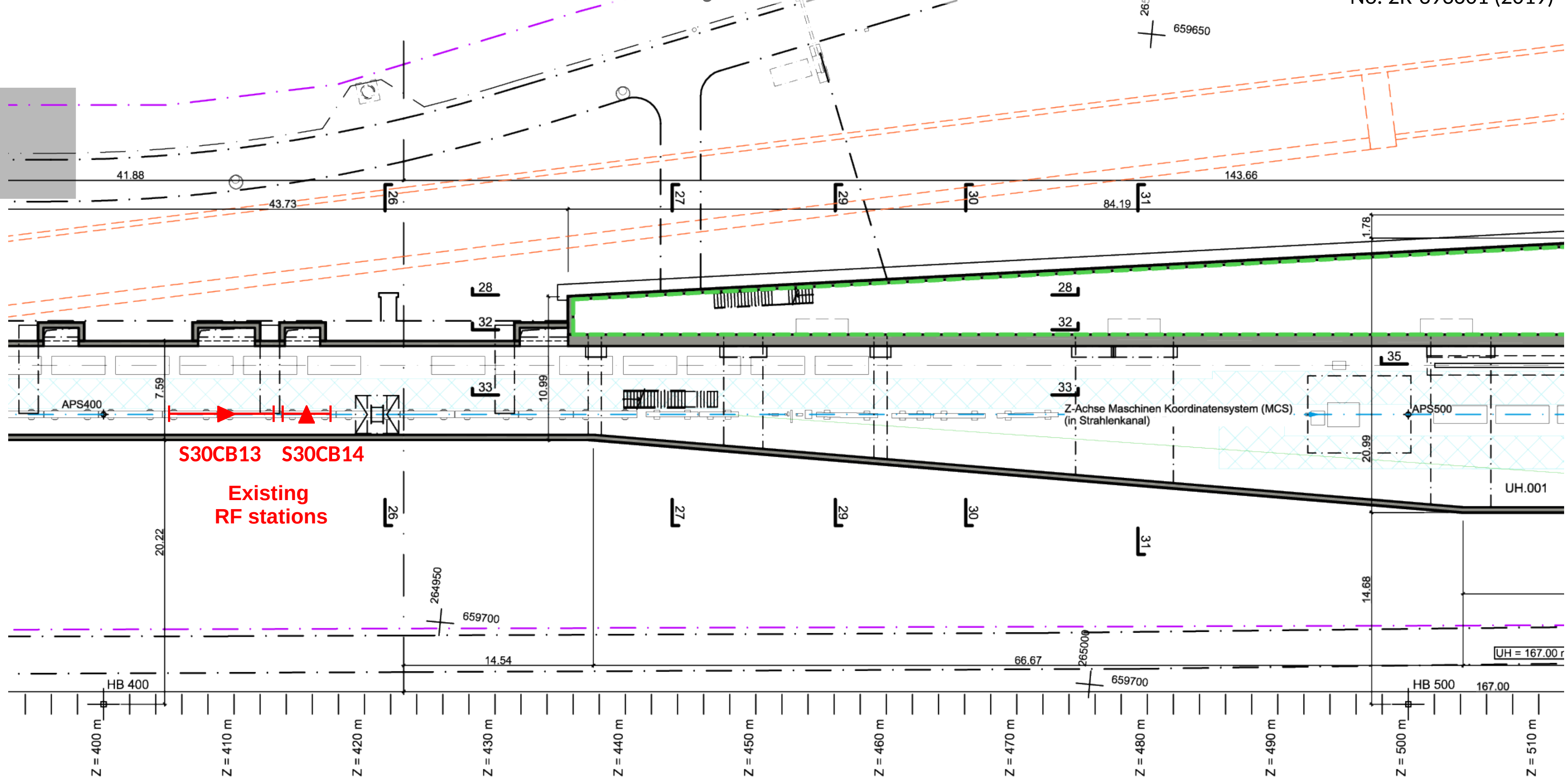
Possible choices of undulator period (12–15 mm)

Target photon energies:
☆ 20 keV
✸ 25 keV

# Porthos switchyard: current situation

PSI drawing
No. 2R-393601 (2019)



**S30CB13** **S30CB14**

**Existing RF stations**

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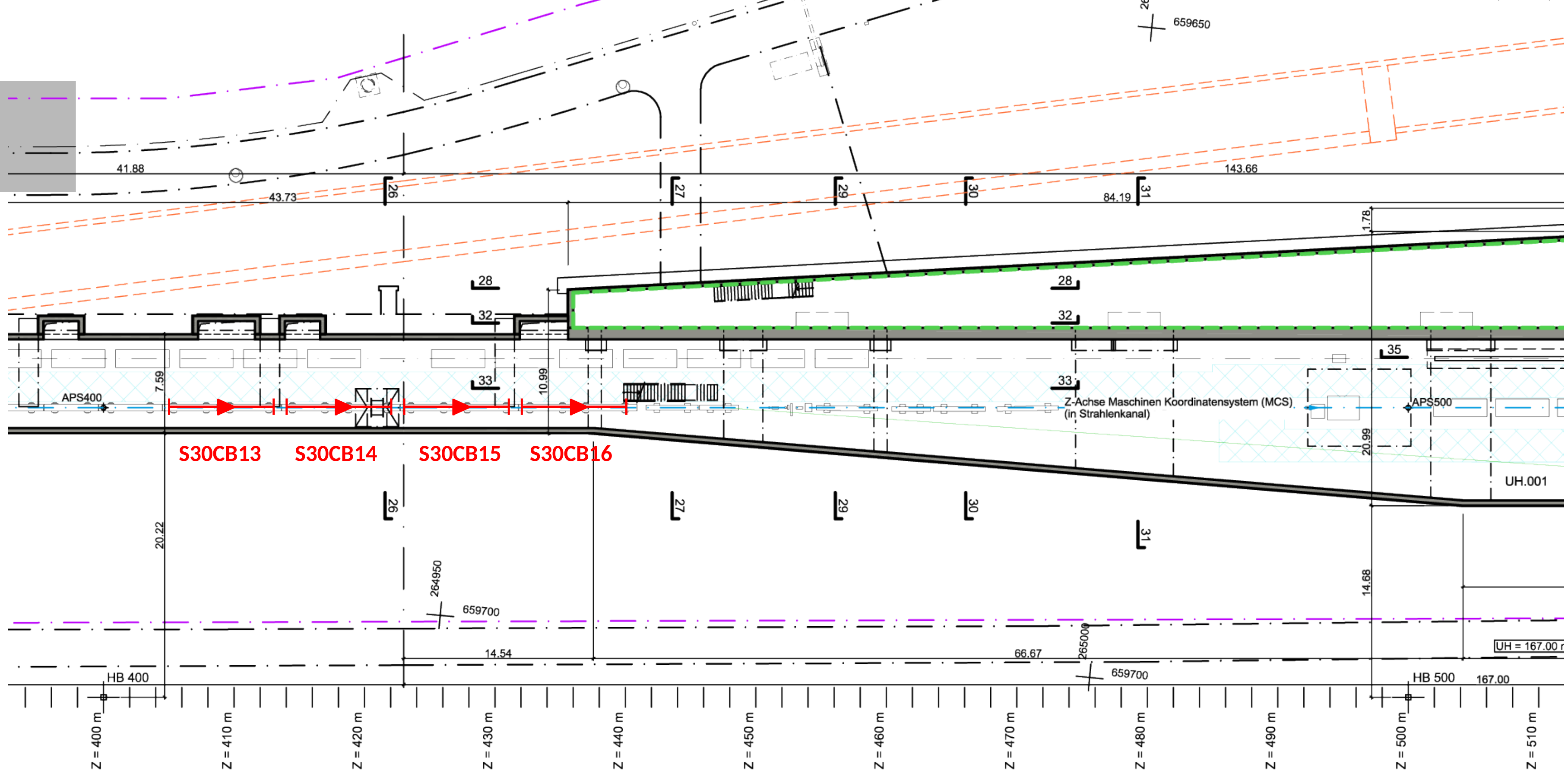
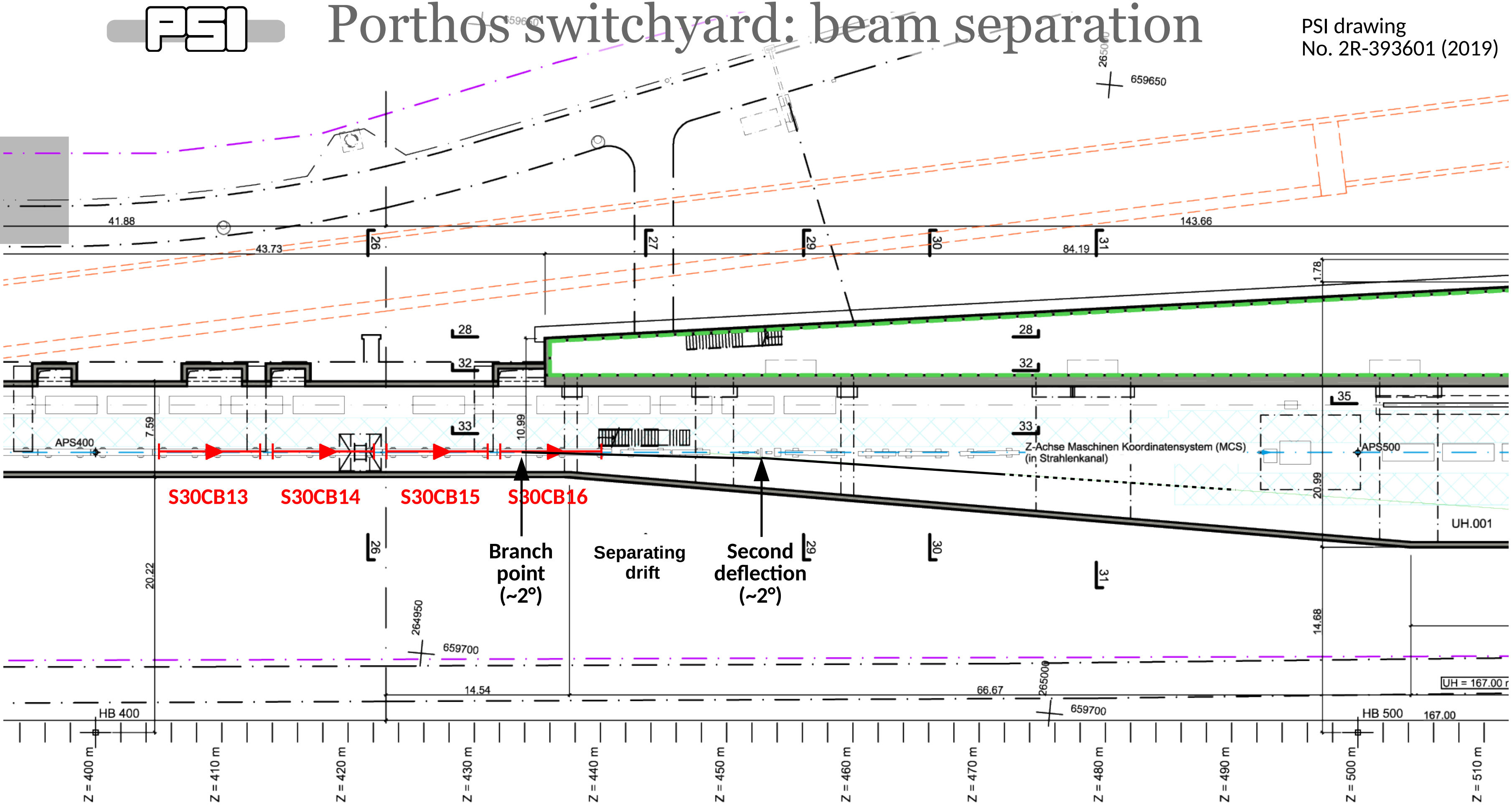
# Porthos switchyard: linac-3 upgrade

PSI drawing
No. 2R-393601 (2019)



# Porthos switchyard: beam separation

PSI drawing
No. 2R-393601 (2019)



**S30CB13** **S30CB14** **S30CB15** **S30CB16**

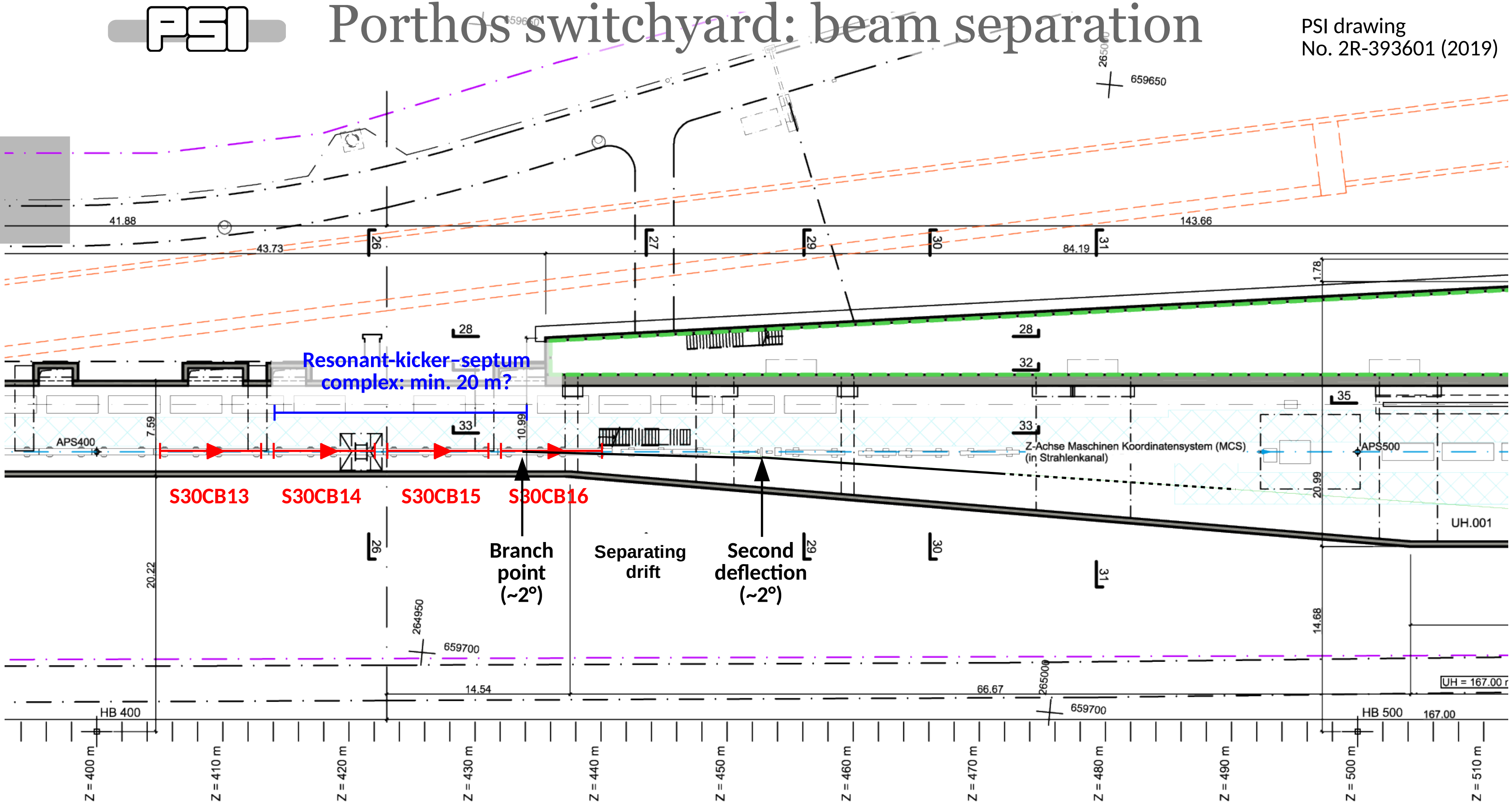
**Branch point (~2°)**

**Separating drift**

**Second deflection (~2°)**

# Porthos switchyard: beam separation

PSI drawing
No. 2R-393601 (2019)



Resonant-kicker-septum complex: min. 20 m?

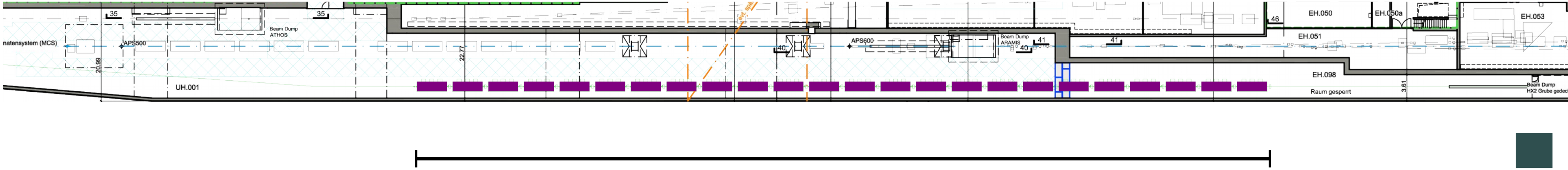
S30CB13 S30CB14 S30CB15 S30CB16

Branch point (~2°)

Separating drift

Second deflection (~2°)

# Porthos undulator line: original provision

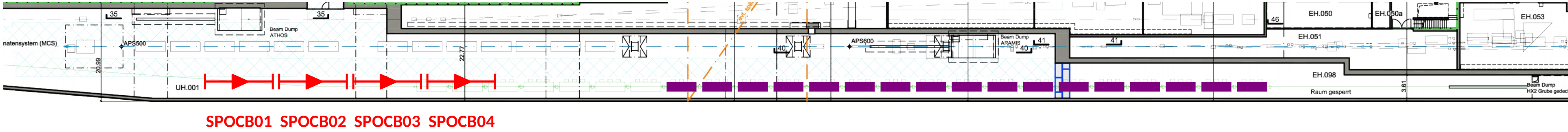


Original provision: 24 x 4.75 m = 114 m undulator line

Beam dump
(7 GeV)

PSI drawing
No. 2R-393601 (2019)

# Porthos undulator line with C-band linac



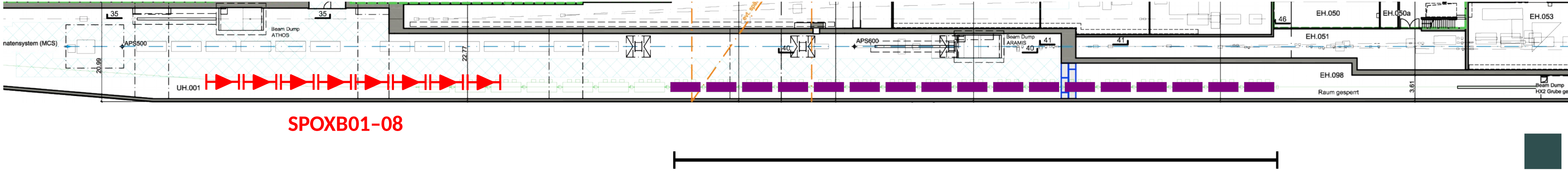
Porthos C-band linac: 6±1 GeV

80 m undulator line (example)

Beam dump
(7 GeV)

PSI drawing
No. 2R-393601 (2019)

# Porthos undulator line with X-band linac



**SPOXB01–08**

Porthos X-band linac: 6±2 GeV??

80 m undulator line (example)

Beam dump
(7 GeV)

- Klystron gallery?
- Beam dump specification?

PSI drawing
No. 2R-393601 (2019)

# Possible decision matrix for upper management

| | 40 m Apple-X 20 mm PM | 40 m Apple-X 20 mm PM<br>+<br>40 m planar 13 mm (C)PM |
|---|---|---|
| **6 GeV** | **Science potential: …**<br>**Price tag: …** | **Science potential: …**<br>**Price tag: …** |
| **7 GeV** | **Science potential: …**<br>**Price tag: …** | **Science potential: …**<br>**Price tag: …** |
| **8 GeV** | **Science potential: …**<br>**Price tag: …** | **Science potential: …**<br>**Price tag: …** |

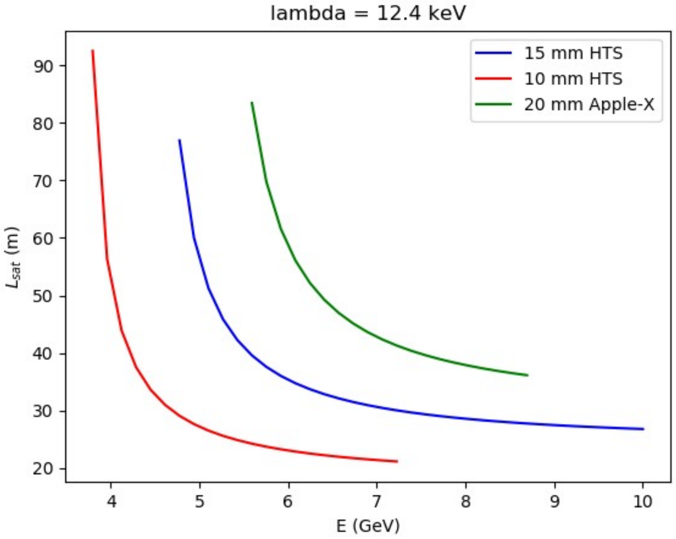
Budget items independent of chosen solution:
- Extra laser with building extension
- Kicker-septum upgrades for three bunch operation
- Experimental hall (building extension)
- Minimal equipment for end stations

# Additional material

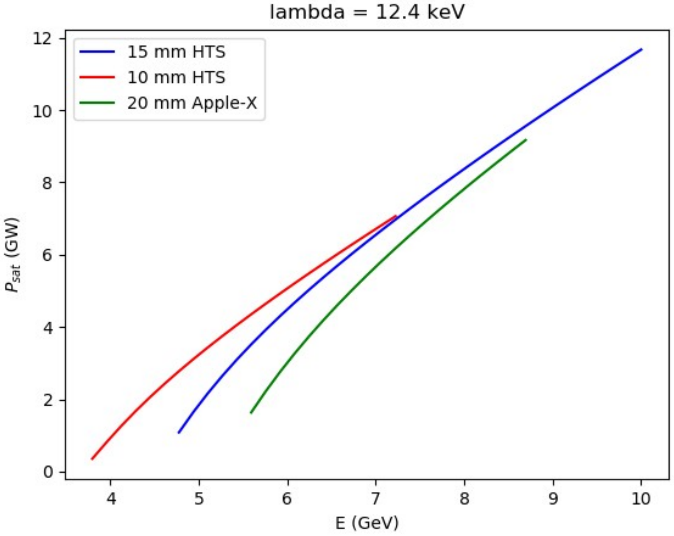
# Ming-Xie studies for $E_\gamma$ = 12.4 keV

S. Reiche

Saturation length:



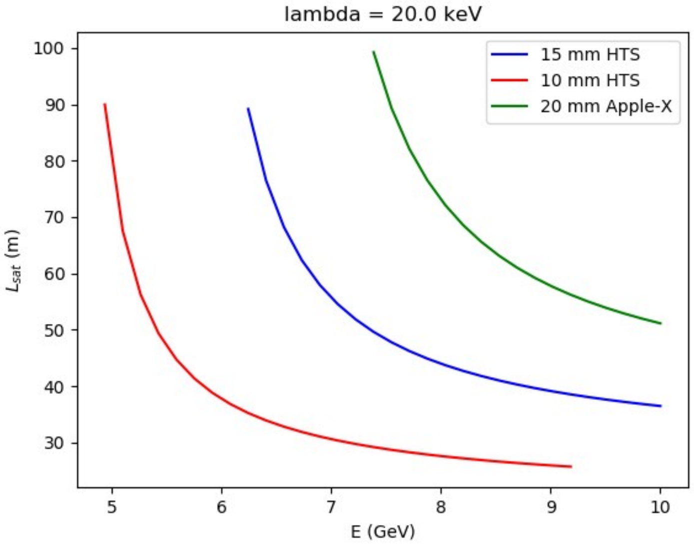
Saturation power:



# Ming-Xie studies for $E_\gamma$ = 20.0 keV

S. Reiche

Saturation length:



Saturation power: